

A Performance Review of Ethanol-Diesel Blended Fuel Samples in Compression-Ignition Engine

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Abstract

The use of ethanol blended with diesel is receiving more attention by many researchers in recent times. It was shown that ethanol-diesel blends were technically acceptable for existing diesel engines. Ethanol as an attractive alternative fuel is a renewable bio-based resource and it is oxygenated, thereby providing the potential to reduce particulate emissions in compression-ignition engines. In this review the properties and specifications of ethanol blended with diesel fuel are discussed. Special emphasis is placed on the factors critical to the potential commercial use of these blends. These factors include blend properties such as stability, viscosity and lubricity, safety and materials compatibility. The effect of the fuel on engine performance, durability and emissions is also considered. The formulation of additives to correct certain key properties and maintain blend stability is suggested as a critical factor in ensuring fuel compatibility with engines. However, maintaining vehicle safety with these blends may require special materials and modification of the fuel tank design. Further work is required in specifying acceptable fuel characteristics, confirming the long-term effects on engine durability, and ensuring safety in handling and storing ethanol-diesel blends.

Keywords: Ethanol; Renewable; Blend; Bio-fuel; Diesel engines

Introduction

The rising price of petroleum products coupled with increasing threat to the environment due to exhaust emissions and global warming have generated an intense international interest in developing alternative non-petroleum fuels for engines. Ethanol has been identified as one of the possible alternative fuels [1]. Ethanol can be produced from crops with high sugar or starch contents. Some of these crops include: sugarcane, sorghum, corn, barley, cassava, sugar-beets, etc. Besides being a biomass based renewable fuel, ethanol has cleaner burning and higher octane rating than the various vegetable oils [2]. Gasohol (a mixture of 10% alcohol with 90% gasoline) is already a commercial fuel in over 35 countries of the World including the USA, Canada and France. In Brazil, cars with modified engines have been running for years on neat alcohol [3]. The use of ethanol blended with diesel was a subject of research in the 1980s and it has been shown that ethanol-diesel blends were technically acceptable for existing diesel engines. The relatively high cost of ethanol production at that time meant that the fuel could only be considered in cases of fuel shortages. Recently, the economics have become much more favorable in the production of ethanol and it is able to compete with standard diesel. Consequently, there has been renewed interest in the ethanol-diesel blends with particular emphasis on emissions reduction. An additional factor that makes ethanol attractive as a fuel extender or substitute is that it is a renewable resource [4]. When considering an alternative fuel for use in diesel engines, a number of issues are important. These issues include supply and distribution, integrity of the fuel being delivered to the engine, emissions and engine durability. The purpose of this review is to discuss the properties and specifications of ethanol blended with diesel fuel with special emphasis on the factors critical to the potential commercial use of these blends. These factors include blend properties such as stability, viscosity and lubricity, safety and materials compatibility. The effect of the fuel on engine performance, durability and emissions would also be considered.

Ethanol as a Fuel

Although ethanol has been traditionally thought of as a beverage

product for use in spirits, beer and wine, ethanol is an important, viable alternative to unleaded gasoline fuel [5]. Ethanol is used as an automotive fuel; it can be used alone in specially designed engines, or blended with gasoline and used without any engine modifications. Motorboats, motorcycles, lawnmowers, chain saws etc. can all utilize the cleaner gasoline/ethanol fuel. Most importantly, the millions of automobiles on the road today can use this improved fuel [5]. Farmers, cities, counties, and rural electric co-op fleets, plus snowmobile racers and fishing guides in the US use ethanol blends exclusively with no performance problems. Adjustments may be required for air intake. Ethanol fuel referred to as "gasohol" - the most common blends contain 10% ethanol mixed with 90% gasoline (E10). Ethanol is a high-octane fuel (2.5 - 3 points above the octane of the blending gasoline) with high oxygen content (35% oxygen by weight), for this reason it allows the engine to completely combust the fuel, resulting in fewer emissions. Since ethanol is produced from plants that harness the power of the sun, ethanol is also considered as a renewable fuel. Therefore, ethanol has many advantages as an automotive fuel [5]. In America E85 is a federally designated fuel that is composed of 85% ethanol and 15% gasoline. Currently there are thousands of E85 vehicles on the roads in America, driving millions of miles every year. E85 vehicles are flexible fuel vehicles, meaning they will run on whatever is in the tank, from 100% gasoline to 85% ethanol, but run best on E85. Ethanol is a water-free alcohol and therefore can withstand low temperatures. Its low freezing point has made it useful as fluid in thermometers

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for temperatures below -40°C , the freezing point of mercury, and for other low temperature purposes, such as for antifreeze in automobile radiators [5].

Blend Properties

The blend properties that are essential to the proper operation of a Compression Ignition engine are of important, because the addition of ethanol to diesel fuel affects certain key properties with particular reference to blend stability, viscosity and lubricity, energy content and cetane number [5]. Also, materials compatibility and corrosiveness are vital factors that need to be considered. Meanwhile properties that affect safety should be foremost considered in any fuel evaluation. These properties include flashpoint and flammability. Finally fuel biodegradability has become a significant factor with respect to ground water contamination [5].

Blend stability

The main factors that affect ethanol solubility are temperature and water content of the blend. At warm ambient temperatures dry ethanol blends readily with diesel fuel. However, below about 10°C the two fuels separate, a temperature limit that is easily exceeded in many parts of the world for a large portion of the year [6]. Prevention of this separation can be accomplished in two ways: by adding an emulsifier which acts to suspend small droplets of ethanol within the diesel fuel, or by adding a co-solvent that acts as a bridging agent through molecular compatibility and bonding to produce a homogeneous blend [7]. Emulsification usually requires heating and blending steps to generate the final blend, whereas co-solvents allow fuels to be “splash-blended”, thus simplifying the blending process. Both emulsifiers and co-solvents have been evaluated with ethanol and diesel fuel. Moses et al. investigated micro-emulsions of aqueous ethanol (5% water) and diesel fuel using a commercial surfactant [8]. They reported that the blends formed spontaneously and required only minor stirring. They also appeared transparent indicating that the dispersion sizes were less than a quarter of a wavelength of light and were regarded as “infinitely” stable, i.e., thermodynamically stable with no separation even after several months. Approximately 2% surfactant was required for each 5% aqueous ethanol added to diesel fuel. Boruff et al. developed formulations for two micro-emulsion surfactants, one ionic and the other detergentless [9]. Blends of these surfactants with aqueous ethanol and diesel were transparent and stable at temperatures as low as 15.5°C . In studies, Letcher, Meiring et al. and Letcher identified as effective co-solvents tetra-hydro-furan, obtained at low cost from agricultural waste materials, and ethyl acetate that could be made inexpensively from ethanol [10,11,7]. Ternary liquid-liquid phase diagrams illustrating the relative effects of moisture content and temperature on blend stability and also the increasing amounts of co-solvent required with increasing moisture and temperature to maintain a single phase liquid are shown in Figures 1 and 2. Letcher concluded that the ratio of ethyl acetate to ethanol to ensure complete miscibility down to 0°C was consistently 1:2 [7].

Recent studies in the US have made use of additives from three different manufacturers. Pure Energy Corporation (PEC) of New York was the first manufacturer to develop an additive package that allowed ethanol to be splash-blended with diesel fuel using a 2-5% dosage with 15% anhydrous ethanol and proportionately less for 10% blends [12]. A small amount of commercially available cetane improver ($<0.33\%$ by volume) also was added to restore the cetane value of the blend. The second additive manufacturer was AAE Technologies of the United Kingdom, who have been testing 7.7% and 10% ethanol-diesel blends

containing 1% and 1.25% AAE proprietary additive in different states in the USA [12]. The third manufacturer was GE Betz, a division of General Electric, Inc., who has developed a proprietary additive derived purely from petroleum products, compared to the previous two, which are produced from renewable resources.

Viscosity and lubricity

Fuel viscosity and lubricity play significant roles in the lubrication of fuel injection systems, particularly those incorporating rotary distributor injection pumps that rely fully on the fuel for lubrication within the high pressure pumping mechanism. In the common rail accumulator fuel-injection system, the high-pressure pump that delivers fuel to the rail also relies on the fuel for lubrication. In in-line pumps and unit injectors, there is less reliance on the fuel for lubrication; however, there are still some metal interfaces that require lubrication by the fuel such as between plunger and barrel. Injector lubrication also is affected, particularly at the needle guide-nozzle body interface. Hansen et al. reported that lower fuel viscosities lead to greater pump and injector leakage, reducing maximum fuel delivery and ultimately power output [4]. Hot restart problems also may be encountered as insufficient fuel may be injected at cranking speed when fuel leakage in the high-pressure pump is amplified because of the reduced viscosity of the hot fuel. Irshed stated that low lubricity can result in fuel pump failure and injector degradation at an accelerated rate even when ethanol is used in as small quantity as 5%. In the study, it was averred that *Puranol* was designed to address both lubricity and

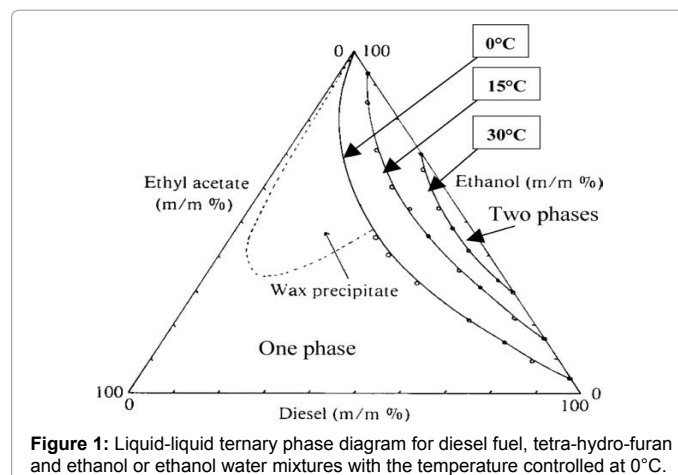


Figure 1: Liquid-liquid ternary phase diagram for diesel fuel, tetra-hydro-furan and ethanol or ethanol water mixtures with the temperature controlled at 0°C .

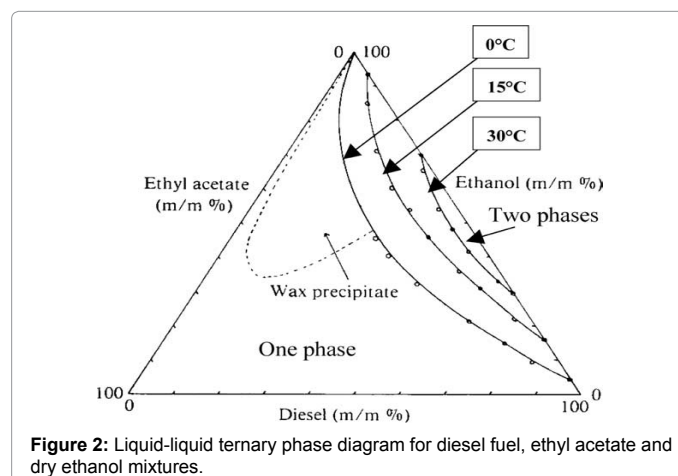


Figure 2: Liquid-liquid ternary phase diagram for diesel fuel, ethyl acetate and dry ethanol mixtures.

cetane property limitations [13]. Also Wrage and Goering investigated the variation of kinematic viscosity with percentage of ethanol present in the fuel blend [14]. They concluded that a blend of 18.5% dry ethanol (1.1 mm²/s viscosity) with No. 2 diesel (2.46 mm²/s viscosity) would equal the ASTM minimum viscosity of 2.0 mm²/s at 37.8°C and would be well above the minimum for No. 1 diesel as shown in Figure 1. Moreover, Speidel and Ahmed reported a viscosity of 2.25 mm²/s for a blend containing 15% dry ethanol, 5% PEC additive and 80% diesel [15]. It should be noted that the final blend viscosity is dependent on the viscosity of the diesel fuel. Blending ethanol with a diesel fuel that has a viscosity close to the minimum is likely to yield an overall viscosity lower than the ASTM minimum. Hardenberg and Schaefer included 1% castor oil in a 95% ethanol fuel that was used successfully in a fleet of trucks and buses in Brazil [16]. Minimum specifications for viscosity and lubricity of ethanol-diesel blends are required in order to ensure that fuel injection system durability is not compromised relative to diesel fuel usage and that engines are able to start reliably when hot. The lack of reports of specific measurements to corroborate these trends with ethanol-diesel blends indicates a need to investigate their atomization and spray characteristics, as these parameters have a significant effect on the combustion process.

Materials compatibility

Ethanol is chemically very different from diesel fuel components and will interact differently with *elastomers* and metal surfaces. Based on past experience with impurities in ethanol that have led to degradation of fuel systems, fuel ethanol must have a specification to control its acidity and its blending properties. It might be appropriate to set a maximum total acidity for ethanol-diesel blends of 0.08 mg KOH/g [17]. This can be achieved with the use of corrosion inhibitors and ensuring a high quality ethanol fuel. Some metallic materials are known to oxidize by contact with fuel ethanol blends having high alcohol concentrations. Zinc, brass, lead, copper and aluminum are some of these sensitive metals. Meanwhile a concern in using ethanol to fuel vehicles is associated with corrosion in the fuel system and storage facilities. Energy Technology System Analysis Programme in 2010 investigated that the most notable compatibility problems identified in fleet tests include: degradation of plastic materials and rubber (i.e., soften and swell) caused by the solvent-like nature of ethanol; and degradation of metals due to the acidic or galvanic nature of ethanol. Although anhydrous ethanol is only slightly corrosive, its hygroscopic nature makes water contamination unavoidable, with metal corrosion risk increasing significantly in the presence of water contaminants such as sodium chloride and organic acids [18,19]. Kane et al. and Chandler et al. reported that in both non Flexible Fuel Vehicles (non-FFVs) and Flexible Fuel Vehicles (FFVs), corrosion and degradation problems in the fuel system have been solved by using stainless steel substituting for aluminum, magnesium, lead, and brass among other metals [20,21]. Polyvinyl chloride and some rubber parts have been replaced by materials such as high-density polyethylene, nylon, and fluorinated plastics such as Teflon.

Energy content

The loss of engine maximum power was the most significant adverse performance effect due to the lower energy content of ethanol. Since the energy content of a fuel has a direct influence on the power output of the engine. Carmen et al. found that an increase in fuel consumption approximately equivalent to the reduction in energy content of the fuel can be expected when using ethanol-diesel blends [22]. However, with ethanol percentages of 10% or less, vehicle operators have reported no noticeable differences in performance compared to running on diesel fuel.

Wrage and Goering stated that it would be desirable for ethanol-diesel blends to have gross energy contents at least 90-95% of that for No. 2 diesel to permit existing engines to deliver adequate power for the loads for which the vehicle is designed [14]. The energy content of ethanol-diesel blends decreases by approximately 2% for each 5% of ethanol added, by volume, assuming that any additive included in the blend has the same energy content as diesel fuel.

Cetane number

The minimum cetane number specified by ASTM Standard D 975-02 for No. 2 diesel is 40. Typical No. 2 diesel fuels have cetane numbers of 45-50. Hansen et al. reported that with the inverse relationship of octane number and cetane number, ethanol exhibits a low cetane rating. Hence, increasing the concentration of ethanol in diesel lowers the cetane number proportionately [23]. Hardenberg and Ehnert stated that using cetane number to describe the ignition characteristics of ethanol-diesel blends is unreliable, because of discrepancies in the determination of cetane numbers below 30 [24]. However, they estimated that the cetane number of ethanol was between 5 and 15. Lower cetane numbers mean longer ignition delays, allowing more time for fuel to vaporize before combustion starts. Initial burning rates are higher causing more heat release at constant volume, which is a more efficient conversion process of heat to work. Nevertheless, it is preferable to add an ignition improver to raise the cetane number of ethanol-diesel blends so that they fall within an acceptable range equivalent to that expected of No. 2 diesel fuel. Schaefer and Hardenberg evaluated a number of ignition improvers for ethanol fuel with special emphasis on biomass-derived nitrates [25]. They noted a significant dependence of the energy release per equivalent nitrate on the molecular weight of the ignition improving nitrate. Hardenberg and Schaefer found triethylene glycol dinitrate (TEGDN) to be the most satisfactory ignition improver in tests performed in Brazil, especially since it could be manufactured from ethanol [16]. Meiring et al. added 4.5% octyl nitrate ignition improver to a 30% ethanol-diesel blend to achieve the same ignition delay as for diesel fuel [11]. Moses et al. found some differences in cetane numbers between ethanol-diesel emulsions and stable blends of aqueous ethanol and diesel containing no additive [8]. The emulsified ethanol had less effect on cetane than the ethanol in solution. They speculated that this was due to a shielding effect of the emulsion structure delaying evaporation of the alcohol from the fuel droplets, while in the solution the ethanol molecules were free to evaporate immediately.

Safety and biodegradability

According to Battelle, flammability limits are about 13-42°C for ethanol-diesel mixtures without additives regardless of the percentage of ethanol present [26]. For diesel this range is 64-150°C [27]. On the other hand, the low evaporation speed of ethanol keeps the alcohol concentration so low that it is not explosive in accidents [28].

The vapor produced by the evaporation of motor fuels can create flammable conditions in partially filled fuel tanks during refueling, and when damage or leakage occurs in tanks or other fuel system components [29]. In the fuel tank headspace, rising temperatures will produce fuel vapors, which progress from too-lean-to-burn, to combustible, to too-rich-to-burn [9]. Speidel and Ahmed evaluated the biodegradability of alternative fuels, including a diesel blend with 15% ethanol and 5% PEC additive [30]. They found that this blend was 70% more biodegradable than diesel fuel. The impact of sunlight and heat exposure on long term storage stability of this blend also was investigated. Diesel fuel formed a dark irreversible residue under such

conditions, while the blend coloration deepened but no residual matter was detected [31]. Hence, further work is required in this area.

Engine Performance with Blends

Comparisons of engine performance between ethanol-diesel blends and standard diesel in unmodified engines generally show reductions in power that are approximately the same as the reductions in energy content of the blends relative to diesel fuel. Increased leakage in the fuel injection pump with the lower viscosity fuels also contributes to reduced power in the load control range of the engine. Meiring et al. reported a 5% drop in maximum fuel delivery when evaluating a 30% ethanol-diesel blend in a tractor engine fitted with a rotary distributor pump [11]. They adjusted the maximum fuel delivery setting on the pump to partially restore the power lost from reduced energy content and fuel pump leakage. In a study, Hansen et al. measured a 7-10% decrease in power at rated speed with a 15% dry ethanol, 2.35% PEC additive and 82.65% No. 2 diesel fuel blend run in a Cummins 5.9 L engine [32]. Kass et al. checked the torque output from the same model engine with two blends containing 10% and 15% dry ethanol, respectively, and 2% GE Betz additive, and reported an approximate 8% reduction for both fuel blends [33]. As would be expected, the specific fuel consumption (SFC) in kg/kW h increases with increasing concentrations of ethanol in the blend because of the reduced energy content. However, specific energy consumption (SEC) in MJ/kW h is approximately the same as for diesel fuel or has been shown to be slightly better. Moses et al. stated that the improvements in SEC were small but consistent for the ethanol-diesel blends tested and they were assumed to be the result of an improvement in the thermal cycle efficiency [8]. Hansen et al. reported similar trends for a combined harvester operating under field conditions on 10% ethanol, in which the combine on the blend ran consistently with a 2-3% higher brake thermal efficiency [4].

Engine Durability

A limited range of durability tests have been conducted on ethanol-diesel blends both in the laboratory and in the field. In early studies, tests with blends containing approximately 10% and 15% dry ethanol indicated no abnormal wear in engines correctly adjusted for injection timing [34,35,36]. Some engines included in these tests were more sensitive to a lowering of the cetane number and accordingly an increased ignition delay causing piston erosion from severe localized temperatures and pressures. However, a small retardation of injection timing was recommended so as to reduce rates of pressure rise. In the durability tests conducted by Meiring et al. no abnormal deterioration of the engine or fuel injection system was detected after 1000 h of operation on a blend containing 30% dry ethanol, small amounts of octyl nitrate ignition improver and ethyl acetate phase separation inhibitor, and the remainder diesel fuel [11]. Hansen et al. performed a laboratory-based 500 h durability test on a Cummins ISB 235 engine running on a 15% dry ethanol, 2.35% PEC additive and 82.65% diesel fuel [4]. The engine operated at rated speed and maximum load in order to maximize the fuel throughput in the fuel injection system. With the exception of the fuel injection system, no abnormal deterioration in engine condition was detected based on detailed engine component measurements and examination. They said further tests are required to verify these results. Long-term durability tests of at least 1000 h are necessary to provide confirmation that ethanol-diesel blends do not adversely affect engine wear compared to the norms established for diesel fuel usage.

Emissions

Early studies of the effect of ethanol-diesel blends on engine

performance included measurements of soot output in the exhaust with a smoke-meter [14,35]. Substantial reductions in particulate matter (PM) were observed in these tests. Recent studies have shown that the improvement in exhaust emissions provided by oxygenated fuels depended almost entirely on the oxygen content of the fuels, regardless of the oxygenate to diesel fuel blend ratios or the type of oxygenate [37]. In their study of the effect of oxygen enhancement on emissions from a direct injection diesel engine, Donahue and Foster found that the improvement in emissions depends on the local oxygen concentration in the fuel plume regardless of the method of oxygen enhancement [38]. Emissions tests conducted specifically on ethanol-diesel blends confirmed the effect of substantially reducing PM [33,39]. The effect on carbon monoxide (CO), total hydrocarbon (THC) and oxides of nitrogen (NOx) are less clear [33]. In addition, comparative emissions data are influenced by a number of factors that may have caused greater differences than those brought about by the fuel. These factors include engine fuel metering technology, exhaust control technology, age of the vehicle, maintenance history, test procedure, and test conditions. Nevertheless, these tests provide a means of gauging the relative benefits of introducing these blends as a substitute for traditional diesel fuel. In emissions tests performed by Spreen, Schaus et al. and Kass et al. Showed that the test engines, test procedures and base fuels varied considerably [33,39]. The results of Spreen and Kass et al. showed a consistent reduction in PM of 20-27% and 30-41% for 10% and 15% ethanol blends, respectively. Reductions in NOx varied from zero to 4-5% [33,39]. Both decrease and increase in CO emissions occurred, while THC increased substantially, but both were still well below the regulated emissions limit. The measurements reported by Schaus et al. vary considerably for both PM and NOx with both decrease and increase in emissions being dependent on speed and load of the engine [37]. Both Schaus et al. and Kass et al. emphasize the potential to optimize injection characteristics, so as to minimize emissions over the complete performance map of the engine [33,37]. The major variations in emissions measured by Schaus et al. are an indication of the reductions in emissions that could be obtained with ethanol-diesel blends. Further factors that need to be considered are the influence of ethanol-diesel blends on exhaust gas recirculation systems (EGR) [37]. Kass et al. stated that the higher CO and THC emissions suggested that fuel blends might offer a means to enhance advanced emission control systems that require regeneration, such as NOx adsorbers, by supplying a reducing agent [33]. Kass et al. concluded from their tests that ethanol-diesel blends could be applicable as low emission fuels for current and older model vehicles that are not required to meet future EPA emission standards [33]. However, extensive testing of these fuel types in older and late model diesel engines, need to be performed in order to accurately assess performance. The addition of ethanol to diesel naturally reduces the content of sulfur in the fuel in proportion to the amount added, including any sulfur-free additive. As much as a 20% volumetric reduction in sulfur may be provided, thus significantly reducing SO₂ emissions [12].

Conclusions

In conclusion, the following can be drawn from the above reviewed:

1. The properties of ethanol-diesel blends have a significant effect on safety, engine performance and durability, and emissions.
2. A set of specifications that define key fuel characteristics pertaining to ethanol-diesel blends and additives should be established in collaboration with fuel and additive manufacturers and with engine manufacturers before these blends can be commercialized.

- An increase in fuel consumption approximately equivalent to the reduction in energy content of the fuel can be expected when using ethanol–diesel blends. With ethanol percentages of 10% or less, operators have reported no noticeable differences in performance compared to running on diesel fuel.
 - Long-term durability tests in a range of engines with different fuel injection system configurations will help to confirm that diesel oxygenated with diesel does not adversely affect engine wear compared to diesel fuel. Such tests should be performed in collaboration with engine manufacturers.
 - It is accepted that the addition of ethanol to diesel fuel will have a beneficial effect in reducing the PM emissions at least. The amount of improvement varies from engine to engine and also within the working range of the engine itself. While there is considerable value in being able to use the fuel directly in an unmodified engine, small adjustments to fuel injection characteristics may result in further gains in reducing emissions.
 - The flammability of ethanol-diesel blends indicates that, according to the NFPA in the USA they should be treated as Class I liquids as they have flashpoints below 37.8°C, in contrast to diesel fuel, which is a Class II liquid. Therefore, appropriate measures need to be implemented to meet the storage, handling and dispensing requirements that are stipulated for Class I liquids. These measures may include the fitting of flame arresters on fuel tanks.
 - The rapidly increasing use of ethanol as a fuel additive for gasoline provides an opportunity to expand its further use as an oxygenate for diesel fuel, with the beneficial effects of reducing many countries of the world dependence on imported petroleum, and substituting diesel fuel with a renewable resource that will expand markets for agricultural commodities used to produce ethanol.
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