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An investigation of hydrogen supplementation on combustion and emissions of heavy-duty diesel engines

ChetMun Liew
West Virginia University

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**An Investigation of Hydrogen Supplementation on Combustion and Emissions
of Heavy-Duty Diesel Engines**

ChetMun Liew

**Thesis Submitted to the
College of Engineering and Mineral Resources
at West Virginia University
in partial fulfillment of the requirements
for the degree of**

**Master of Science
in
Mechanical Engineering**

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**Morgantown, West Virginia
2010**

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ABSTRACT

An Investigation of Hydrogen Supplementation on Combustion and Emissions of Heavy-Duty Diesel Engines

ChetMun Liew

Hydrogen (H_2) has long been recognized as a carbon-free fuel having excellent combustion characteristics compared to hydrocarbon fuel. This research investigated the effects of H_2 addition on the performance, combustion, and emission characteristics of two turbocharged heavy-duty diesel engines. The effects of H_2 addition, engine load, engine speed, and diesel fuel flow rate on the brake thermal efficiency (BTE), cylinder pressure, combustion process, and exhaust emissions of Oxides of Nitrogen (NO_x), Particulate Matter (PM), Carbon Monoxide (CO), Unburned Hydrocarbon (HC), and Carbon Dioxide (CO_2) were explored. The engine load was varied from 10 to 100% with H_2 concentration in the intake mixture ($H_2/(H_2+Air)$, vol.) varied from 0 to 7.5%. Engine speed was varied from 1200 to 1800 RPM.

The addition of H_2 to a 1999 Cummins ISM370ESP engine and a 2004 Mack MP7 355E engine was shown to reduce substantially the emissions of PM, CO, and CO_2 . In comparison, the effect of H_2 addition on the emissions of HC was relatively small. When operated at 30 to 70%, the addition of H_2 (3-6.5%) enhanced the NO_x emissions of the 1999 Cummins ISM370ESP engine. The emissions of NO_x at 70% load increased almost linearly from 3.34 to 4.66 g/bhp-hr with the addition of 6% H_2 . However, the addition of H_2 had mild effect on the NO_x emissions of the 2004 Mack MP7 355E. The substantial reduction of NO_x emissions was only observed with the addition of relatively large amounts of H_2 (5-6.5%) at a very narrow low load operational range (10-20%). When operated at 10% load, the addition of 6% H_2 to a 1999 Cummins ISM370ESP engine reduced NO_x emissions from 5.23 to 0.54 g/bhp-hr.

The improvement to the BTE has been one of the main objectives of this engine research. The addition of a relatively large amount of H_2 (3-7%) at the range from 20 to 100% load improved the BTE for both engines. When operated at 70% load, the BTE improved from 41.7 to 43.6% with the addition 6% H_2 for 1999 Cummins ISM370ESP. In comparison, the addition of a relatively small amount of H_2 (0-2%) lowered the BTE. When operated at 70% load, the BTE slightly reduced from 41.7 to 41.3% with the addition of 1% H_2 for 1999 Cummins ISM370ESP. The addition of H_2 at 10% load was found to reduce the brake thermal efficiency for the range of data measured. The combustion analysis demonstrated the significant effect of H_2 addition in enhancing the heat release process and increasing the peak cylinder pressure when operated at 30 to 70% load. However, the addition of H_2 at 10 and 15% load was shown to slightly retard the combustion phasing and lower the peak cylinder pressure.

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NONMENCLATURE

ADC	Analog to Digital Converter
B20	Biodiesel 20 (a mixture composed of 20% of biodiesel with 80% of diesel)
BMEP	Brake Mean Effective Pressure
BSN	Bosch Smoke Number
BTE	Brake Thermal Efficiency
CAFEE	Center for Alternative Fuels, Engines and Emissions
CEGR	Cooled Exhaust Gas Recirculation
CFR	Code of Federal Regulations
CFV	Critical Flow Venturi
CO ₂	Carbon Dioxide
CO	Carbon Monoxide
COV	Coefficient of Variation
CVS	Constant Volume Sampler
DC	Direct Current
EERL	Engine and Emissions Research Laboratory
EGR	Exhaust Gas Recirculation
ESC	European Stationary Cycle
ETC	European Transient Cycle
ELR	European Load Response
FSN	Filter Smoke Number
GHG	Green House Gas
H ₂	Hydrogen
H ₂ O	Water
HC	Hydrocarbon
HP	Horsepower
IC Engine	Internal Combustion Engine
ID	Ignition Delay
LFE	Laminar Flow Element
NO	Nitric Oxide
NO _x	Oxides of Nitrogen

NO ₂	Nitrogen Dioxide
O ₂	Oxygen
O/C	Oxygen Carbon Ratio
PM	Particulate Matter
PO	Partial Oxidation
ppm	Parts per Million
REGR	Reformed Exhaust Gas Recirculation
RME	Rapeseed Methyl Ester
RPM	Revolution per Minute
SI Engine	Spark Ignition Engine
SCFM	Standard Cubic Feet per Minute
SME	Soy Methyl Ester
SMPS	Scanning Mobility Particle Sizing
SO ₂	Sulfur Dioxide
SOC	Start of Combustion
SOI	Start of Injection
TDI	Turbocharged Direct Injection
UDDS	Urban Dynamometer Driving Schedule
ULSD	Ultra Low Sulfur Diesel
VGT	Variable Geometry Turbocharger
WVU	West Virginia University

1 INTRODUCTION

1.1 Introduction

Hydrogen (H_2) has long been recognized as a carbon-free fuel having excellent combustion characteristics compared to the hydrocarbon fuel for applications in internal combustion (IC) engines. The burning of H_2 in air produces mainly water (H_2O), small amount of oxides of nitrogen (NO_x) when burned at excessive lean mixture, without fuel-resourced particulate matter (PM) emissions due to the unique fuel composition without bearing any carbon. These features make H_2 an excellent fuel for both traditional power production devices such as IC engines and the latest innovative power devices such as fuel cells. The application of H_2 in these devices makes it possible to potentially meet the ever increasingly stringent emission regulation, including the possible elimination of the on-site green house gas (GHG) emissions. The concise statements and detailed discussions of the positive features of H_2 as a fuel and the associated limitations to its wide application as fuel have been the subject of much research and many publications [Das, 1990; Furuhashi, 1983; Karim, 2003; White et al., 2006]. The past research of H_2 as fuel has focused mainly on its application in spark ignition (SI) engines utilizing its fast flame propagation properties. Hydrogen has also been demonstrated as a fuel being able to support a propagating flame with extremely lean mixture, which is a very attractive property of the H_2 as a SI engine fuel.

Diesel engines are widely used in transportation and off-road vehicles due to their high power density and fuel conversion efficiency. However, the further development of advanced diesel engine technologies is facing significant challenges. These include the

requirements of simultaneously reducing the exhaust emissions of both NO_x and PM. In principle, NO_x is formed under high combustion temperature and oxygen (O_2)-rich operating conditions [Heywood, 1988]. The approaches tending to reduce the combustion temperature will reduce the engine out NO_x emissions. In comparison, PM is formed in a diesel engine due mainly to the heterogeneous combustion characteristics of diesel engine. The presence of a fuel rich mixture under high temperature and pressure enhance the formation of PM. The approaches that help to improve the fuel vaporization and mixing process can reduce the formation of PM and correspondingly reduce PM emissions. The application of cooled exhaust gas recirculation (CEGR) has been demonstrated as an effective approach that can significantly reduce NO_x emissions. However, the application of EGR increases the PM emissions, especially under high load operation.

Hydrogen as fuel can also be burned in compression ignition (CI) engines using a H_2 -diesel dual fuel combustion mode with H_2 or H_2 -rich syngas supplemented to the intake mixture. At the end of the compression stroke, the compressed hot H_2 -air mixture is ignited by a pilot diesel spray. Such a dual fuel combustion mode has been demonstrated as an efficient and reliable approach of burning H_2 in CI engines. Extensive research has been conducted using small single cylinder diesel engines and multi-cylinder light-duty diesel engines to investigate the effect of the addition of H_2 on the performance, combustion, and emissions characteristics of CI engines [Bika et al., 2008; and Varde and Frame, 1983]. These include the brake thermal efficiency (BTE), heat release process, exhaust emissions of NO_x , PM, CO, CO_2 and HC. However, these criteria have not been reported in heavy-duty diesel engines application yet.

1.2 Objective

The objective of this research was to investigate the effect of H₂ addition on combustion and emission characteristics of heavy-duty diesel engines. The effects of the H₂ addition, engine load, engine speed, and the diesel fuel flow rate on the engine performance, combustion process, and exhaust emissions have been explored.

2 LITERATURE REVIEW

2.1 Hydrogen Application as Fuel

As a long time recognized carbon-free fuel, H_2 can be used in traditional IC engines, gas turbines and also the fuel cells. Among these, the operation of the most fuel cells requires high quality pure H_2 . The presence of other components such as carbon monoxide (CO) and Sulfur Dioxide (SO_2) has been shown to deactivate the catalyst of fuel cells and reduce significantly the service life. Such an excessively demanding requirement for high purity H_2 makes the operation of fuel cells economically uncompetitive though high thermal efficiency could be achieved without formation of pollutants. In comparison to fuel cells, IC engines can burn almost any low purity H_2 even with the presence of quite a large amount of diluents. For example, the reformed gas containing mainly H_2 with the presence of carbon dioxide (CO_2), CO, H_2O and nitrogen (N_2), has been demonstrated as a suitable fuel showing H_2 -like desirable combustion properties [Li and Karim, 2005]. The application of H_2 or its mixtures with traditional fuels also offers the opportunity of optimizing engine performance and reducing exhaust emissions.

2.1.1 Application of H_2 in SI Engines

Hydrogen has long been recognized as a fuel having some unique and highly desirable properties, such as low ignition energy, very fast flame propagation speed, and wide lean operational range. The capability of H_2 in supporting a propagating flame at extremely lean mixture was an attractive property of H_2 as SI engine fuel. The extensive research on pure H_2 as fuel has led to the development of the dedicated SI- H_2 engine. For

example, Ford developed P2000 H₂ engine, which was used to power Ford's E-450 Shuttle Bus [Gopalakrishnan et al., 2007; Stockhausen et al., 2002; and Tang et al., 2002]. BMW developed a 6 liter, V-12 engine using liquid H₂ as fuel [Kiesgen et al., 2006]. With an external mixture formation system, this engine has a power out about 170 kW and an engine torque of 340 N.m.

Most of the past research associated with H₂ application in SI engines focused on its substitution to gasoline, a well known H₂ enriching process. The extensive research in this area has demonstrated that H₂ enriching helps to improve the performance of SI engine for the following reasons: (1) Enhancing the H₂ flame propagation rate about 4 times that of traditional fuels. The addition of H₂ to slow burning fuel enhanced substantially the flame propagation rate; (2) The addition of H₂ to traditional fuels has been shown to extend the operational region toward the leaner mixture, which is very important to obtain extremely low NO_x emissions; (3) Improving combustion stability (less cycle to cycle variation) and enhancing combustion efficiency benefiting from the reduced emissions of CO and hydrocarbon (HC). Detailed information can be found in the literature [Das, 1990; Karim, 2003; Li and Karim, 2005; Munshi et al., 2004; Topinka et al., 2004; and White et al., 2006].

2.1.2 Application of H₂ in Compression Ignition Engines as Sole Fuel

Although the energy needed to ignite an H₂-air mixture is much less than most hydrocarbon fuels, but the ignition temperature of H₂ is much higher than other diesel fuel. Wong [1990] investigated the feasibility of using H₂ as the sole fuel in a direct injection diesel engine. The engine combustion chamber was coated with ceramics to

reduce the heat rejection from combustion chamber to coolant so as to increase the bulk gas temperature. By using a compression ratio of 17.9 to obtain a maximum compression temperature of approximately 900 K, the lubrication oil was found to burn prior to that of H_2 fuel. Only sporadic CI of H_2 was achieved in a lower compression ratio of 17.1 and an engine speed of 1450 RPM. The ignition timing cannot be controlled and varied significantly under identical experimental conditions. It was concluded that the application of H_2 as the sole fuel in direct injection diesel engine without an external ignition source, was neither practical nor feasible. A number of researchers demonstrated that it was necessary to employ a suitable ignition assistance device to ignite H_2 -air mixture in CI engine. The approaches tested included glow plug, spark assistance and pilot injection of diesel fuel to achieve reliable ignition of H_2 in CI engines [Gopal et al., 1982; Ikegami et al., 1982; and Karim and Klat, 1982]. For example, Homan et al. [1979] demonstrated that it was very difficult to operate an H_2 engine with just compression. However, the injection of pilot diesel fuel provided reliable ignition of H_2 . Furuhamma and Fukuma [1986] developed a turbo-charged, two-stroke CI engine using H_2 as the sole fuel. A hot surface igniter was developed to help the ignition of H_2 supplied by direct in-cylinder injection. It was reported that such a hot surface igniter successfully ignited the H_2 from low to full load operation.

2.1.3 Application of H_2 in Diesel Engines as Supplemental Fuels

Considering the high temperature needed to ignite an H_2 -air mixture, external ignition resources is needed for the reliable, stable and repeatable ignition of H_2 -air mixtures. When burned in a CI engine, H_2 was usually mixed with air in the intake manifold. At the end of the compression stroke, the H_2 -air mixture was ignited by a pilot

diesel spray, which vaporized, mixed and reacted with O_2 that contained in the H_2 -air mixture and finally ignited. The energy released from diesel combustion provided sufficient energy to initiate the ignition of H_2 and its combustion. Such a dual fuel operation mode has been shown to be the most popular and stable combustion mode for gaseous fuels including H_2 when used as a supplemental fuel in a diesel engine [Karim, 2003]. When burned in a H_2 -Diesel dual fuel engine, the H_2 -air mixture can be either burned through flame propagation like a SI engine if the H_2 -air mixture is rich enough to support the propagation of the flame; or the H_2 can be burned through oxidation of H_2 in air if a H_2 -air mixture was leaner than flammability limit. For example, Gopal et al. [1982] investigated the effect of the addition of H_2 on the combustion and emission of a single cylinder diesel engine. It was shown that the addition of H_2 to diesel fuel increased the energy release rate of the premixed combustion and thereby improved the thermal efficiency. The detailed information of dual fuel engine combustion process could be found in the literature [Boehman and Corre, 2008; and Karim, 2003].

2.2 Literature Review of H_2 -Diesel Dual Fuel Engine

2.2.1 Emissions of NO_x

Many H_2 -diesel dual fuel research projects expressed their wishes to reduce the emissions of NO_x through the substitution of diesel fuel with H_2 . However, the research results reported in the literature did not support the expectations. For example, Varde and Frame [1983] reported some of the earlier work in examining the effect of the H_2 addition on diesel combustion and emissions. They used a single cylinder small diesel engine with a rated power of 5 kW. The addition of H_2 to this diesel engine increased the emissions of NO_x especially when operated under full load. For example, the NO_x emissions increased

almost linearly from about 900 ppm for pure diesel operation to about 1150 ppm with 15% of diesel substituted by H_2 when operated at 82% load. In addition, the NO_x emissions increased from 750 ppm approximately linearly to 950 ppm when 17% of diesel fuel was substituted.

Kumar et al. [2003] investigated the effect of the H_2 addition on NO_x emissions of a single cylinder, four stroke, diesel engine with a rated power of 3.7 kW. For both standard diesel and Jatropa oil as main fuel, the addition of H_2 increased the emissions of NO_x when operated under high load. In comparison, the addition of H_2 had negligible effect on NO_x emissions when operated at low to medium load (<60%). This was consistent with the NO_x emission trends obtained in a 0.64 liter, single cylinder, direct-injection diesel engine [Tomita, et al., 2001]. In this experiment, the overall equivalence ratio was kept as constant with the substitution of up to 80% diesel by H_2 . It was reported that the substitution of diesel by up to 70% of H_2 had negligible effect on NO_x emissions for low to medium load operation with overall equivalence ratio value of 0.3 and 0.4, respectively. However, the substitution of diesel fuels with H_2 increased the emissions of NO_x from 200 ppm for pure diesel operation to 450 ppm when operated at overall equivalence ratio of 0.5. It seems that the engine operating load may dominate the enhancing effect of the H_2 addition on the variation of NO_x emissions.

Saravanan and Nagarajan [2008] reported differently trend in examining the effect of engine load and the addition H_2 on NO_x emissions using a single cylinder, four-stroke diesel engine with a rated power of 3.7 kW. The addition of 10 and 20% H_2 into the diesel engine increased the emissions of NO_x measured in the examined load range. However, the NO_x emissions decreased with further increase in the amount of diesel fuel

substituted by H₂ (>30% H₂ substitution) when operated at 60% load. A minimum NO_x emissions level of 575 ppm was achieved when 90% of diesel was substituted by H₂.

It should be noted that most of the H₂-diesel dual fuel engine research was conducted using single cylinder small diesel engines, which were designed without using the advanced diesel engine technologies. The exhaust emissions were measured at constant speed with a number of different loads without following emission measurement cycles specified in national or international emission regulations. For example, the emissions of NO_x were reported in concentration (ppm) other than those presented in specific rate such as g/kW-h or equivalent. This made it difficult to evaluate the compliance of these engines with past and current emission regulations.

Recently, some interests rises on examined the effect of H₂ addition on exhaust emissions using specific emission measurement cycle. For example, Tsolakis, et al. [2005] investigated the effect of H₂-rich gases on the exhaust emissions of a single cylinder diesel engine measured at 9 different engine operating conditions, which were part of the 13-mode European Stationary Cycle (ESC). The addition of H₂-riches syngas was found to reduce the emissions of PM and NO_x. More recently, a number of research studies were conducted using light-duty multi-cylinder diesel engines with modern engine technologies following the modern emission measurement approach. For example, Bika et al. [2008] examined the effect of H₂ addition on NO_x emissions of a 1999 Volkswagen 4 cylinder, 1.9 L, turbocharged direct injection (TDI) diesel engine. The addition of H₂ for the substitution up to 40% of total energy had negligible effect on NO_x emissions reported in ppm. The addition of H₂ into diesel engine increased the nitrogen dioxide (NO₂)/NO_x ratio especially under low load operation. Shirk et al. [2008]

examined the effect of H₂ supplementation on exhaust emissions of a modern production 1.3 L, turbo-charged, light-duty diesel engine with a common-rail fuel system. When installed in the engine test cell, eight steady state operating points were tested with H₂ flow rate equivalent to 0, 5, and 10% of the total fuel energy. The addition of H₂ was shown to slightly increase the emissions of NO_x. However, its effect on the thermal efficiency was small. This engine was also installed in a 2005 Chevrolet Equinox and tested on a chassis dynamometer following the Urban Dynamometer Driving Schedule (UDDS) and 505 urban driving cycles. The addition of 5% H₂ showed negligible effect on NO_x emissions. However, the substitution of 10% diesel by H₂ reduced the NO_x emission rate from 0.75 to 0.6 g/mile, a 20% reduction compared to diesel operation.

Exhaust gas recirculation (EGR) has been widely used in modern diesel engines to reduce the engine-out NO_x emissions. For example, McWilliam et al. [2008] investigated the effects of H₂ addition on the combustion and emissions of a modern 2.0 L, turbo-charged, 4 cylinders, four stroke diesel engine with EGR. The effects of engine load, EGR rate and the addition of H₂ on exhaust emissions were experimentally investigated. The NO_x emissions data were reported in g/kW-hr. The addition of H₂ into this light-duty diesel engine increased substantially the emissions of NO_x especially for low load operation without EGR. When operated at 2.7 brake mean effective pressure (BMEP), the emissions of NO_x were increased almost linearly from 6.1 to 19.2 g/kW-hr with the addition of 6% H₂. In comparison, the emissions of NO_x were 5.3 g/kW-hr when operated with pure diesel operation at 10% of EGR. With the addition of 6% H₂, the emissions of NO_x were 12.0 g/kW-hr, which was 2.2 times that of pure diesel engine operation. With the help of EGR, it was possible to obtain lower NO_x emissions with the

addition of H_2 . The researchers also tested similar criteria but higher load was applied. With the help of H_2 as supplemental fuel, it was possible to develop suitable engine operation strategies that could substantially reduce the emissions of NO_x while overcoming the penalty in fuel economies when EGR was employed.

2.2.2 Emissions of PM

Particulate matter has continued to be one of the problematic pollutants associated with diesel engines since the stringent emission control standards were implemented. In the early decades of H_2 -diesel dual fuel emissions research, the PM emissions were usually qualitatively measured using simple smoke meters such as the devices developed by AVL and Bosch. The PM emissions were reported as Filter Smoke Number (FSN) or Bosch Smoke Number (BSN). For example, Varde and Frame [1983] examined the effect of H_2 substitution to diesel fuel on PM emissions using an air-cooled single cylinder diesel engine. The smoke level was reduced when a small percentage of diesel was substituted by H_2 until the minimum PM emissions were observed. Beyond the limit, increasing further in H_2 flow rate produced more PM as represented by the increased BSN number. This was due to the displacement of air by H_2 , which reduced the overall air/fuel ratio of diesel fuel and resulted in increased formation of PM. Tomita et al. [2001] examined the PM emissions of a 0.64 L, single cylinder, direct-injection, diesel engine supplemented with H_2 while using a Bosch type smoke meter (Zexel, DSM10). The addition of H_2 to this small diesel engine was demonstrated to reduce the smoke emission level especially when operating at higher load (60% of load).

Recently, some research was conducted using light-duty multi-cylinder diesel engines. For example, McWilliam et al. [2008] examined the effect of H₂ addition on the PM emissions through measuring variation of FSN of a turbo-charged diesel engine. The addition of H₂ into the diesel engine reduced substantially the PM emissions especially when operated at high load without EGR. Bika et al. [2008] examined the effect of H₂ addition on PM emissions of a 1.9 L Volkswagen TDI engine. The PM emissions were measured using a Scanning Mobility Particle Sizer (SMPS). The amount of H₂ added varied from 10-40% when evaluated on the total intake energy basis. For all load conditions examined, the addition of H₂ reduced the PM emissions ranging from 10 to 50% in both total PM concentration and total PM number. Using the PM concentration, soot diameter distribution and the assumed density of 1 g/cm³ of the spherical soot particles, the PM mass flow rate was calculated. This demonstrated that the addition of H₂ into the diesel engine reduced the PM mass emissions beyond the amount expected from the reduction of diesel fuel flow rate.

Saravanan and Nagarajan [2008] reported PM emissions quantitatively using the gravimetric method with a single cylinder small diesel engine. The PM emissions were reported in g/kW-h. However, the approach to quantitatively measure the emissions of PM was not reported. The PM emissions were observed to reduce dramatically with the increased addition of H₂. For example, the PM emissions were reduced by 70% with the substitution of 90% diesel by H₂. Masood et al. [2007] examined the effect of compression ratio and H₂ substitution ratio on PM emissions at full load operation using a single cylinder diesel engine with a rated power of 3.7 kW. The PM emissions rated as g/m³ were reported without describing the measurement method. As H₂ substitution

percentage increased from 10 to 90%, the PM emissions reduce by 92.7% when operated at compression ratio of 18.35.

2.2.3 Emissions of HC, CO, and CO₂

The addition of H₂ to a diesel engine has been demonstrated to reduce the exhaust emissions of HC, CO, and CO₂. The literature data obtained from a number of diesel engines with different fuel mixing and engine technologies demonstrated the varying trend of HC, CO, and CO₂ emissions. Most of the researchers reported the addition of H₂ to diesel engine would reduce HC, CO, and CO₂ emissions [Lambe and Watson, 1992; McWilliam et al., 2008; and Saravanan and Nagarajan, 2008]. For example, McWilliam et al. [2008] investigated the effects of H₂ addition on CO emissions of a multi-cylinder light-duty diesel engine with EGR. The addition of H₂ decreased substantially the emissions of CO especially for high load operation. When operated at 5.4 bmep, the emissions of CO decreased almost linearly from 24.0 to 9.50 g/kW-hr with the addition of 6% H₂. McWilliam et al. [2008] also investigated the effects of H₂ addition on HC emissions but only reported in ppm concentration. The addition of H₂ produced negligible amount of HC emission between 150 to 200 ppm at 2.7 and 5.4 bmep, respectively. However, research conducted by Varde and Frame [1983] reported that both CO and HC emissions increased with H₂ addition.

2.2.4 Brake Thermal Efficiency

Thermal efficiency is one of the main parameters associated with power and fuel economy. Most of the early research associated with the H₂-diesel dual fuel engines evaluated the improvement of the engine efficiencies. For example, Varde and Frame

[1983] examined the effect of H_2 substitution on the brake thermal efficiency using a direct injection single cylinder diesel engine. With the addition of H_2 into diesel engine, the brake thermal efficiency was found to increase significantly. When operated at full load, the BTE increased from 30.5% for pure diesel operation to 33.7% for dual fuel operation with 12.5% of the energy supplied by H_2 . However, the addition of small portion of H_2 (<5% of total energy) into diesel engine reduced the BTE. It was believed that this was due to the extremely lean H_2 -air mixture, which cannot support the flame propagation and resulted in low combustion efficiency.

Figure 1 Effect of H_2 Addition on Fuel Conversion Efficiency at 2500 RPM [McWilliam et al., 2008]

Recently, McWilliam et al. [2008] investigated the effect of H_2 addition on the thermal efficiency of a light-duty diesel engine. As shown in Figure 1, the addition of H_2 to this modern multi-cylinder diesel engine significantly improved the thermal efficiency. As shown in Table 1 for operation at 5.4 BMEP with 10% EGR, the addition of 6% H_2 into intake manifold improved the thermal efficiency from 23.8% for pure diesel

operation to 30.8%, an improvement of 29.2%. When operated at 2.7 BMEP, the brake thermal efficiency was increased by 37.4% with the addition of 6% H₂.

Table 1 Variation of Thermal Efficiency with the Addition of H₂ [McWilliam et al., 2008]

Load (BMEP)	H ₂ /(H ₂ +air), %	Thermal efficiency, %	Thermal efficiency increase compared to that of pure diesel operation, %
5.4	0	23.8	0
	2	25.2	5.78
	4	26.7	12.0
	6	30.8	29.2
2.7	0	19.8	0
	2	21.8	10.1
	4	23.4	18.2
	6	27.2	37.4

3 EXPERIMENTAL SETUP AND SAFETY APPROACH

3.1 Test Engines

The Engine and Emissions Research Laboratory (EERL) of West Virginia University's (WVU) is located in Morgantown, West Virginia. The laboratory was built to meet the specification of CFR 40, Part 86 Subpart N [CFR (1), 1998]. The laboratory is facilitated with four engine test skids and two full flow dilution tunnels. In this research study, two class-8 heavy-duty diesel engines were used. The detail specifications of these test engines are shown in Table 2.

Table 2 The Specifications of the Test Engines

Engine Manufacturer	Mack	Cummins
Engine Model	MP7 355E	ISM370ESP
Model Year	2004	1999
Displacement	10.8 Liter	10.8 Liter
Power Rating	355 bhp @ 1800 RPM	370 bhp @ 2100 RPM
Torque Rating	1360 ft-lb @ 1200 RPM	1350 ft-lb @ 1200 RPM
Configuration	Inline 6-cylinder	Inline 6-cylinder
Bore x Stroke	4.84 in. x 5.98 in.	4.92 in. x 5.79 in.
Induction	Turbocharged with in-house Aftercooler	Turbocharged with in-house Aftercooler
Fuel Type	Diesel	Diesel
Engine Strokes per Cycle	4	4
Injection	Direct Injection, Electronic	Direct Injection, Electronic
Cooled EGR	Yes	No
Variable Geometry Turbo Charger (VGT)	Yes	No

3.2 Dynamometer

The engine dynamometer was designed to absorb the load or output of the engine. When testing an engine in the test cell, a computer program was commanded the dynamometer to control the load of an engine. In this research, a 550 hp DC dynamometer manufactured by GE was used. The detailed of specification of the dynamometer can be found in Figure 2 and Table 3.

Figure 2 GE Dynamometer

Table 3 Dynamometer Specification

Dynamometer Manufacturer	General Electric
Model	DYC 243
Absorbing Capacity	550 hp @ 474 V @ 812 amp
Motoring Capacity	500 hp @ 507 V @ 812 amp
Current	Direct Current
Serial Number	ZG-2-44-2G

3.3 The Measurement of Exhaust Emissions

3.3.1 Dilution Tunnel

The engine exhaust was ducted to a full-scale dilution tunnel (18 inches in diameter, 20 feet in length (Figure 3) with flow control accomplished using a critical flow venturi-constant volume sampler (CFV-CVS) system. A 10-inch diameter orifice located 3 feet from the tunnel entrance, ensured that exhaust was thoroughly mixed with dilution air before it reached the emissions sampling zone, located ten tunnel diameters downstream. The CFV-CVS controlled the dilute exhaust flow at a nominal 2400 standard cubic feet per minute (scfm) throughout the test program. Instantaneous measurement of CFV-CVS flow was accomplished using a fast-response thermocouple and pressure transducer at the venturi entrance. Dilute exhaust samples were drawn from the tunnel using heated sample probes and lines to individual emissions analyzers. Dilute exhaust was also drawn from the dilution tunnel sample plane through a series of two 70 mm filters to collect PM samples.

Figure 3 Dilution Tunnel for Diluted Exhaust

3.3.2 Measurement of Gases Emissions

The WVU EERL is capable of measuring multiple types of exhaust gas emissions. The specification and setup of all analyzers are shown in Table 4 and Figure 4. The diluted exhaust was drawn from the full flow dilution tunnel into an insulated sample line that was connected to analyzers. Heated pumps were installed prior to the each analyzer in order to maintain the flow pressures and flow temperatures. Prior to the test, the analyzers were calibrated with specific gas concentration. In addition, span/zero, flow temperatures, and flow pressures were checked before and after each test. These procedures were conducted according to WVU Center for Alternative Fuels, Engines and Emissions (CAFEE) protocols per 40 CFR Part 86 Subpart N §1310-90 [CFR (2), 1998].

Table 4 Exhaust Gas Analyzer Specifications

Exhaust Gas Constituent	Measurement Technology	Manufacturer	Model
Oxides of Nitrogen (NO _x)	Chemiluminescence	Eco Physics	CLD822CMH
Nitric Oxide (NO)	Chemiluminescence	Eco Physics	CLD822CMH
Hydrocarbon (HC)	Flame Ionization Detection	California Analytical Instruments	600M HFID
Carbon Monoxide (CO)	Non-dispersive infrared	Horiba	AIA-210
Carbon Dioxide (CO ₂)	Non-dispersive infrared	Horiba	AIA-210
Particulate Matter (PM)	Gravimetric Analysis	PM Sampling Accordance to 40 CFR Part 86	-

Figure 4 Analyzers Bench

3.3.3 Measurement of PM Emissions

PM was measured by the gravimetric method accordance to 40 CFR Part 86 Subpart N § 1312-88 [CFR (3), 1998]. Diluted exhaust was drawn from the full flow dilution tunnel into a stainless steel 4 inch diameter by 30 inch long secondary dilution tunnel and, then passes through a stainless steel filter holder that contained two Pallflex 70 mm diameter Model T60A20 fluorocarbon-coated glass microfiber filters in series. The sample stream was maintained at temperatures below 125 °F as measured at the inlet of the PM filter holder. Secondary dilution air, which can be used to lower the

temperature of the dilute sample upstream of the sample filters, was not required during this evaluation. Prior to weighing (both before and after PM measurement), sample filters were conditioned for at least an hour in an environmentally controlled room to a nominal 22 °C dry bulb, 9.5 °C dew point, and 45% relative humidity, in compliance with requirements presented in CFR 40, Part 86 Subpart N § 1312-88 [CFR (3), 1998]. Filters were weighed using a Sartorius microbalance in a controlled environment as shown in Figure 5.

Figure 5 PM Filter Weighting Devices

3.4 Hydrogen Fuel System

As shown in Figure 6, the H₂ fuel system consisted of a high pressure H₂ supply system, low pressure H₂, fuel metering and delivery system, and safety system.

Figure 6 Schematic Diagram of H₂ Fuel System

3.4.1 High Pressure H₂ Fuel System

The high pressure H₂ fuel system was located outside the engine laboratory as shown in Figure 7. The module consisted of two sets of pressure regulators. Each regulator was connected to six H₂ tanks with maximum pressure of 2000 psi and used to steadily provide H₂ with gauge pressure of 45 psi. One emergency shut-down valve driven by the pneumatic actuator operated by compressed air was installed after the pressure regulator as shown in Figure 7.

Figure 7 Hydrogen Station with Pressure Regulation Module and Emergency Valve A

3.4.2 Low Pressure H₂ Fuel System

The low pressure H₂ fuel system consisted of an emergency shut-down valve B, H₂ filter, mass flow controller, and mixer as shown in Figure 8. The H₂ filter was installed prior to all other devices in order to trap particulate. A second emergency shut-down valve B was located prior to the filter. Both emergency shut-down valves acted

simultaneously to cut off H_2 flow if the switch was activated. A mass flow controller was used to control and meter the flow rate of H_2 . An in-house made fuel mixer as shown in Figure 9 was installed about 0.5 feet prior to the flame arrester. The mixer was designed for delivering H_2 into the main stream of the intake air.

Figure 8 Hydrogen Fuel Metering and Control System with Safety Devices and Emergency Valve B

3.4.3 Safety System and Safety Operation Procedure

The safety system consisted of a stainless steel flame arrester, a pressure relief valve and the control system as shown in Figure 8. The flame arrester and pressure relief valve were installed prior to the engine intake manifold. The flame arrester was used to quench the flame propagation beyond the flame arrester and the pressure relief valve was acted to release the pressure established in the intake system in case of backfire.

Figure 9 In-House H₂ Mixer

Leakage check of the entire H₂ fuel system using Snoop® product was conducted during the first day of testing and every week of the experimental period. In addition, verification of pressure drop along the H₂ fuel system was conducted every day in order to ensure the system leakage free. Although leakage check was performed, but it may not guarantee leakage free. Therefore, the H₂ fuel module was placed outside the research laboratory under a shed to avoid H₂ accumulation. In the research laboratory, ventilation fans within the engine lab were turned on prior to, during, and at least 20 minutes after testing. The ventilation of the laboratory was maintained to avoid any H₂ accumulation if an emergency or H₂ system leak occurred.

Additional safety approaches were also implemented into the engine control system and the operation of H₂ mass flow controller. The control system was designed to force the engine back to idle and shut down the mass flow controller if any of the following cases were detected: (1) the engine load was higher than the set value; (2) the flow of H₂ was higher than the set value.

A pressure transducer was installed prior to the mass flow controller and used as a reference signal for the opening and closing of the mass flow controller. The test cell control system was designed in such a way that it would not open the mass flow controller before the H_2 pressure prior to the mass flow controller reached the set value and close the mass flow controller once the H_2 pressure dropped below the set value. This prevented the over-opening of the mass flow controller in the event of a malfunction with the emergency valve.

3.5 Flow Measurement of H_2 , Diesel, and Intake Air

The diesel fuel flow rate was measured using a MAX 710 Fuel Measurement System manufactured by Max Machinery Inc. The intake air flow was measured using a laminar flow element (LFE) capable of measuring the flow of air from 0.2 to 957.12 scfm. The flow rate of H_2 was controlled and measured using a compact-size digitally controlled mass flow controller manufactured by Sierra Instruments Inc. The small and large flow rate of H_2 was controlled and measured using two compact-size, digitally controlled mass flow controllers. The small and large flow rate mass flow controller was capable of measuring and controlling from 0 to 10 standard liters per minute (slpm) and from 10 to 1200 slpm, respectively. In this research, the flow of H_2 was controlled according to the air flow measured to obtain the pre-set H_2 flow. The amount of H_2 supplemented was reported as the volumetric concentration in the intake mixture noted as $H_2/(H_2+air)$. This made it easier to estimate the potential occurrence of backfire and engine knock and also to compare the emissions results obtained in different engines on the same basis.

3.6 In Cylinder Pressure Measurement

The measurement of in-cylinder pressure was necessary to obtain the heat release rate. In this research, a piezoelectric pressure transducer was used to measure the dynamic cylinder pressure. The in-cylinder pressure for 1999 Cummins ISM370ESP engine and 2004 Mack MP7 355E engine were acquired at cylinder 6 and 1, respectively. The pressure transducer signal was converted to an amplified voltage through a charge amplifier, whereby this signal was sent to a high speed data acquisition system to record the in-cylinder pressure data in order to accommodate the in-cylinder pressure results. An incremental shaft encoder as shown in Figure 10 was installed to measure the crank angle.

Figure 10 The Incremental Shaft Encoder

At the end of each emission sampling period, the cylinder pressure of 200 consecutive cycles were collected and averaged. A low-pass filter was applied to the measured in-cylinder pressure to minimize fluctuations caused by the pressure wave and reduce the high frequency combustion noise. The cut-off frequencies applied to the in-cylinder pressure of the 2004 Mack MP7 355E engine and 1999 Cummins ISM370ESP

was 2000 Hz and 2500 Hz, respectively. The filtered cylinder pressure was further processed to obtain the heat release process.

3.7 Data Acquisition System

During the experiment, the engine operation and performance data were acquired using the software and data acquisition hardware of WVU EERL. The engine testing data were collected using a signal conditioning backplane with Analog Devices 3B system modules and RTI-815 analog-to-digital converter data acquisition boards housed inside of the computer. The transducers and sensors needed were calibrated before initial testing. The engine data were first recorded in ADC code and then processed with an in-house software to convert them into engineering units. The setup of the instrumentation and data acquisition system is shown in Figure 11.

Figure 11 Instrumentation Control and Data Acquisition Bench

3.8 Engine Mapping

Both engines were mapped prior to the initial test. Engine mapping procedures were followed in accordance to CFR 40, Part 86 Subpart N §86.1332-90 [CFR (4), 1998]. At least five maps were performed on each engine. Prior to the start of the mapping, the engine was warmed up at 3 minutes free idle, 7 minutes of 50% peak torque speed and 10 minutes for rated speed and wide open throttle. Then, the engine was operated at wide open throttle and minimum engine speed. Engine speed was increased at an average rate of 8 RPM/sec (± 1 RPM/sec) from minimum to maximum speed. The engine speed and torque points were recorded at 1 Hz. The maximum torque for 2004 Mack MP7 355E and 1999 Cummins ISM370ESP at 1200 RPM was found to be 1399 and 1260 ft-lb, respectively. As shown in Figure 12, the installation of H₂ flame arrester has negligible effect on one of the engine map.

Figure 12 Effect of Flame Arrester on Engine Map of the 2004 Mack MP7 355E Engine

3.9 Uncertainty Analysis

Experimental data are often used to supplement engineering analysis as a basis for design. Not all data are equally good, the validity of data should be documented before test results are used for design. Uncertainty analysis is the procedure used to quantify data validity and accuracy. Errors always are present when experimental measurements are made. There are two typical types of errors, the fixed error and random error. Fixed error is the same for each reading that can be removed by proper calibration or correction. However, random error is different for every reading and hence cannot be removed. The factors that introduce random error are uncertain by nature. The objective of uncertainty analysis is to estimate the probable random error in an experimental result.

In this research project, the validity of the experimental data is crucial when presenting the result. As shown in Figure 13, the calculated BTE with respect to the $H_2/(H_2+Air)$ flow, involved with instrument's error such as LFE, fuel flow meter, and mass flow controller. Disregarding these probable errors in the BTE and $H_2/(H_2+Air)$ flow calculation will deteriorate the validity of the experimental results. Therefore, the objective of this section is to determine the acceptable range for the experimental data by implementing the uncertainty analysis.

The calculation for the brake thermal efficiency and $H_2/(H_2+Air)$ flow involved with many parameters including intake air flow, diesel fuel flow, dynamometer speed and torque. Each parameter associate with an error percentage that provided from manufacturer's specification sheet as shown in Table 5. These range of errors will be integrate into the uncertainty analysis for calculation. The uncertainty analysis of BTE and $H_2/(H_2+Air)$ flow for 2004 MACK MP7 355E at 30% load with the addition of 6%

H₂ was performed. The BTE accounted with LFE, mass flow controller, and fuel meter as the error parameter. The H₂/(H₂+Air) flow accounted LFE and mass flow controller as the error parameter. Due to the complexity of the equation, a MATLAB program as shown in the appendix was developed to perform the uncertainty analysis. The uncertainty results for the BTE and H₂/(H₂+Air) flow for 2004 MACK MP7 355E at 30% (6% H₂) were 38.8% ± 0.36% and 5.84% ± 0.102%, respectively.

Figure 13 Effect of H₂ Addition and Engine Load on BTE for 2004 Mack MP7 355E, N=1200 RPM, 30% Load

Table 5 Percentage Error of Measurement Instruments [Sierra Instrument, 2008; Meriam, 2010; Max Machinery, 2004]

Manufacturer	Instrument	Error (Full scale at operating condition)
Sierra Instrument	Mass flow controller	1%
Meriam	Laminar flow element	0.86%
Max Machinery	Fuel meter	0.50%

4 INVESTIGATION OF EMISSIONS AND COMBUSTION OF A 1999 CUMMINS ISM370ESP ENGINE SUPPLEMENTED WITH H₂

4.1 Test Matrix

The test matrix was designed to investigate the effect of H₂ addition, engine load, and engine speed on the engine performance, exhaust emissions, and combustion process of diesel engine operation. The effect of H₂ addition on the exhaust emissions was also measured using 13-mode ESC. The mode was set according to the ESC standard as shown in Figure 14 and Table 6. The effect of the addition of 2 and 4% H₂ on the exhaust emissions was investigated using 13-mode ESC.

Figure 14 Set Points for 13-Mode ESC Emission Testing

Table 6 Set Points for 13-Mode ESC, 1999 Cummins ISM370ESP

Mode	Speed, RPM	Torque, ft-lb	Weighting Factor, %
1	700	0	15
2	1272	1258	8
3	1580	606	10
4	1580	908	10
5	1272	629	5
6	1272	944	5
7	1272	315	5
8	1580	1211	9
9	1580	303	10
10	1887	1011	8
11	1887	253	5
12	1887	758	5
13	1887	506	5

The detailed effect of H₂ addition on the combustion and exhaust emissions was investigated under constant load varied from 10 to 70% with addition of up to 6.5% H₂ into intake air. The complete constant load test matrix for 1999 Cummins ISM370ESP was described in Table 7. Figure 15 shows the effect of H₂ addition on equivalent ratio. The equivalent ratio of H₂ increased linearly from 0 to 0.17, with the addition of H₂ from 1 to 6.5%, respectively.

Table 7 Constant Load Test Matrix for 1999 Cummins ISM370ESP, N=1200 RPM

Torque, %	H₂/(H₂+Air), vol. %
10	0.0, 1.0, 2.0, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, and 6.0
15	0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 2.0, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, and 6.5
20	0.0, 1.0, 2.0, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, and 6.5
30	0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 2.0, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, and 6.5
50	0.0, 1.0, 2.0, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, and 6.5
70	0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, and 6.0

Figure 15 Effect of H₂ Addition on H₂ Equivalence Ratio, 1999 Cummins ISM370ESP

Table 8 shows the variation of H₂ flow rate and diesel substitution with the change in engine load at 6% H₂ addition into the intake mixture. Figure 16 shows the variation of the substitution of diesel by H₂ with the changes in engine load and the

addition of H₂. The addition of 6% H₂ contributed to 92.1% of the intake energy including H₂ and diesel fuel.

Table 8 Hydrogen Flow Rate at H₂/(H₂+Air)= vol. 6% for 1999 Cummins ISM370ESP

H₂ Flow at H₂/(H₂+Air)= vol. 6%			
Load, %	Kg/hr	L/min	Diesel Substitution, %
10	2.10	391.07	92.1
15	2.08	387.52	77.4
20	2.10	391.44	64.5
30	2.30	430.08	49.3
50	2.78	518.37	37.3
70	3.30	615.25	31.7

Figure 16 Effect of H₂ Addition on Diesel Substitution, 1999 Cummins ISM370ESP, N=1200 RPM, 10-70% Load

Figure 17 shows the effect of H₂ addition on the equivalent ratio of diesel fuel. The equivalent ratio on every load decreased linearly with the addition of H₂ up to 6.5%.

The addition of H_2 reduced the equivalence ratio of diesel fuel due to the reduced diesel flow rate. The lowest equivalent ratio of 0.015 was observed at 10% load with 6% H_2 addition. The total equivalent ratio of H_2 and diesel fuel was calculated with respect to the addition of H_2 as shown in Figure 18. The effect of H_2 addition on total equivalent ratio was small.

Figure 17 Effect of H_2 Addition on Diesel Fuel Equivalence Ratio, 1999 Cummins ISM370ESP, N=1200 RPM, 10-70% Load

Figure 18 Effect of H_2 Addition on Total Equivalence Ratio, 1999 Cummins ISM370ESP, N=1200 RPM, 10-70% Load

The operating conditions under constant diesel fuel flow rate at 1200 RPM were shown in Table 9. The engine load was varied by adjusting the amount of H₂ supplemented into the diesel engine. When running this test for 1999 Cummins ISM370ESP, the flow rate of diesel fuel was kept approximately at a constant 22.35 kg/hr, corresponding to 50% load for pure diesel operation. The maximum H₂ supplemented was 5.5%.

Table 9 Test Matrix for Constant Diesel Fuel Flow Rate, 1999 Cummins ISM370ESP

Diesel Flow Rate, kg/hr	H₂/(H₂+Air), vol. %
22.35	0.0, 1.0, 2.0, 3.0, 4.0, 4.5, 5.0, and 5.5

As shown in Table 10, the effect of engine speed and H₂ addition was examined under constant torque of 700 ft-lb with the addition of 4% H₂ in the intake mixture and engine speed ranging from 1200 to 1800 RPM.

Table 10 Test Matrix for Constant Torque with Variable Engine Speed, 1999 Cummins ISM370ESP

Engine Torque (ft-lb)	H₂/(H₂+Air), vol. %	Engine Speed, RPM
700	4	1200, 1300, 1400, 1500, 1600, 1700, and 1800

4.2 Repeatability of Exhaust Emissions and Fuel Consumption Measurement

The engine test used in this research was able to obtain good repeatability of exhaust emissions [Tincher, 2007] and fuel consumption. In this research, the repeatability of this engine test cell was examined by measuring the exhaust emissions of a 1999 Cummins ISM370ESP diesel engine using 13-mode ESC. As shown in Table 11,

the emissions of NO_x, NO, PM, CO, HC and CO₂ were shown to have good repeatability for four tests. The coefficient of variation (COV) for NO_x, NO, PM, CO, HC and CO₂ emissions were 0.30, 0.27, 7.70, 0, 4.16, and 0.06%, respectively.

Table 11 Repeatability of NO_x Exhaust Emissions Measured Using 13-Mode ESC, g/bhp-hr

Emissions (g/bhp-hr)	NO_x	NO	PM	CO	HC	CO₂
Test 1	3.50	3.38	0.025	0.22	0.12	473.8
Test 2	3.49	3.36	0.028	0.22	0.12	473.6
Test 3	3.49	3.37	0.027	0.22	0.13	473.4
Test 4	3.48	3.36	0.024	0.22	0.12	473.0
Average	3.49	3.37	0.026	0.22	0.12	473.5
Std Deviation	0.01	0.01	0.002	0.00	0.005	0.3
COV, %	0.30	0.27	7.70	0.00	4.16	0.06

As shown in Table 12, the COV of NO_x emissions measured for each mode was within 1.03%. The NO_x emissions of each mode are shown in Figure 19. The accuracy of engine test cell was also examined by comparing the diesel fuel consumption measured using diesel fuel flow meter and the carbon balance method. As shown in Table 13, the maximum difference of diesel fuel flow rate measured using these two approaches were 2.8%.

Table 12 Repeatability of NO_x Exhaust Emissions of Each Mode Measured Using 13-Mode ESC, g/bhp-hr

Mode	2	3	4	5	6	7	8	9	10	11	12	13
Test 1	2.86	3.13	3.65	3.73	3.57	4.09	3.33	4.16	3.44	4.30	3.66	4.03
Test 2	2.83	3.10	3.64	3.74	3.58	4.07	3.33	4.19	3.44	4.31	3.63	4.02
Test 3	2.79	3.09	3.64	3.78	3.57	4.10	3.30	4.19	3.43	4.32	3.65	4.00
Test 4	2.80	3.09	3.63	3.74	3.54	4.06	3.30	4.19	3.44	4.26	3.62	4.00
Average	2.82	3.10	3.64	3.75	3.56	4.08	3.31	4.18	3.44	4.30	3.64	4.01
Std Dev	0.03	0.02	0.01	0.02	0.02	0.02	0.02	0.01	0.00	0.02	0.02	0.01
COV, %	1.03	0.64	0.27	0.63	0.47	0.42	0.47	0.36	0.00	0.56	0.44	0.33

Figure 19 Repeatability of NO_x Emissions of Each Mode Measured During 13-Mode ESC, g/bhp-hr

Table 13 Comparison of Diesel Flow Rate Measured Using 13-Mode ESC

Mode	2	3	4	5	6	7	8	9	10	11	12	13
Diesel Flow Meter (kg/hr)	45.97	27.76	39.91	23.08	33.71	12.44	53.50	15.51	54.02	16.71	41.16	28.58
Carbon Balance (kg/hr)	45.78	28.46	39.95	23.21	33.72	12.68	53.04	15.77	53.60	17.17	41.23	28.78
Difference, %	0.41	-2.49	-0.09	-0.59	-0.04	-1.98	0.86	-1.68	0.79	-2.80	-0.17	-0.71

4.3 13-Mode ESC

In this research, the effect of H₂ addition (H₂/ (H₂+Air), vol=2 and 4%) on regulated emissions was measured using 13-mode ESC. As shown in Table 14 the addition of 2% H₂ increased PM emissions from 0.032 to 0.037 g/bhp-hr (+15.6%). In comparison, the addition of 4% H₂ reduced the PM emissions to 0.029 g/bhp-hr (-9.4%).

Table 14 Effect of H₂ Addition on Exhaust Emissions Measured Using 13-Mode ESC, g/bhp-hr

H ₂ /(H ₂ +Air), vol. %	PM	NO _x	CO	HC	CO ₂
0	0.032	3.41	0.25	0.12	474.7
2	0.037	3.59	0.26	0.12	416.7
4	0.029	3.94	0.21	0.13	347.9

As shown in Table 14, the addition of 2 and 4% H₂ increased the emissions of NO_x from 3.41 to 3.59 (+5.28%) and 3.94 g/bhp-hr (+15.5 %), respectively. The effect of H₂ addition on NO_x emissions measured in each mode is shown in Figure 20. The addition of 2 and 4% of H₂ increased the NO_x emissions in all modes with the exception of mode 9 (1578 RPM, 306 ft-lb) and 11 (1886 RPM and 254 ft-lb), representing the low load operation. This may reflect to the different response of NO_x emissions with the addition of H₂ under high and low load operation.

Figure 20 Effect of H₂ Addition on NO_x Emissions, 13-Mode ESC

As shown Table 14, the addition of 2% H₂ slightly increased the CO emissions from 0.25 to 0.26 g/bhp-hr (+4.0%) compared to pure diesel operation. However, the addition of 4% H₂ reduced CO emissions from 0.25 to 0.21 g/bhp-hr (-16.0%). The detailed effect of H₂ addition on CO emissions measured at each mode is shown in Figure 21. The addition of 2% H₂ increased the emissions of CO at mode 2, 4, 5, 6, and 8. The addition of 4% H₂ reduced the emissions of CO at all modes with exception on mode 2.

Figure 21 Effect of H₂ Addition on CO Emission, 13-Mode ESC

As shown in Table 14, the addition of 2% H₂ had negligible effect on the emission of HC. In comparison, the addition of 4% H₂ slightly increased the emissions of HC from 0.12 to 0.13 g/bhp-hr (+8.3%). As shown in Figure 22, the addition of 4% H₂ increased the HC emissions for all of the emissions modes. However, the addition of 2% H₂ slightly increased the HC emissions with the exception of mode 2, 4, 6, 7, and 8.

Figure 22 Effect of H₂ Addition on HC Emissions, 13-Mode ESC

As shown in Table 14, the addition of 2 and 4% H₂ reduced CO₂ emissions from 474.7 to 416.7(-12.2%) and 347.9 g/bhp-hr (-26.7%), respectively. The detailed effect of H₂ addition on CO₂ emissions can be found in Figure 23. The addition of 2 and 4% H₂ reduced the CO₂ emissions measured at each mode.

Figure 23 Effect of H₂ Addition on CO₂ Emissions, 13-Mode ESC

4.4 Effect of H₂ Addition and Engine Load on Exhaust Emissions

4.4.1 Effect of H₂ Addition on the Emissions of NO_x, NO, and NO₂

The effect of H₂ addition on NO_x emissions was examined under constant load operation. As shown in Figure 24 for medium to high load operation, the addition of H₂ into the intake mixture of this 1999 Cummins ISM370ESP diesel engine increased gradually the NO_x emissions, which was consistent with the data reported in the literature [McWilliam et al., 2008; and Varde and Frame, 1983]. This was due to the increased combustion temperature when H₂ was added. As shown in Figure 25 for 70% load operation, the addition of a small amount of H₂ into the diesel engine slightly reduced the maximum averaged bulk mixture temperature without reducing the NO_x emissions. The addition of a relatively large amount of H₂ increased substantially the maximum averaged bulk mixture temperature, which was accompanied by the increased NO_x emissions. As shown in Figure 26, the addition of H₂ also enhanced the conversion of NO to NO₂.

Figure 24 Effect of H₂ Addition on NO_x Emissions, N=1200 RPM, 30-70% Load

Figure 25 Effect of H₂ Addition on NO_x Emissions and Maximum Average Bulk Mixture Temperature Calculated Using Cylinder Pressure, N=1200 RPM, 70% Load

Figure 26 Effect of H₂ Addition on the Emissions of NO_x, NO, and NO₂, N=1200 RPM, 70% Load

The effect of H₂ addition on NO_x emissions was also examined under low load operation. As shown in Figure 27, the addition of a small amount of H₂ (<3%) at 10% load had a negligible effect on NO_x emissions. Increasing the addition of H₂ beyond 3% substantially reduced the emissions of NO_x. In comparison, the addition of H₂ at 15 and

20% load slightly increased the emissions of NO_x until a maximum value was observed. Further increasing the addition of H_2 started to reduce the emissions of NO_x . The substantial reduction of NO_x emissions was only obtained at a very narrow low load operational range with the addition of a relatively large amount of H_2 .

Figure 27 Effect of H_2 Addition on NO_x Emissions, $N=1200$ RPM, 10-20% Load

As shown in Figure 28, the addition of a small amount of H_2 at 15% load slightly reduced the averaged bulk mixture temperature accompanied with slightly increasing NO_x emissions. This was not consistent with the traditional NO_x formation mechanism. As shown in Figure 29, the addition of a small amount of H_2 substantially enhanced the conversion of NO to NO_2 . As shown in Figure 28, the dramatic reduction in NO_x emissions associated with the addition of a large amount of H_2 at 15% load was due to the reduced bulk mixture temperature. The emission of NO , NO_2 , and NO_x were reduced.

Figure 28 Effect of H_2 Addition on NO_x Emissions (mass) and Maximum Average Bulk Mixture Temperature, $N=1200$ RPM, 15% Load

Figure 29 Effect of H_2 Addition on the Emissions of NO_x , NO, and NO_2 , $N=1200$ RPM, 15% Load

Figure 30 Effect of H₂ Addition on NO_x Emissions Operated with Constant Diesel Flow Rate of 22.45 kg/hr (Corresponding to 50% Load for Pure Diesel Operation). N=1200 RPM. For Constant Diesel Fuel Flow Rate Operation, Engine Load was varied by Adding H₂

The enhancement of H₂ on the NO_x emissions was also examined under constant diesel flow rate. As shown in Figure 30, the addition of H₂ under constant diesel flow rate increased substantially the emissions of NO_x.

4.4.2 Effect of H₂ Addition on the Emissions of PM

The effect of H₂ addition on the emissions of PM is shown in Figure 31 and Figure 32. As shown in Figure 31 for medium to high load operation, the emissions of PM were reduced gradually with the addition of H₂ until 4.5% H₂ was added. Further increasing the amount of H₂ had negligible effect on the PM emissions.

Figure 31 Effect of H₂ Addition on PM Emissions, N=1200 RPM, 30-70% Load

A similar trend was observed for the addition of the H₂ under low load operation. As shown in Figure 32, the addition of up to 4.5% H₂ gradually reduced the emissions of PM. However, the addition of H₂ beyond 4.5% increased the emissions of PM especially for 10% load. This may have been due to the burning of diesel in the hot bulk gases when the H₂-air mixture was rich enough to support a fast propagating flame. The detailed explanation of this phenomenon may need further detailed experimental research. It was evident that the addition of H₂ below 4% reduced the PM emissions, which was consistent with those obtained in 13-mode emissions measurement. Compared to pure diesel operation, the maximum PM reduction obtained was 40 to 65% when operated from 10 to 70% load.

Figure 32 Effect of H₂ Addition on PM Emissions, N=1200 RPM, 10-20% Load

4.4.3 Effect of H₂ Addition on the Emissions of CO

CO is formed in the diesel engine due to the incomplete combustion of diesel fuels and also the dissociation of CO₂ under high temperature conditions. As shown in Figure 33 and Figure 34, the CO emissions decreased almost linearly with the addition of H₂ with the exception of 70% load operation. As shown in Figure 33, the addition of H₂ beyond 5% at 20% load started to increase the CO emissions. As shown in Figure 34 for 70% load operation, the addition of a small amount of H₂ (< 3.5%) had a negligible effect on CO emissions. Increasing the amount of H₂ beyond 4% increased the CO emissions.

Figure 33 Effect of H₂ Addition on CO Emissions, N=1200 RPM, 10-20% Load

Figure 34 Effect of H₂ Addition on CO Emissions, N=1200 RPM, 30-70% Load

4.4.4 Effect of H₂ Addition on the Emissions of HC

The effect of H₂ addition on HC emissions is shown Figure 35 and Figure 36. As shown in Figure 35, the addition of H₂ at low load slightly increased the HC emissions. When operated at medium to high load, the effect of H₂ addition on HC emissions was

very small as shown in Figure 36. This was consistent with the results reported in the 13-mode ESC, which showed a very small effect of H₂ on HC emissions.

Figure 35 Effect of H₂ Addition on HC Emissions, N=1200 RPM, 10-20% Load

Figure 36 Effect of H₂ Addition on HC Emissions, N=1200 RPM, 30-70% Load

4.4.5 Effect of H₂ Addition on the Emissions of CO₂

The effect of H₂ addition on CO₂ emissions is shown in Figure 37. The addition of H₂ into the diesel engine gradually reduced the CO₂ emissions. With the addition of a small amount of H₂, the operation at high load produced less CO₂ than low load operation due to the higher BTE at higher load operation. With the addition of 4% H₂ into the intake mixture, the CO₂ emissions obtained were comparable for the range of engine load examined. Further increasing the condition of H₂, the operation at lower load produced less CO₂ than higher load operation. This was due mainly to the substitution of higher percentage of diesel fuel by H₂ for lower load operation. As shown in Table 8, the addition of 6% H₂ to intake mixture contributed to 92.1% of the total intake energy. When operated at 70% load, the addition of 6% H₂ contributed to 31.7% of the total intake energy.

Figure 37 Effect of H₂ Addition on CO₂ Emissions, N=1200 RPM, 10-70% Load

4.5 Brake Thermal Efficiency and Its Improvement

As shown in Figure 38 for 30% load operation, the addition of a small amount of H_2 reduced the BTE with its minimum value observed with the addition of 2% H_2 . The addition of H_2 beyond 2% started to improve the BTE. With the addition of 3.5% H_2 , the BTE obtained was comparable to that of pure diesel operation. With the addition of 6.5% H_2 into the intake mixture, the BTE obtained was 41.9%, a much better value than 38.9% obtained for pure diesel operation. The BTE of H_2 -diesel dual fuel operation was further processed to calculate the improvement to the BTE relative to pure diesel operation. As shown in Figure 38, the addition of H_2 beyond 3% improved the BTE. The addition of 6.5% H_2 improved the brake thermal efficiency by 7.7% (relative).

Figure 38 Effect of H_2 Addition on BTE and Its Improvements, $N=1200$ RPM, 30% Load

As shown in Figure 39, the addition of H_2 at 10% load was shown to reduce the BTE. When operated at higher load, the addition of a relatively large amount of H_2 improved the BTE. It was evident that there was a minimum H_2 addition rate, beyond which a positive effect on BTE was obtained. Such a rate was defined as the minimum H_2

addition limit. For example, improved BTE was obtained with the addition of H_2 beyond 4.5 at 15% load operation. When operated at 50% load, the addition of H_2 over 1% improved the BTE.

Figure 39 Effect of H_2 Addition and Engine Load on the Improvement to BTE, $N=1200$ RPM, 10-70% Load

As shown in Figure 40, with the increased engine load, the H_2 addition limit to obtain a positive effect in improving the BTE expanded toward lower H_2 concentration. For example, the addition of H_2 beyond 3% improved BTE when operated at 20% load. When operated at 50% load, the improved BTE could be obtained with the addition of H_2 beyond 1%. It was evident that the operation under lower load required the addition of more H_2 to obtain an improvement to the BTE.

Figure 41 shows the effect of H_2 addition on the improvement of the BTE. The maximum improvement to the BTE of 14.1% was obtained at 20% load operation with the addition of 6.5% H_2 .

Figure 40 Effect of Engine Load on the Minimum H_2 Supplementation Rate Needed for Positive Effect on the BTE

Figure 41 Effect of H_2 Addition in Improving the BTE, $N=1200$ RPM, 10-70% Load

As shown in Figure 42 for the addition of 6% H_2 , the improvement to the BTE was found to decrease with the increased engine load with the exception of 10% load operation. The addition of H_2 at 10% load operation did not improve the BTE. The effect of the engine speed and the 4% H_2 addition on the BTE is shown in Figure 43. The engine speed had negligible effect on the improvement to the BTE resulted from the

addition of 4% H_2 . The addition of 4% H_2 improved the BTE by 3.7% for the range of engine speed examined.

Figure 42 Effect of Engine Load on the Improvement to BTE with the Addition of 6% H_2 , $N=1200$ RPM

Figure 43 Effect of H_2 Addition and Engine Speed on BTE and Improvement, Torque=700 ft-lb, Pure Diesel and $H_2/(H_2+Air)=4\%$, vol.

The effect of H_2 addition on the BTE was also investigated while the diesel fuel flow rate was held constant. The engine load was increased by gradually adding more H_2 into the intake mixture. Compared to pure diesel operation, the addition of a small amount of H_2 reduced the BTE as shown in Figure 44. With the addition of 2% H_2 , the BTE obtained was comparable to that of pure diesel operation. Further increasing the addition of H_2 beyond 2% substantially improved the BTE. The maximum BTE of 44.8% was obtained with the addition of 5.5% H_2 . Compared to the BTE of 41.6% obtained with pure diesel operation at same load, the BTE was increased by 7.7% (relative).

Figure 44 Effect of H_2 Addition on BTE, $N=1200$ RPM for Constant Diesel Flow Operation, Engine Load Was Increased by the Addition of H_2

4.6 Effect of H_2 Addition on Cylinder Pressure and Heat Release Process

Figure 45 shows the effect of H_2 addition on cylinder pressure when operated at 70% load. With the addition of a relatively small amount ($<3\%$) of H_2 , the cylinder pressure prior to the initiation of combustion was found to be higher than that of pure

diesel operation. This was due to the increased intake pressure as shown in Figure 46. The maximum intake pressure was observed with the addition of 2% H_2 . Further increasing the addition of H_2 beyond 2% gradually reduced the intake pressure and also the cylinder pressure prior to the initiation of combustion. As shown in Figure 45, the addition of H_2 substantially increased the cylinder pressure after the combustion was initiated. This was further demonstrated by examining the effect of H_2 addition on the peak cylinder pressure. As shown in Figure 47, the addition of a small amount of H_2 slightly increased the peak cylinder pressure with negligible effect on the phasing when peak cylinder pressure was observed. Further increasing the addition of H_2 beyond 3% substantially increased the peak cylinder pressure. The addition of 6% H_2 increased the peak cylinder pressure from 107.2 to 120.9 bar. As shown in Figure 47, the addition of H_2 beyond 3.5% gradually advanced the phasing when peak cylinder pressure was observed.

Figure 45 Effect of H_2 Addition on Cylinder Pressure, $N=1200$ RPM, 70% Load

Figure 46 Effect of H_2 Addition on Intake Manifold Pressure, N=1200 RPM, 70% Load

Figure 47 Effect of H_2 Addition on Peak Cylinder Pressure and Its Phasing, N=1200 RPM, 70% Load

The cylinder pressure was processed to obtain the heat release rate. As shown in Figure 48 for the premixed combustion, the addition of H_2 slightly retarded the initiation of premixed combustion and reduced the peak heat release rate observed in the premixed combustion stage. As shown in Figure 49, the addition of H_2 into this diesel engine enhanced the mixing controlled diffusion combustion process. When a large amount of

H₂ (>4%) was added, the traditional two-stage combustion process of diesel operation as shown in Figure 50, developed to a three-stage combustion process featured with a significantly enhanced heat release peak observed at the middle of diffusion combustion. This was further demonstrated in Figure 51 for the addition of 6% H₂. Following the premixed combustion, the diffusion combustion of the H₂-diesel dual fuel engine was initiated by the continuous injection, atomization, vaporization, and mixing of diesel fuel with air, followed by an extremely high heat release rate beyond that observed in traditional diesel diffusion combustion. It was believed that such a “huge” heat release peak was due to the initiation of multi H₂-air flames, which burned the H₂ quickly through the propagation of multi turbulent flames. The combination of the diesel diffusion combustion and the turbulent flames of H₂-air fuel mixture created the high heat release peak observed in H₂-diesel dual fuel combustion. After the turbulent H₂-air flames propagated through the entire bulk mixture or quenched due to the slow reaction rate, the diffusion combustion of diesel continued until completion, noted as late diesel diffusion combustion. As shown in Figure 50 and Figure 51, the peak heat release rate of H₂-diesel dual fuel engine was over two times that of pure diesel combustion. In comparison, the diffusion combustion of pure diesel operation was relatively “flat”. As shown in Figure 51, the dual fuel diesel engine combustion consisted of premixed diesel combustion, early stage diffusion combustion of diesel, burning of H₂ by multi turbulent flames and late state diffusion combustion of diesel fuel.

Figure 48 Effect of H₂ Addition on Heat Release Rate of Premixed Combustion, N=1200 RPM, 70% Load

Figure 49 Effect of H₂ Addition on Heat Release Rate, N=1200 RPM, 70% Load

Figure 50 The Two-Stage Heat Release Process of Pure Diesel Operation, N=1200 RPM, 70% Load

Figure 51 The Three-Stage Heat Release Process of H₂-Diesel Dual Fuel Engine, N=1200 RPM, 70% Load, H₂/ (H₂+Air)=6%, vol.

As shown in Figure 50, the start of injection (SOI) was defined as the crank angle when the first tiny “heat release” bump associated with diesel injection was observed. The start of combustion (SOC) was defined as the crank angle when the heat release rate at premixed stage reached 0.05 kJ/deg CA. The crank angle period between the SOI and

SOC was defined as the ignition delay. As shown in Table 15, the addition of H₂ was found slightly retarded the SOC. Compared to pure diesel operation, the addition of 6% H₂ retarded the SOC by approximately 0.84 deg CA. In comparison, the effect of the addition of H₂ on ignition delay was small. With addition of H₂ at 70% load, the retardation of the premixed combustion was due mainly to the retarded fuel injection.

Table 15 Effect of H₂ Addition on SOI, SOC, and Ignition Delay (ID) When Operated at 1200 RPM, 70% Load

H₂/(H₂+Air), vol. %	SOI, CA ATDC	SOC, CA ATDC	Ignition Delay, CA
0	-5.20	-1.10	4.10
1	-5.10	-0.85	4.25
2	-5.05	-0.75	4.30
3	-5.00	-0.68	4.32
4	-4.90	-0.55	4.35
5	-4.40	-0.37	4.03
6	-4.20	-0.26	3.94

As shown in Figure 52, the addition of a small amount of H₂ (<3%) slightly enhanced the peak heat release rate without affecting the phasing when peak heat release rate was observed. However, further increasing the addition of H₂ beyond 3.5% substantially increased the peak heat release rate and also advanced the phasing when the peak heat release rate was observed. This was due to the gradual development of the turbulent H₂ flame at the early stage of diesel diffusion combustion, which released more energy at advanced phasing as shown in Figure 49 and Figure 51.

Figure 52 Effect of H₂ Addition on Peak Heat Release Rate and Its Phasing, N=1200 RPM, 70% Load

Figure 53 to Figure 57 shows the effect of H₂ addition on cylinder pressure, intake pressure, heat release process, and the peak heat release rate when operated at 30% load. As shown in Figure 53 and Figure 54, the addition of H₂ at 30% load increased slightly the cylinder pressure and the intake pressure after combustion was initiated. However, its effect on the peak cylinder pressure and their phasing was relatively small as shown in Figure 55. Similar to that of peak cylinder pressure, the addition of H₂ at 30% load slightly increased the peak heat release rate. However, its effect on the phasing of the peak heat release rate was small. As shown in Figure 56 and Figure 57, the addition of H₂ at 30% load enhanced the premixed combustion and retarded its phasing, due to the retarded injection timing. In comparison, its addition was shown slightly inhibit the diffusion combustion. Compared to high load operation, the peak heat release rate was obtained at the premixed combustion stage when operated at 30% load as shown in Figure 56.

Figure 53 Effect of H₂ Addition on Cylinder Pressure, N=1200 RPM, 30% Load

Figure 54 Effect of H₂ Addition on Intake Manifold Pressure, N=1200 RPM, 30% Load

Figure 55 Effect of H_2 Addition on Peak Cylinder Pressure and Its Phasing, N=1200 RPM, 30% Load

Figure 56 Effect of H_2 Addition on Heat Release Rate, N=1200 RPM, 30% Load

Figure 57 Effect of H₂ Addition on Peak Heat Release Rate and Its Phasing, N=1200 RPM, 30% Load

Figure 58 to Figure 62 shows the effect of H₂ addition on the cylinder pressure, and heat release process when operated at 15% load. As shown in Figure 58 and Figure 59, the addition of H₂ at 15% load reduced substantially the cylinder pressure with negligible effect on the phasing when the peak cylinder pressure was observed. This was mainly due to the deteriorated premixed combustion process as shown in Figure 60. In comparison, the diffusion combustion process was further retarded with enhanced heat release rate at the late stage of diffusion combustion. Similar to 30% load operation, the peak heat release rate was observed at the premixed combustion stage. As shown in Figure 61, the addition of a small amount of H₂ (less than 2%) had negligible effect on the peak heat release rate and its phasing. Increasing the amount of H₂ beyond 3% was shown to substantially reduce the peak heat release rate with negligible effect on the phasing when peak heat release rate was observed. The reduction in the peak heat release rate may be due to the reduction in diesel flow rate. As shown in Figure 62, the peak heat

release rate was found to decrease with the reduced diesel flow following the addition of the increasing amount of H_2 .

Figure 58 Effect of H_2 Addition on Cylinder Pressure, N=1200 RPM, 15% Load

Figure 59 Effect of H_2 Addition on Peak Cylinder Pressure and Its Phasing, N=1200 RPM, 15% Load

Figure 60 Effect of H₂ Addition on Heat Release Rate, N=1200 RPM, 15% Load

Figure 61 Effect of H₂ Addition on Peak Heat Release Rate and Its Phasing, N=1200 RPM, 15% Load

Figure 62 Effect of Diesel Flow Rate on Peak Heat Release Rate of H₂-Diesel Dual Fuel Engine, N=1200 RPM, 15% Load

Table 16 shows the effect of H₂ addition on the SOI, SOC and ignition delay at 15% load operation. The addition of H₂ had negligible effect on the SOI and also the ignition delay.

Table 16 Effect of H₂ Addition on the SOI, SOC, and Ignition Delay When Operated at 1200 RPM, 15% Load

H ₂ /(H ₂ +Air), vol. %	SOI, CA ATDC	SOC, CA ATDC	Ignition Delay, CA
0	0.0	3.82	3.82
2	0.1	3.92	3.82
4	0.0	3.75	3.75
5	-0.1	3.72	3.82
6	0.0	4.08	4.08

Figure 63 compared the effect of engine load and the addition of H₂ on the changes of the peak heat release rate. The significant effect of H₂ addition on peak heat release rate was observed when the amount of H₂ addition was beyond 4%. When

operated at 70% load, the addition of H₂ beyond 4% substantially increased the peak heat release rate, which was due to the development of the H₂ turbulent flames. When operated at 15% load, the addition of H₂ beyond 4% reduced the peak heat release rate due mainly to the reduction of diesel fuel flow rate, which resulted in deteriorated premixed combustion. When operated at 30% load, the effect of H₂ addition on peak heat release rate was small.

Figure 63 Effect of H₂ Addition and Engine Load on the Peak Heat Release Rate, N=1200 RPM, 15, 30, and 70% Load

4.7 Summary

The effect of the addition of H₂, engine load, and engine speed on performance, combustion, and exhaust emissions of a 1999 Cummins ISM370ESP diesel engine has been experimentally investigated without modifying the engine control and fuel injection strategies. Following is a brief summary based on the limited results obtained in this research:

- The addition of H₂ at medium to high load (30-70%) substantially increased the emissions of NO_x. When operated at low load (10-15%), the addition of a small amount of H₂ (<3%) had negligible effect on NO_x emissions. However, the addition of a relatively large amount of H₂ (beyond 3-4% depending on load) at this very narrow low load operational region reduced substantially the emissions of NO_x. When measured using the 13-mode ESC, the addition of 2 and 4% H₂ increased the emissions of NO_x by 5.28 and 15.5%, respectively.
- The addition of H₂ reduced substantially the PM emissions measured under constant load. When operated at 10-70% load, the addition of H₂ (0-6.5%) reduced the PM emissions by up to 40 to 65%. When measured using the 13-mode emission cycle, the addition of 2% H₂ increased PM emissions from 0.032 to 0.037 g/bhp-hr (+15.6%). In comparison, the PM emission obtained at 4% H₂ reduced to 0.029 g/bhp-hr (-9.4%).
- The addition of H₂ under constant load reduced substantially the emissions of CO with the exception of 70% load. When operated at 70% load, the addition of relatively large amount of H₂ (4-6%) slightly increased the emissions of CO. When measured using the 13-mode ESC, the addition of 2% H₂ increased from 0.25 to 0.26 g/bhp-hr (+4.0%) compared to pure diesel operation. In comparison, the addition of 4% H₂ reduced CO emissions from 0.25 to 0.21 g/bhp-hr (-16.0%)
- The addition of H₂ at medium to high load (30-70%) had a negligible effect on the emissions of HC. In comparison, the addition of H₂ at low load (10-20%) slightly increased the emissions of HC. When measured using the 13-mode ESC, the

addition of 2% H₂ had negligible effect on HC emissions. In comparison, the addition of 4% H₂ increased slightly from 0.12 to 0.13 g/bhp-hr (+8.3%).

- The addition of H₂ reduced substantially the emissions of CO₂. When measured using 13-mode ESC, the addition of 2 and 4% H₂ substantially reduced the emissions of CO₂ from 474.7 to 416.7(-12.2%) and 347.9 g/bhp-hr (-26.7%), respectively.
- The addition of a small amount of H₂ (<1%) at 10 to 70% load deteriorated the BTE. However, the addition of H₂ (3-6.5%) at 15 to 70% load improved the brake thermal efficiency. The addition of 6% H₂ improved the BTE by 8.72-4.56% (relative) when operated at 15-70% load.
- When operated at high load, the addition of H₂ mainly affected the diffusion combustion process. In comparison, the addition of H₂ at low load mainly affected the premixed combustion. With the addition of H₂ at large amounts under high load, a featured three-stage combustion process of H₂-diesel dual fuel engine was observed.
- The addition of a large amount of H₂ (6%) at 70% load increased the peak cylinder pressure and peak heat release rate from 107.2 to 120.9 bar and 0.25 to 0.53 kJ/CA, respectively. In comparison with the addition of a large amount of H₂ (6%) at 15% load decreased the peak cylinder pressure and peak heat release rate from 59.2 to 48.6 bar and 0.34 to 0.14 kJ/CA, respectively.

5 INVESTIGATION OF EMISSIONS AND COMBUSTION OF A 2004 MACK MP7 355E ENGINE SUPPLEMENTED WITH H₂

5.1 Test Matrix

The test matrix for the 2004 Mack MP7 355E was similar to that of the 1999 Cummins ISM370ESP engine. The details of the engine testing set point for 13-Mode ESC, constant load, and constant diesel fuel flow are shown in Table 17, Table 18, and Table 19.

Table 17 Set Points for 13-Mode ESC, 2004 Mack MP7 355E

Mode	Speed	Torque, ft-lb	Weighting Factor, %
1	700	0	15
2	1225	1399	8
3	1501	640	10
4	1501	959	10
5	1225	700	5
6	1225	1049	5
7	1225	350	5
8	1501	1279	9
9	1501	320	10
10	1776	1091	8
11	1776	273	5
12	1776	818	5
13	1776	546	5

Table 18 Constant Load Test Matrix for 2004 Mack MP7 355E, N=1200 RPM

Load, %	H₂/(H₂+Air), vol. %
10	0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 2.0, 3.0, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, and 7.5
15	0.0, 1.0, 2.0, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, and 7.0
20	0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 2.0, 3.0, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, 7.0, and 7.5
30	0.0, 1.0, 2.0, 3.0, 4.0, 4.5, 5.0, 5.5, 6.0, and 7.0
50	0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 2.0, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5, 6.0, and 6.5
70	0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, and 6.0
100	0.0, 2.0 (1225 RPM), 3.0, 4.0 (1225 RPM), and 5.0

Table 19 Test Matrix for Constant Diesel Fuel Flow Rate, 2004 Mack MP7 355E

Diesel Flow Rate, kg/hr	H₂/(H₂+Air), vol.%
16.44	0.0, 1.0, 2.0, 2.5, 3.0, 4.0, 4.5, 5.0, 5.5, 6.0, 6.5, and 7.0
25.05	0.0, 1.0, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, and 5.5

Figure 64 shows the effect of H₂ addition on the equivalent ratio of diesel fuel. The equivalent ratio at every load decreased linearly with the addition of H₂ up to 7.5% indicating that the diesel fuel flow reduced. The lowest diesel fuel equivalent ratio was 0.1 at 10% load with 7.5% H₂ addition. The total equivalent ratio of H₂ and diesel fuel was shown in Figure 65. The addition of up to 3% H₂ slightly increased the total equivalence ratio. However, the addition of H₂ beyond 3% decreased slowly towards the baseline total equivalent ratio. The effect of H₂ addition on total equivalent ratio for 30-100% load showed negligible effect up to 3% H₂ addition. However, the addition of H₂ beyond 3% slightly increased the total equivalence ratio.

Figure 64 Effect of H_2 Addition on Equivalence Ratio of the Diesel Fuels, 2004 Mack MP7 355E, N=1200 RPM, 10-100% Load

Figure 65 Effect of H_2 Addition on Total Equivalence Ratio Including That of H_2 and Diesel, 2004 Mack MP7 355E, N=1200 RPM, 10-100% Load

5.2 13-Mode ESC

The effect of H₂ addition on regulated emissions was measured using the 13-mode ESC. As shown in Table 20, the addition of 2 and 4% H₂ into this 2004 Mack MP7 355E diesel engine reduced PM emissions from 0.040 to 0.033 and 0.029 g/bhp-hr, respectively. Compared to pure diesel operation, the PM emissions were reduced by 17.5 and 27.5%, respectively.

Table 20 Effect of H₂ Addition on Exhaust Emissions Measured using 13-Mode ESC, g/bhp-hr

H ₂ /(H ₂ +Air), vol.%	PM	NO _x	CO	HC	CO ₂
0	0.040	2.02	0.76	0.072	497.0
2	0.033	2.03	0.74	0.078	431.0
4	0.029	2.10	0.82	0.072	360.2

As shown in Table 20, the addition of 2% H₂ had negligible effect on NO_x emissions while the addition of 4% H₂ slightly increased the NO_x emissions from 2.02 to 2.10 g/bhp-hr. Compared to pure diesel operation, the emissions of NO_x were increased by 4.0%. As shown in Table 21, the addition of 2 and 4% H₂ into the 1999 Cummins ISM370ESP engine increased NO_x emissions by 5.3 and 15.5%, respectively. It is evident that the addition of H₂ into the 2004 Mack MP7 355E engine has less effect on NO_x emissions compared to that of the 1999 Cummins ISM370ESP diesel engine.

Table 21 Effect of H₂ Addition on NO_x Emissions of a 2004 Mack MP7 355E and a 1999 Cummins ISM370ESP Engine Measured Using 13-Mode ESC, g/bhp-hr

H₂/(H₂+Air), vol. %	2004 Mack MP7 355E		1999 Cummins ISM370ESP	
	NO_x Emissions, g/bhp-hr	Changes, %	NO_x Emissions, g/bhp-hr	Changes, %
0	2.02	-	3.41	-
2	2.03	+ 0.5	3.59	+5.3
4	2.10	+4.0	3.94	+15.5

The detailed effect of the addition of H₂ on NO_x emissions of each mode is shown in Figure 66. The addition of 2% H₂ increased NO_x emissions at mode 5, 6, 7, 9, 10, 11, and 13. Compared to diesel operation, the addition of 4% H₂ increased the NO_x emissions at mode 3, 5, 7, 9, 10, and 11.

Figure 66 Effect of H₂ Addition on NO_x Emissions, 13-Mode ESC

As shown in Table 20, the addition of 2% H₂ reduced CO emissions from 0.76 to 0.74 g/bhp-hr (-2.6%). However, the addition of 4% H₂ increased the CO emissions from 0.76 to 0.82 g/bhp-hr (+7.9%). As shown in Figure 67, the addition of 2 and 4% H₂

reduced the CO emissions at all modes with the exception of mode 2, 6, and 8 which were the high load operating conditions in 13-mode ESC.

Figure 67 Effect of H₂ Addition on CO Emissions, 13-Mode ESC

As shown in Table 20, the addition of 2% H₂ increased the emissions of HC from 0.072 to 0.078 g/bhp-hr (+8.3%). In comparison, the addition of 4% H₂ had negligible effect on HC emissions. As shown in Figure 68, the addition of 2% H₂ slightly increased the HC emissions at all modes with the exception of mode 2. However, the addition of 4% H₂ produced more HC at mode 11 but less or comparable HC emissions at other modes.

As shown in Table 20, the addition of 2 and 4% H₂ reduced the CO₂ emissions from 497.0 to 431.0 (-13.3%) and 360.2 g/bhp-hr (-27.5%), respectively. The detailed effect of the addition of H₂ on CO₂ emissions can be found in Figure 69. The addition of 2 and 4% of H₂ reduced the CO₂ emissions observed at all modes.

Figure 68 Effect of H₂ Addition on HC Emissions, 13-Mode ESC

Figure 69 Effect of H₂ Addition on CO₂ Emissions, 13-Mode ESC

5.3 Effect of H₂ Addition and Engine Load on Exhaust Emissions

5.3.1 Effect of H₂ Addition on the Emissions of NO_x, NO, and NO₂

The effect of H₂ addition on the NO_x emissions was examined when operated under 10-100% load. As shown in Figure 70, the addition of a small amount of H₂ at 10% load reduced slightly the NO_x emissions until the concentration of H₂ reached 4% in the

intake mixture. Further increasing the addition of H_2 beyond 4% reduced substantially the emissions of NO_x . The addition of H_2 at 15% load increased slightly the emissions of NO_x . Further increasing the addition of H_2 beyond 6% reduced the emissions of NO_x . The addition of H_2 up to 5% at 20% load had mild effect on NO_x emissions with exception of the addition of H_2 at 3%. Further increasing the addition of H_2 beyond 5% slightly increased the emissions of NO_x .

Figure 70 Effect of H_2 Addition and Engine Load on NO_x Emissions, $N=1200$ RPM, 10-20% Load

As shown in Figure 71, the addition of a small amount of H_2 at 30% load slightly reduced the NO_x emissions with its minimum value observed with the addition of 4.5% H_2 . Further increasing the amount of H_2 added beyond 5% gradually increased the emissions of NO_x . The NO_x emissions obtained with the addition of 6% H_2 was comparable to that of pure diesel operation. The high NO_x emissions at 3% H_2 may be due to the unexpected operation of EGR and VGT, which will be discussed for 50% load operation.

Figure 71 Effect of H₂ Addition on NO_x Emissions, N=1200 RPM, 30% Load

As shown in Figure 72 for 50% load, the addition of 0.2 and 0.4% H₂ had negligible effect on the emissions of NO_x. However, a sudden increase in NO_x emission was observed for the addition of 0.6, 0.8, 1, and 2% H₂. This may be due to the sudden change in the VGT and EGR valve positions, which depended to a large extent on engine speed and the flow rate of diesel. As shown in Figure 73, the increased NO_x emissions were accompanied with increased air flow, indicating the reduced EGR rate. If EGR system responded properly, the addition of a small amount of H₂ should have negligible effect on NO_x emissions. At the same time, the position of VGT may also has changed, which might affect the NO_x emissions.

Figure 72 Effect of H₂ Addition on NO_x Emissions, N=1200 RPM, 50% Load

Figure 73 Effect of H₂ Addition on NO_x Emissions and Intake Air Flow (liter per second (lps)) Measured Continuously, N=1200 RPM, 50% Load

As shown in Figure 74, the addition of H₂ slightly reduced the emissions of NO_x with their minimum values observed with the addition of 4.5% H₂. Further increasing the addition of H₂ beyond 4.5% started to increase the emissions of NO_x. As shown in Figure 75, the addition of H₂ had negligible effect on NO_x emissions for full load

operation. Similar to that of the 1999 Cummins ISM370ESP engine, the addition of H_2 was found to enhance the conversion of NO to NO_2 as shown in Figure 76.

Figure 74 Effect of H_2 Addition and Engine Load on NO_x Emissions, N=1200 RPM, 70% Load

Figure 75 Effect of H_2 Addition and Engine Load on NO_x Emissions, N=1200 RPM, 100% Load

Figure 76 Effect of H₂ Addition on the Emissions of NO_x, NO, and NO₂, N=1200 RPM, 10% Load

Figure 77 shows the effect of H₂ addition on the emissions of NO_x, NO, and NO₂ at 70% load operation. The addition of H₂ reduced the emissions of NO_x and NO with their minimum values observed with the addition of 4.5% H₂. As shown in Figure 77, the addition of H₂ enhanced the formation of NO₂ with the maximum NO₂ emissions observed with 1-2% H₂. Further increasing the addition of H₂ started to reduce the NO₂ emissions but still produces more NO₂ than diesel operation.

Figure 77 Effect of H₂ Addition on the Emissions of NO_x, NO, and NO₂, N=1200 RPM, 70% Load

5.3.2 Effect of H₂ Addition on the Emissions of PM

Figure 78 through Figure 81 shows the effect of H₂ additions on PM emissions. Similar to that of the 1999 Cummins ISM370ESP engine, the addition of H₂ to the 2004 Mack MP7 355E engine reduced substantially the PM emissions. As shown in Figure 78, the addition of H₂ at 70% load reduced gradually the emissions of PM. However, the H₂ addition at full load operation had negligible effect on PM emissions. As shown in Figure 79, the addition of H₂ (<1%) reduced substantially the PM emissions. However, the H₂ addition beyond 1% gradually increased the PM emissions until 3.5%. Then, PM emissions reduced again beyond 3.5% H₂ addition. Figure 80 shows the same trend as 50% load, the PM emissions reduced substantially until 3% H₂ addition. The PM emissions increased between 3 and 4% H₂ addition and decreased again beyond 4% H₂ addition. With the addition of H₂ up to 7.5% at 10-70% load, the maximum PM reduction of 65 to 80% was obtained.

Figure 78 Effect of H₂ Addition on the Emissions of PM, N=1200 RPM, 70 and 100% Load

Figure 79 Effect of H₂ Addition on the Emissions of PM, N=1200 RPM, 50% Load

Figure 80 Effect of H₂ Addition on the Emissions of PM, N=1200 RPM, 30% Load

As shown in Figure 81 for low load (10-20%) operation, the addition of a small amount of H₂ (<3%) drastically reduced the PM emissions especially for 10% load. Further increasing the amount of H₂ would continue to reduce PM emissions but at a lower rate.

Figure 81 Effect of H₂ Addition on the Emissions of PM, N=1200 RPM, 10-20% Load

5.3.3 Effect of H₂ Addition on the Emissions of CO

As shown in Figure 82, the addition of H₂ at low to medium load reduced the emissions of CO. This was consistent with the experimental results reported in the literature and those obtained in the 1999 Cummins ISM370ESP engine. This may be due to the reduction in the amount of diesel fuel burned and also the enhancement of H₂ on oxidation of CO to CO₂. However, the addition of a small amount of H₂ at high load operation increased the emissions of CO with the maximum CO emissions observed with the addition of 4% H₂ as shown in Figure 83. Further increasing the addition of H₂ reduced the emissions of CO. This could be due to the development of the H₂ flame, which helps to burn the CO survived the main combustion process.

Figure 82 Effect of H₂ Addition on the Emissions of CO, N=1200 RPM, 10-50% Load

Figure 83 Effect of H₂ Addition on the Emissions of CO, N=1200 RPM, 70-100% Load

5.3.4 Effect of H₂ Addition on the Emissions of HC

As shown in Figure 84, the addition of H₂ had negligible effect on the emissions of HC at all loads with the exception of 10% load. The addition of up to 5% H₂ at 10% load had minor effect on HC emissions. The addition of H₂ beyond 5% substantially reduced the HC emissions.

Figure 84 Effect of H₂ Addition on the Emissions of HC, N=1200 RPM, 10-100% Load

5.3.5 Effect of H₂ Addition on the Emissions of CO₂

The effect of H₂ addition on the emissions of CO₂ can be found in Figure 85. As expected, the addition of H₂ into this diesel engine gradually reduced the emissions of CO₂. This was due to the reduction in diesel fuel flow and also the improvement in BTE when a relatively large amount of H₂ was added. The lower CO₂ emissions observed at low load with the addition of large amount of H₂ was due mainly to the substitution of large percentage of diesel fuel by H₂. As shown in Figure 86, the addition of 6% H₂ at 10% load contributed up to 51% of the total intake energy. When operated at 70% load, the addition of 6% H₂ contributed to 32% to the total intake energy.

Figure 85 Effect of H₂ Addition on the Emissions of CO₂, N=1200 RPM, 10-70% Load

Figure 86 Effect of H₂ Addition on Diesel Substitution for 2004 Mack MP7 355E, N=1200 RPM, 10-70% Load

5.4 Brake Thermal Efficiency and Its Improvement

The brake thermal efficiency depends on the combustion efficiency of the fuel, combustion phasing, compression ratio, the heat transfer from the bulk gas to coolant and the mechanical efficiency. As shown in Figure 87, the addition of H₂ at 10% load

substantially reduced the BTE with its minimum value of 26.1% observed when the $H_2/(H_2+Air)$ reached 4.5%. Further increasing the amount of H_2 added beyond 4.5% improved gradually the BTE. However, the BTE with the addition of H_2 at 10% load was lower than that of pure diesel operation (28.3%). No benefit in the brake thermal efficiency was obtained with the addition of H_2 at 10% load.

Benefiting from the improved H_2 combustion efficiency, the positive effect of the addition of H_2 in improving the BTE was observed at higher load operation. As shown in Figure 88 for 20% load operation, the improved BTE was observed when the H_2 addition reached 5.5%. With the addition of 7.5% H_2 into the intake mixture, the BTE of 36.3% was observed. Compared to pure diesel operation, the BTE was improved from 35.2 to 36.3% with 3.1% improvement.

Figure 87 Effect of H_2 Addition on the BTE, N=1200 RPM, 10% Load

Figure 88 Effect of H₂ Addition on the BTE, N=1200 RPM, 20% Load

Benefiting from the improvement of H₂ combustion efficiency and also an enhanced combustion process with the increasing engine load, the penalty in BTE was gradually limited to the lower H₂ addition range as shown in Figure 89. When operated at medium to high load, the negative effect of H₂ addition on the BTE was only observed when a small amount of H₂ (<1%) was added as shown in Figure 90 for 50, 70, and 100% load operation.

Figure 89 Effect of H₂ Addition and Engine Load on BTE under Low Load Operation, N=1200 RPM, 10-30% Load

Figure 90 Effect of H₂ Addition and Engine Load on BTE When Operated from Medium to High Load Operation, N=1200 RPM (For 100% Operation, 2 and 4% H₂ Data Was Measured at 1225 RPM)

The effect of H₂ addition on the BTE was also explored by examining the improvement to the BTE relative to that of pure diesel operation. As shown in Figure 91, the positive effect of H₂ addition on the BTE could only be obtained when a relatively large amount of H₂ was added at loads higher than 15%. With the increasing engine load, the positive effect of H₂ addition in improving BTE could be obtained with the addition of less H₂. As shown in Figure 92 for medium to high load operation, the improvement of BTE can be obtained with the addition of H₂ as low as 1%.

Figure 91 Effect of H₂ Addition and Engine Load in Improving the BTE under Low Load Operation, N=1200 RPM, 10-30% Load

Figure 92 Effect of H₂ Addition and Engine Load in Improving the BTE under Medium to High Load Operation, N=1200 RPM, 50-100% Load

The effect of the engine load on the improvement to the BTE was also examined with the addition of 6% H₂ into the intake mixture. As shown in Figure 93, the maximum

benefit on the BTE for the 2004 Mack MP7 355E was about 4%. Compared to that of the 1999 Cummins ISM370ESP engine, the addition of H_2 to the 2004 Mack MP7 355E engine was less effective in improving the BTE, especially at low load operation. Due to the application of EGR, the addition of H_2 to 2004 Mack MP7 355E substituted less diesel fuel from the reduced intake air flow rate. This was supported by the data shown in Figure 16 and Figure 86, respectively.

Figure 93 Effect of Engine Load on BTE Improvement with the Addition of 6% H_2 , $N=1200$ RPM

Figure 94 compared the effect of engine load on the minimum H_2 supplementation rate needed to achieve a positive effect on the brake thermal efficiency of both engines. It was shown that more H_2 was needed for the 2004 Mack MP7 355E to obtain a positive effect in improving the BTE. This may be due to the application of cooled EGR in the 2004 Mack MP7 355E engine.

Figure 94 Effect of Engine Load on the Minimum H₂ Supplementation Rate Needed for Positive Effect on BTE, N=1200 RPM

For constant diesel fuel flow rate operation, engine load was varied by altering the amount of H₂ added. As shown in Figure 95, the addition of a small amount of H₂ slightly deteriorated the BTE compared to the burning of pure diesel. The addition of H₂ beyond 4% improved the BTE. A similar result was obtained for the addition of H₂ at a higher diesel flow rate. As shown in Figure 96, the positive effect on BTE was obtained for the addition of H₂ beyond 3%.

Figure 95 Effect of H₂ Addition on the BTE, N=1200 RPM. For Constant Diesel Fuel Flow Rate (16.44 kg/hr) Operation, Engine Load Was Changed by the Addition of H₂

Figure 96 Effect of H₂ Addition on the BTE, N=1200 RPM. For Constant Diesel Fuel Flow Rate (25.05 kg/hr) Operation, Engine Load Was Changed by the Addition of H₂

5.5 Effect of H₂ Addition on Cylinder Pressure and Heat Release Process

The addition of H₂ into this diesel engine at high load significantly enhanced the combustion process. As shown in Figure 97 for 70% load operation, the addition of H₂ increased the cylinder pressure after combustion was initiated. As shown in Figure 98,

the addition of a small amount of H_2 (<3%) increased the peak cylinder pressure with negligible effect on the phasing when peak cylinder pressure was observed. However, further increasing the addition of H_2 beyond 3% continued to increase the peak cylinder pressure but at advanced the phasing when peak cylinder pressure was observed.

Figure 97 Effect of H_2 Addition on Cylinder Pressure, N=1200 RPM, 70% Load

Figure 98 Effect of H_2 Addition on Peak Cylinder Pressure and Its Phasing, N=1200 RPM, 70% Load

As shown in Figure 99, the addition of H_2 was shown to slightly retard the phasing of the premixed combustion. As shown in Table 22, the slight retarding to the phasing of premixed combustion was due to the slightly retarded fuel injection timing and also the slightly longer ignition delay. This made the premixed combustion slightly stronger as more diesel fuel was well mixed with air and ready to be burned in the premixed combustion stage. Also, the addition of H_2 to the diesel engine enhanced the heat release rate during the switching process between premixed combustion and diffusion combustion. When $H_2/(H_2+air)$ reached 6%, the induction period from premixed combustion to mixing controlled diffusion combustion became negligible. It seems that the premixed combustion may have ignited the H_2 -air mixture prior to the initiation of diffusion combustion of diesel fuel.

Figure 99 Effect of H_2 Addition on Premixed Combustion, $N=1200$ RPM, 70% Load

Table 22 Effect of H₂ Addition on SOI, SOC, and Ignition Delay When Operated at 1200 RPM, 70% Load

H₂/(H₂+Air), %	Start of Injection, CA ATDC	Start of Combustion, CA ATDC	Ignition Delay, CA
0	-7.15	-2.20	4.95
2	-7.10	-1.95	5.15
4	-6.95	-1.75	5.20
5	-6.95	-1.70	5.25
6	-6.90	-1.68	5.22

The effect of H₂ addition on the heat release process of the diffusion combustion is shown in Figure 100. The addition of H₂ at 70% load has more significant effect on diffusion combustion compared to premixed combustion. The addition of H₂ over 2% enhanced gradually the heat release rate during the middle stage of diffusion combustion. When the concentration of H₂ reached 4% in the intake mixture, the enhanced late diffusion combustion developed gradually to the peak heat release rate at a later phasing compared to diesel combustion. As shown in Figure 101 for the addition of 6% H₂, the featured two-stage combustion process of the diesel engine developed into a three-stage combustion process of dual fuel engine including premixed diesel combustion, early stage diesel diffusion combustion, the combustion of H₂ by propagating turbulent flames and late stage diffusion combustion of diesel fuel. The enhanced heat release peak in diffusion combustion represented a combination of the diffusion combustion of diesel fuel and the propagation of multi turbulent H₂-air flames. Also, the combustion of H₂ finished earlier than the slow diesel diffusion combustion. The fast burning of H₂ fuel

contributed to the advanced phasing of peak cylinder pressure obtained in H₂-diesel dual fuel combustion mode.

Figure 100 Effect of H₂ Addition on Heat Release Process, N=1200 RPM, 70% Load

Figure 101 The Heat Release Process of H₂-Diesel Dual Fuel Engine Operation, N=1200 RPM, 70% Load, H₂/(H₂+Air)=6%, vol.

Figure 102 shows the effect of H₂ addition on the peak heat release rate and its phasing. The addition of a small amount of H₂ (<3%) slightly increased the peak heat

release rate but had negligible effect on the phasing when peak heat release rate was observed. A sudden retard in phasing of peak heat release rate with the addition of 2.5 and 3% H_2 was due to the development of peak heat release rate obtained at late stage of diffusion combustion. As described before, this late heat release bump was due to the gradual development of H_2 combustion. As shown in Figure 102, further increasing the amount of H_2 beyond 3% was found to drastically enhance the combustion process represented by the increased peak heat release rate observed at substantially advanced phasing.

Figure 102 Effect of H_2 Addition on Peak Heat Release Rate and Its Phasing, N=1200 RPM, 70% Load

Figure 103 to Figure 107 shows the effect of H_2 addition on the variation of cylinder pressure and heat release process for 50% load operation. As shown in Figure 103 and Figure 104, the addition of a small amount of H_2 (<3%) increased slightly the peak cylinder pressure but had negligible effect on its phasing. Similar to 70% load operation, the sudden retard in the phasing of peak cylinder pressure for 3.5 and 4% H_2

addition, as shown in Figure 104, was due to the development of the second heat release peak in diffusion combustion as shown in Figure 106. Increasing the amount of H_2 added beyond 5% was found to drastically increase the peak cylinder pressure with gradually advanced phasing as shown in Figure 107.

Figure 103 Effect of H_2 Addition on Cylinder Pressure, N=1200 RPM, 50% Load

Figure 104 Effect of H_2 Addition on Peak Cylinder Pressure and Its Phasing, N=1200 RPM, 50% Load

As shown in Figure 105, the addition of a small amount of H_2 (<4.5%) increased slightly the peak heat release rate with negligible effect on its phasing. Also, the addition of H_2 was found to enhance the late diffusion combustion as shown by the gradual development of the second heat release peak observed at late diffusion combustion as shown in Figure 106. Further increasing the addition of H_2 enhanced and advanced the heat release peak associated with H_2 until it merged with that of diesel diffusion combustion as shown in Figure 107 for the addition of 6% H_2 . In comparison, the addition of H_2 at 50% load had negligible effect on the premixed combustion process.

Figure 105 Effect of H_2 Addition on Peak Heat Release Rate and Its Phasing, N=1200 RPM, 50% Load

Figure 106 Effect of H₂ Addition Heat Release Rate, N=1200 RPM, 50% Load, H₂/(H₂+Air)=5%, vol.

Figure 107 Effect of H₂ Addition on Heat Release Rate, N=1200 RPM, 50% Load

Figure 108 to Figure 111 shows the effect of H₂ addition on the cylinder pressure and heat release process for 30% load operation. Compared to 50 and 70% load operation, the addition of H₂ at 30% load had mild effect on the cylinder pressure and also peak cylinder pressure. As shown in Figure 108 and Figure 109, the addition of H₂

below 6% had a negligible effect on the cylinder pressure after combustion was initiated including the peak cylinder pressure and the phasing when peak cylinder pressure was observed. Further increasing the addition of H_2 beyond 6% slightly increased the peak cylinder pressure observed at a retarded phasing. As shown in Figure 110, the addition of H_2 at 30% load retarded the initiation of premixed combustion, enhanced premixed combustion, inhibited the early stage diffusion combustion and slightly enhanced the late stage diffusion combustion. With the addition H_2 over 6%, the late stage diffusion combustion developed into a third heat release peak. Further increasing the amount of H_2 advanced and enhanced the third heat release peak until it dominated the heat release process. This might be due to the gradual development of the healthy H_2 flame. As shown in Figure 111, the addition of H_2 at 30% load enhanced slightly the peak heat release rate and retarded its phasing. Compared to that of 50 and 70% load with peak heat release rate observed at diffusion combustion, the peak heat release rate was observed in the premixed combustion stage when operated at 30% load. In comparison, the diffusion combustion was relatively weak for low load operation.

Figure 108 Effect of H_2 Addition on Cylinder Pressure, N=1200 RPM, 30% Load

Figure 109 Effect of H_2 Addition on Peak Cylinder Pressure and Its Phasing, N=1200 RPM, 30% Load

Figure 110 Effect of H_2 Addition on Heat Release Rate, N=1200 RPM, 30% Load

Figure 111 Effect of H₂ Addition on Peak Heat Release Rate and Its Phasing, N=1200 RPM, 30% Load

Figure 112 to Figure 115 shows the effect of H₂ addition on the cylinder pressure and heat release process when operated at 15% load. Compared to medium and high load operation (>30% load), the addition of H₂ at 15% load reduced the peak cylinder pressure, which was observed at a retarded phasing as shown in Figure 112 and Figure 113. As shown in Figure 114, the retarded peak cylinder pressure was due to the retarded combustion phasing. As shown in Table 23, the retarding in combustion phasing with the addition of H₂ at 15% load was mainly due to the retarded injection timing. In comparison, the effect of H₂ addition on ignition delay was negligible. Similar to 30% load operation, the peak heat release rate was observed in premixed combustion as shown in Figure 114. In comparison, the diffusion combustion becomes extremely weak. The addition of H₂ retarded the premixed combustion but slightly enhanced the diffusion combustion.

Figure 112 Effect of H₂ Addition on Cylinder Pressure, N=1200 RPM, 15% Load

Figure 113 Effect of H₂ Addition on Peak Cylinder Pressure and Its Phasing, N=1200 RPM, 15% Load

Figure 114 Effect of H₂ Addition on Heat Release Rate, N=1200 RPM, 15% Load

Table 23 Effect of H₂ Addition on SOI, SOC, and Ignition Delay When Operated at 1200 RPM, 15% Load

H ₂ /(H ₂ +Air), vol. %	SOI, CA ATDC	SOC, CA ATDC	Ignition Delay, CA
0	-2.50	1.62	4.12
2	-2.05	2.25	4.30
4	-1.00	3.35	4.35
5	-0.50	3.70	4.20
6	-0.15	4.02	4.17

Figure 115 Effect of H₂ Addition on Peak Heat Release Rate and Its Phasing, N=1200 RPM, 15% Load

Figure 116 to Figure 119 shows the effect of H₂ addition on cylinder pressure and heat release process at 10% load. As shown in Figure 116, the addition of H₂ at 10% load retarded the initiation of combustion and substantially reduced the cylinder pressure after the combustion was initiated. As shown in Figure 117, the addition of a relatively small amount of H₂ (<4%) reduced slightly the peak cylinder pressure observed at gradually retarded phasing. Further increasing the addition of H₂ beyond 4.5% reduced the peak cylinder pressure and substantially retarded the phasing when the peak cylinder pressure was observed. As shown in Figure 118, the retarded peak cylinder pressure was due mainly to the retarded combustion phasing with the addition of less than 5% H₂. Further increasing the addition of H₂ beyond 5% retarded the combustion phasing and substantially inhibited the premixed combustion process, which resulted in a much enhanced late diffusion combustion compared to pure diesel combustion. As shown in Table 24, the retarded combustion phasing with H₂ addition was also due mainly to the retarded injection timing with notable contribution of lengthened ignition delay for the

addition of H₂ over 6%. As shown in Figure 119, the significant effect of H₂ addition on peak heat release rate was observed when the amount of H₂ added reached 5%.

Figure 116 Effect of H₂ Addition on Cylinder Pressure, N=1200 RPM, 10% Load

Figure 117 Effect of H₂ Addition on Peak Cylinder Pressure and Its Phasing, N=1200 RPM, 10% Load

Figure 118 Effect of H₂ Addition on Heat Release Rate, N=1200 RPM, 10% Load

Table 24 Effect of H₂ Addition on SOI, SOC, and Ignition Delay When Operated at 1200 RPM, 10% Load

H ₂ /(H ₂ +Air), vol. %	SOI, CA ATDC	SOC, CA ATDC	Ignition Delay, CA
0	-1.10	3.18	4.28
2	-0.35	3.80	4.15
4	0.0	4.36	4.35
5	0.90	5.22	4.32
6	1.90	6.54	4.64
7	2.20	7.15	4.95

Figure 119 Effect of H₂ Addition on Peak Heat Release Rate and Its Phasing, N=1200 RPM, 10% Load

Figure 120 shows the effect of engine load on the heat release process of pure diesel operation. The increase in engine load advanced the combustion phasing, inhibited the heat release process of the premixed combustion with significantly enhanced and longer diffusion combustion. When operated at low load, the peak heat release rate was observed at premixed combustion. When operated at high load, the featured injection of large amount of diesel fuel, and also higher compression temperature and pressure contributed to the weak premixed combustion. In comparison, the mixing controlled diffusion combustion was substantially enhanced and lengthened. The diffusion combustion gradually developed into the main combustion process and dominated the heat release process.

Figure 120 Effect of Engine Load on Heat Release Process, N=1200 RPM, Diesel Only

Figure 121 shows the effect of engine load on the heat release process of H₂-diesel dual fuel operation with the addition of 6% H₂. Similar to pure diesel operation, the increase in the engine load advanced the phasing of both premixed and diffusion combustion resulted from the advanced fuel injection. The maximum heat release rate of

premixed combustion increased first and then dropped gradually with the development of strong diffusion combustion. With the increase in the engine load, the burning of the increasing amount of H_2 produced a unique and featured heat release peak as shown Figure 121 for 50 and 70% load operation. The diesel engine featured two-stage (premixed and diffusion diesel combustion) developed gradually into a three-stage combustion process including premixed and diffusion combustion of diesel fuel, and fast combustion of H_2 burned by the turbulent flames as shown in Figure 121 for 70% load operation with the addition of 6% H_2 .

Figure 121 Effect of Engine Load on Heat Release Process, $N=1200$ RPM, $H_2/(H_2+Air)=6\%$, vol.

5.6 Summary

The effect of the addition of H_2 , engine load, and engine speed on performance, combustion, and exhaust emissions of a 2004 Mack MP7 355E diesel engine has been experimentally investigated without modifying the engine control and fuel injection strategies. Following is a brief summary based on the results obtained in this research:

- The addition of H₂ at 10 to 20% load had a weak effect on NO_x emissions with the exception of 10% load. The addition of a relatively large amount of H₂ addition (4-7.5%) at 10% load reduced the NO_x emissions. When operated at medium to high load (30-70%) operation, the addition of a small amount of H₂ (<4% for 30% load, <3% for 50% load, and <4% for 70% load) reduced slightly on the emissions of NO_x. The addition of a relatively large amount of H₂ (>5% for 30% load, >3% for 50% load, and >5% for 70% load) increased the emissions of NO_x. When operated at full load, the addition of H₂ had negligible effect on NO_x emissions with the addition of up to 5% H₂. When measured using the 13-mode ESC, the addition of 2% H₂ had negligible effect on NO_x emissions. The addition of 4% H₂ was shown to increase from 2.02 to 2.10 g/bhp-hr (+4%) compared to pure diesel.
- The addition of H₂ into this diesel engine reduced the emissions of PM. The extent of reduction in PM emissions depended on the amount of H₂ added and engine load. With the addition of H₂ up to 7.5% at 10-70% load, the maximum PM reduction of 65 to 80% was obtained. The PM emissions measured using the 13-mode ESC was reduced from 0.040 to 0.033 (-17.5%) and 0.029 g/bhp-hr (-27.5%) with the addition of H₂ at 2 and 4%, respectively.
- The addition of H₂ reduced substantially the emissions of CO when operated at 10 to 20% load. When operated at 30 to 100% load, the addition of small amount of H₂ (<2% for 30% load, <3% for 50% load, <4% for 70 and 100% load) increased the emissions of CO. Increasing the amount of H₂ corresponded to each load reduced the emissions of CO. When measured using the 13-mode ESC, the

addition of 2% H₂ into the diesel engine reduced CO emissions from 0.76 to 0.74 g/bhp-hr (-2.6%). The addition of 4% H₂ increased CO emissions from 0.76 to 0.82 g/bhp-hr (+7.9%).

- The addition of H₂ reduced the emissions of HC with the exception of 10% load operation. When operated at 10% load, the addition of H₂ less than 5% had a negligible effect on the emissions of HC. The addition of H₂ beyond 5% reduced substantially the emissions of HC. When measured using the 13-mode ESC, the addition of 2% H₂ increased HC emissions from 0.072 to 0.078 g/bhp-hr (+8.3%). The addition of 4% H₂ had a negligible effect on HC emissions.
- The addition of a relatively small amount of H₂ (<1%) lowered the BTE. The desirable positive effect of H₂ in improving the BTE was obtained with the addition of H₂ at relatively large amounts (3-7.5%) at 50 and 70% load. With the addition of 6% H₂, the improvement to the BTE was found to be 0.8-3.4% for 20-70% load operation. When operated at low load, the positive effect of H₂ addition on the BTE was not observed.
- The addition of a large amount of H₂ (6%) at 70% load increased the peak cylinder pressure and peak heat release rate from 153.7 to 178.5 bar and 0.33 to 0.87 kJ/CA, respectively. In comparison with the addition of a large amount of H₂ (6%) at 15% load decreased the peak cylinder pressure and peak heat release rate from 73.5 to 68.3 bar and 0.46 to 0.44 kJ/CA, respectively.

6 CONCLUSIONS AND RECOMMENDATIONS

This research investigated the performance, combustion, and emission characteristics of H₂-enriched diesel engines using a 1999 Cummins ISM370ESP and a 2004 Mack MP7 355E. The H₂ was mixed to the intake air well before entering the intake manifold with suitable backfire protection devices installed. The engine load was varied from 10 to 100% with the addition of H₂ up to 7.5% into the intake mixture. The potential of H₂ enriching in improving the brake thermal efficiency and associated penalty in NO_x emissions was discussed.

6.1 Conclusions

Based on the experimental data obtained in this research, the following conclusion can be drawn:

- The addition of H₂ into these two heavy-duty diesel engines reduced the emissions of PM, CO, HC, and CO₂.
- The addition of H₂ to the Cummins engine increased the emissions of NO_x when operated at medium to high load. The substantial reduction in NO_x emissions was only observed with the addition of relatively large amount of H₂ when operated under a very low narrow low load operational region.
- The addition of H₂ to 2004 Mack MP7 355E has mild effect on NO_x emissions. The addition of medium amount of H₂ under medium to high load slightly reduced the emissions of NO_x. The substantial reduction in NO_x emissions were

only observed with the addition of relatively large amount of H_2 when operated under very narrow low load operational region.

- The substantial reduction of NO_x emissions through the supplementation of a small amount of H_2 to heavy-duty diesel engines seems infeasible.
- When operated at medium to high load ($>5\%$), a featured three-stage heat release process of H_2 -diesel dual fuel engine was observed. The unique high heat release rate observed in diffusion combustion was a combination of diesel diffusion combustion and the turbulent flames controlled combustion of H_2 -air mixture ignited at multi-point by diesel sprays.
- The addition of relatively large amount of H_2 to heavy-duty diesel engines was shown to improve the brake thermal efficiency. In comparison, the addition of relatively small amounts was found to deteriorate the brake thermal efficiency. The addition of H_2 at low load should be avoided.
- The addition of H_2 relatively large amount of H_2 at high load improved the BTE and substantially increased the peak cylinder pressure, which raised the concerns to safety and durability.
- The addition of a relatively large amount of H_2 at high load significantly increased the peak cylinder pressure. The addition of 6% H_2 to Cummins engine increased peak pressure from 107.2 to 120.9 bar (+12.8%). In comparison, the addition of 6% H_2 to MACK engine increased cylinder pressure from 153.7 to 178.5 bar (+16.1%).

6.2 Recommendations

Based on the results obtained in this research and those reported in the literature, I would like to make the following recommendations for future research in this area.

- To optimize engine control strategies to maximize the positive effect of H_2 enrichment in improving the brake thermal efficiency. As shown by the combustion data, the addition of H_2 at high load enhanced the diffusion combustion process, which makes the injection timing away from the optimized one. Further optimization of injection timing could further improve the BTE.
- The application of H_2 enrichment in a light-duty diesel engine. The data reported in literature demonstrated substantial improvement to the thermal efficiency (+29.2 and +37.4% with the addition of 6% H_2 into intake mixture for 5.4 bar and 2.7 bar BMEP, respectively) [McWilliam et al., 2008]. This may make H_2 enrichment very attractive in improving the brake thermal efficiency of the diesel engine with the NO_x emissions reduced through the application of EGR and even SCR.
- The exhaust emissions of H_2 contribute to the deterioration of the brake thermal efficiency [Gatts et al., 2009]. Further literature review and experimental work should be conducted to explore the approaches which can utilize the unburned H_2 presented in the exhaust gas of H_2 -diesel dual fuel engine. The enhancement of H_2 to the operation of after-treatment system may be considered as one of the approaches.

7 REFERENCES

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8 APPENDIX

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% Chet-Mun Liew
% West Virginia University
% Uncertainty analysis for H2/(H2+Air)

clc;
clear all;

%Display Program information
disp('Chet-Mun Liew')
disp('November 17, 2009')
disp(' ')

maple restart %restart the library

% This part assigns numerical values to the variables -----
H2=13.072; %Full range of H2 MFC(scfm), 6% at E02586-03
deltaH2=0.13072; %Variation in H2(scfm);1% of full scale at
operating conditions

LFE=210.8147; %Full range of LFE(scfm)
deltaLFE=1.813; %Variation in Intake(scfm);0.86% of full scale
at operating conditions

%-----

% This part set up the symbolic variables and assigns the equations -
syms Flow H_2 L_F_E %Define the symbolic variables

%Calculate Flow from given equation

Flow=(H_2/(H_2+L_F_E))*100

DFlow_DH_2=diff(Flow,H_2); %Calculate the partial of Flow wrt H2
DFlow_DL_F_E=diff(Flow,L_F_E); %Calculate the partial of Flow wrt dP

%-----

% This part calculates the numerical values of the parameters -----
DFlow_DH_2Value=abs(double(subs(DFlow_DH_2,{H_2,L_F_E},{H2,LFE})));
%Substitute in the values and calculate the numerical value of the
partial of Flow wrt H2
DFlow_DL_F_EValue=abs(double(subs(DFlow_DL_F_E,{H_2,L_F_E},{H2,LFE})));
%Substitute in the values and calculate the numerical value of the
partial of Flow wrt LFE
FlowValue=double(subs(Flow,{H_2,L_F_E},{H2,LFE}));
%Substitute in the values and calculate the numerical value of the
partial of Flow

errorDFlow_DH_2Term=DFlow_DH_2Value*deltaH2;
%Calculate the error associated with partial of Flow wrt Pf
errorDFlow_DL_F_ETerm=DFlow_DL_F_EValue*deltaLFE;
%Calculate the error associated with partial of Flow wrt dP

sumerror=errorDFlow_DH_2Term+errorDFlow_DL_F_ETerm;
%Calculate the total error

```

```
%-----  
  
disp('Final Results')  
fprintf('Flow= %6.3f ',FlowValue) %Display the results  
    fprintf(' +/- %6.3f \n',sumerror)  
%-----  
% The uncertainty result is  
  
% Flow=  5.839 +/-  0.102 %
```



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% Chet-Mun Liew
% West Virginia University
% Uncertainty analysis for Brake Thermal Efficiency

clc;
clear all;

%Display Program information
disp('Chet-Mun Liew')
disp('March 10, 2010')
disp(' ')

maple restart %restart the library

% This part assigns numerical values to the variables -----
H2=13.072; %Full range of H2 MFC(scfm), 6% at E02586-03
deltaH2=0.13072; %Variation in H2(scfm);1% of full scale at
operating conditions

LFE=210.8147; %Full range of LFE(scfm)
deltaLFE=1.813; %Variation in LFE(scfm);0.86% of full scale
at operating conditions

Fuel=10.13367; %Full range of Fuel consumption rate(kg/hr)
deltaFuel=0.050668; %Variation in Fuel(kg/hr);0.5% of full scale
at operating conditions

Intake=7.36; %Full range of Intake air mass flow(kg/min)
deltaIntake=0.063296; %Variation in Intake(kg/min);0.86% of full
scale at operating conditions
%-----

% This part set up the symbolic variables and assigns the equations -
syms BTE H_2 L_F_E F_uel I_ntake %Define the symbolic variables

%Calculate BTE(%) from given equation

BTE=(( (1206*418.7*0.7457)/5252)*(3600/(((H_2/(H_2+L_F_E)))/(1-
(H_2/(H_2+L_F_E))))*(I_ntake/28.96*2)/43200*120000*60))+Fuel))*100)/4320
0

DBTE_DH_2=diff(BTE,H_2); %Calculate the partial of BTE wrt H2
DBTE_DL_F_E=diff(BTE,L_F_E); %Calculate the partial of BTE wrt LFE
DBTE_DF_uel=diff(BTE,F_uel); %Calculate the partial of BTE wrt
Fuel
DBTE_DI_ntake=diff(BTE,I_ntake); %Calculate the partial of BTE wrt
Intake

%-----
% This part calculates the numerical values of the parameters -----

DBTE_DH_2Value=abs(double(subs(DBTE_DH_2,{H_2,L_F_E,F_uel,I_ntake},{H2,
LFE,Fuel,Intake}))) ;

```

```

%Substitute in the values and calculate the numerical value of the
partial of BTE wrt H2
DBTE_DL_F_EValue=abs(double(subs(DBTE_DL_F_E,{H_2,L_F_E,I_intake},{H2,LFE,Intake})));
%Substitute in the values and calculate the numerical value of the
partial of BTE wrt LFE
DBTE_DF_uelValue=abs(double(subs(DBTE_DF_uel,{H_2,L_F_E},{H2,LFE})));
%Substitute in the values and calculate the numerical value of the
partial of BTE wrt Fuel
DBTE_DI_intakeValue=abs(double(subs(DBTE_DI_intake,{H_2,L_F_E,I_intake},{H2,LFE,Intake})));
%Substitute in the values and calculate the numerical value of the
partial of BTE wrt Intake
BTEValue=double(subs(BTE,{H_2,L_F_E,F_uel,I_intake},{H2,LFE,Fuel,Intake}));
%Substitute in the values and calculate the numerical value of the
partial of BTE

errorDBTE_DH_2Term=DBTE_DH_2Value*deltaH2;
%Calculate the error associated with partial of BTE wrt H2
errorDBTE_DL_F_ETerm=DBTE_DL_F_EValue*deltaLFE;
%Calculate the error associated with partial of BTE wrt LFE
errorDBTE_DF_uelTerm=DBTE_DF_uelValue*deltaFuel;
%Calculate the error associated with partial of BTE wrt Fuel
errorDBTE_DI_intakeTerm=DBTE_DI_intakeValue*deltaIntake;
%Calculate the error associated with partial of BTE wrt Intake

sumerror=errorDBTE_DH_2Term+errorDBTE_DL_F_ETerm+errorDBTE_DF_uelTerm+errorDBTE_DI_intakeTerm ;
%Calculate the total error

%-----

disp('Final Results')
fprintf('BTE= %6.3f ',BTEValue) %Display the results
fprintf(' +/- %6.3f \n',sumerror)

%-----
% The uncertainty result is
% BTE= 38.830 +/- 0.361%

```

**An Investigation of Hydrogen Supplementation on Combustion and Emissions
of Heavy-Duty Diesel Engines**

ChetMun Liew

**Thesis Submitted to the
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for the degree of**

**Master of Science
in
Mechanical Engineering**

Department of Mechanical and Aerospace Engineering

APPROVAL OF THE EXAMINING COMMITTEE

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Date