EXPERIMENTAL INVESTIGATIONS ON DIMETHYL ETHER FUELLED COMPRESSION IGNITION ENGINE UNDER HCCI MODE

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by

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Submitted

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CERTIFICATE

This is to certify that the thesis entitled **"Experimental Investigations on Dimethyl Ether Fuelled Compression Ignition Engine Under HCCI Mode"** submitted by **Mr. Anilkumar Ramesh Shere** to the **Indian Institute of Technology Delhi**, New Delhi-110016, for the award of the degree of the **Doctor of Philosophy** is a record of bona fide research work carried out by him. He has worked under my guidance and supervision, and has fulfilled the requirement for the submission of this thesis, which has attained the requisite standard required for a Ph.D. degree of the Institute.

The research report and the results presented in this thesis have not been submitted in parts or in full to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

The transport sector is in the transient stage transforming from conventional fuel to decarbonized fuel. The Dimethyl ether (DME) as fuel gets more attention for compression ignition engines as it has lower carbon content fuel (DME: 0.337, Diesel: 0.516) and higher cetane number (DME: 58, Diesel: 51) compared to conventional diesel. The fuel could be stored in a liquid state at high pressure (above 5 bar) in cylinders and converted into a gaseous state at atmospheric (standard temperature pressure) conditions. A DME fuelled compression ignition engine could operate with low levels of NO_x and particulate/smoke emissions.

A four-stroke common rail direct injection (CRDI) single cylinder automotive compression ignition (CI) engine with a rated power output of 8.2 kW at 3000 rpm was used for this study. The engine's hardware was modified for operating under dual fuel mode (DME-diesel). The DME fuel was injected into the intake manifold of the CRDI CI engine, whereas diesel fuel was injected directly into the combustion chamber near the end of the compression stroke. The maximum DME energy share (DME ES) at optimum injection timing (15°BTDC) for all loads is limited in the range of 52% to 63% due to knock occurrence and uncontrolled auto-ignition (UAI). Further, the combined strategy of retarded injection timing (12°BTDC), split injection (25°BTDC) and exhaust gas recirculation (EGR) extended the maximum DME ES from 52% to 72% by mitigating the knocking tendency. Smoke emission decreased drastically to zero level at higher DME ES. However, NO_x, CO and HC emissions increased. Hence, the engine was further modified to operate under homogeneous charge compression ignition (HCCI) mode fuelled with neat DME (100%). Zero smoke and ultra-low NO_x emissions were observed under DME HCCI mode. However, reduction in load due to knock and increased CO and HC emissions were observed under DME HCCI mode. Further, the maximum load of the engine with the EGR under HCCI mode is extended with controlled auto-ignition (CAI). Further, the experimental tests were conducted on the engine with hydrogen addition under DME HCCI mode. A compression ignition engine fuelled with DME under HCCI mode could operate with enhanced hydrogen energy share (HES),

improved energy efficiency and zero smoke emission with ultra-low CO, HC, NO_x, and CO_2 emissions.

A notable conclusion that emerged from this study is that the compression ignition engine fuelled with DME under HCCI mode with the EGR and hydrogen could reduce the smoke emission to zero level with ultra-low levels of other emissions (NO_x, CO, HC and CO_2) along with energy efficiency improvement and extended the maximum load limit by mitigating the knock tendency.

सार

परिवहन क्षेत्र पारंपरिक ईंधन से विकार्बनीकृत ईंधन में रूपांतरित होने के संक्रमणी चरण में है। ईंधन के रूप में डाइमेथिल ईथर (डीएमई) संपीडन ज्वलन इंजन हेतु अधिक ध्यान आकर्षित करता है क्योंकि इसमें पारंपरिक डीजल की तुलना में कम कार्बन अंशवाला ईंधन (डीएमई: 0.337, डीजल: 0.516) और उच्च सीटेन संख्या (डीएमई: 58, डीजल: 51) होती है। ईंधन को सिलेंडरों में उच्च दबाव (5 बार से ऊपर) पर तरल अवस्था में संगृहीत किया जा सकता है और वायुमंडलीय (मानक तापमान दबाव) परिवेश में गैसीय अवस्था में परिवर्तित किया जा सकता है। डीएमई इंधन भरित संपीडन ज्वलन इंजन अल्प स्तर के एनओएक्स और विविक्त/ धूम्र उत्सर्जन पर कार्य कर सकता है।

3000 आरपीएम पर 8.2 किलोवाट की घोषित शक्ति के निर्गम के साथ चार-स्ट्रोक कॉमन रेल डायरेक्ट अंत:क्षेपण (सीआरडीआई) एकल सिलेंडर यांत्रिक संपीडन ज्वलन (सीआई) इंजन का उपयोग इस अध्ययन के लिए किया गया । इंजन के हार्डवेयर को द्वि ईंधन प्रणाली (डीएमई-डीजल) के तहत प्रचालित करने हेतु रूपांतरित किया गया। डीएमई ईंधन को सीआरडीआई सीआई इंजन के अंतर्गृहीत बहुमुख में अंत:क्षेपित किया गया, जबकि डीजल ईंधन को संपीडन स्ट्रोक के निकटवर्ती दहन वेश्म में सीधे अंत:क्षेपित किया गया। इष्टतम अंत:क्षेपण कालमापन (15^0 बीटीडीसी) पर अधिकतम डीएमई ऊर्जा अंश सभी प्रकार के भारों में (डीएमई ईएस) आघात घटना और अनियंत्रित यांत्रिक ज्वलन(यूएआई) के कारण 52% से 63% के परिसर में सीमित है। इसके अलावा, मंद अंत:क्षेपण कालमापन (12° बीटीडीसी), विभक्त अंत:क्षेपण (25^0 बीटीडीसी), और निर्वातक गैस पुन:संचरण (ईजीआर) की सम्मिलित कार्यरीति ने नाकिंग की प्रवृत्ति को मंद करते हुए अधिकतम डीएमई ईएस को 52% से 72% तक बढ़ा दिया। धूम्र उत्सर्जन उच्च डीएमई ईएस पर शून्य स्तर

तक अत्यधिक रूप से कम हो गया। हालांकि, एनओएक्स, सीओ और एचसी उत्सर्जन में वृद्धि हुई। इसलिए, स्वच्छ डीएमई (100%) ईंधन से भरी हुई इंजन को समांग चार्ज संपीडन ज्वलन (एचसीसीआई) मोड के तहत प्रचालित करने हेतु और अधिक रूपांतरित किया गया । शून्य धूम्र और अत्यल्प एनओएक्स उत्सर्जन डीएमई एचसीसीआई मोड के तहत प्रेक्षित किया गया। तथापि, डीएमई एचसीसीआई मोड के अंतर्गत नॉक के कारण भार में कमी और सीओ तथा एचसी उत्सर्जन में वृद्धि प्रेक्षित की गई। इसके अलावा, एचसीसीआई मोड के तहत ईजीआर से इंजन का अधिकतम भार नियंत्रित यांत्रिक ज्वलन (सीएआई) से बढ़ जाता है। साथ ही, डीएमई एचसीसीआई मोड के तहत हाइड्रोजन वर्धन वाली इंजन पर प्रायोगिक परीक्षण किए गए। एचसीसीआई मोड के तहत डीएमई ईंधन से भरित संपीडन ज्वलन इंजन वर्धित हाइड्रोजन ऊर्जा अंश (एचईएस), बेहतर ऊर्जा बचत और अत्यल्प सीओ, एचसी, एनओएक्स और सीओ 2 उत्सर्जन के कारण शून्य धूम्र उत्सर्जन के साथ प्रचालित हो सकती है।

इस अध्ययन से प्राप्त उल्लेखनीय निष्कर्ष यह है कि ईजीआर और हाइड्रोजन के कारण एचसीसीआई मोड के तहत डीएमई ईंधन से भरित संपीडन ज्वलन इंजन ऊर्जा बचत में सुधार के साथ-साथ अत्यल्प स्तर पर अन्य उत्सर्जन (एनओएक्स, सीओ, एचसी और सीओ 2) करते हुए धुएं के उत्सर्जन को शून्य स्तर तक कम कर सकती है और नॉक प्रवृत्ति को मंद करके अधिकतम भार सीमा बढ़ा सकती है।

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NOMENCLATURE AND NOTATION

ASTM	American Society for Testing and Materials
aTDC	After Top Dead Center
aBDC	After Bottom Dead Center
bBDC	Before Bottom Dead Center
BDC	Bottom Dead Center
BMEP	Brake Mean Effective Pressure
BP	Brake Power
BSEC	Brake Specific Energy Consumption
BSFC	Brake Specific Fuel Consumption
BS VI	Bharat Stage VI
bTDC	Before Top Dead Center
BTE	Brake Thermal Efficiency
CA	Crank Angle
CAI	Controlled Auto-Ignition
CAILF	Controlled Auto-Ignition Limited Factor
CD	Combustion Duration
CHR	Cumulative Heat Release
CI	Compression Ignition

CN	Cetane Number
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COV	Coefficient of Variation
CPC	Controlled Premixed Combustion
CR	Compression Ratio
CRDI	Common Rail Direct Injection
CV	Calorific Value
DI	Direct Injection
DICI	Direct Injection Compression Ignition
DME	Dimethyl Ether
DME ES	Dimethyl Ether Energy Share
ECU	Electronic Control Unit
EGR	Exhaust Gas Recirculation
EGT	Exhaust Gas Temperature
EJ	Exa-Joule
EOI_M	End of Injection_Main fuel
EOI_P	End of Injection_Pilot fuel

ES	Energy Share
EVC	Exhaust Valve Open (degree Crank Angle)
EVO	Exhaust Valve Close (degree Crank Angle)
HC	Hydrocarbon
HCCI	Homogeneous Charge Compression Ignition
H_2O	Water
H_2	Hydrogen
HES	Hydrogen Energy Share
HRR	Heat Release Rate
HTR	High Temperature Reaction
IDA	International DME Association
IMEP	Indicated Mean Effective Pressure
ISO	International Organization for Standardization
ITE	Indicated Thermal Efficiency
IVC	Inlet Valve Close (Crank Angle Degree)
IVO	Inlet Valve Open (Crank Angle Degree)
IW	Industrial Waste
K	Kelvin
KI	Knocking Intensity

KOER	Knocking Occurring Equivalence Ratio
LHV	Lower Heating Value
LPG	Liquified Petroleum Gas
LTR	Low Temperature Reaction
MI	Main Injection
MIE	Minimum Ignition Energy
MMT	Million Metric Tonnes
MOPNG	Ministry of Petroleum and Natural Gas
MORTH	Ministry of Road Transport and Highway
MSW	Municipal Solid Waste
NDIR	Non-Dispersive Infrared
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NO_x	Oxides of Nitrogen
O_2	Oxygen
OEM	Original Equipment Manufacturer
ON	Octane Number
PCCI	Premixed Charge Compression Ignition
PCCI-DI	Premixed Charge Compression Ignition – Direct Injection

PHCCI	Partial Homogenous Charge Compression Ignition
PI	Pilot Injection
PIQ	Pilot Injection Quantity
PM	Particulate Matter
PPM	Parts Per Million
RCCI	Reactivity Controlled Compression Ignition
RIT	Retarded Injection Timing
ROPR	Rate of Pressure Rise
RPM	Revolution Per Minute
SI	Spark Ignition
SIT	Split Injection Timing
SOI_M	Start of Injection_Main fuel
SOI_P	Start of Injection_Pilot fuel
SOC	Start of Combustion
TDC	Top Dead Center
UAI	Uncontrolled Auto-Ignition
ULSD	Ultra-Low Sulphur Diesel

NOTATION

η	Brake Thermal Efficiency
η_i	Indicated Thermal Efficiency
η_c	Combustion Efficiency
η_v	Volumetric Efficiency
η_{EE}	Energy Efficiency
ϕ	Equivalence Ratio
τ_{id}	Ignition Delay
θ	Crank Angle (Degree)
C_p	Specific Heat at Constant Pressure
C_v	Specific Heat at Constant Volume
γ	Ratio of specific heat (C_p/C_v)
$\circ$	Degree