

**STUDY ON BACKFIRE, PERFORMANCE AND
EMISSIONS CHARACTERISTICS OF A
HYDROGEN FUELLED SPARK IGNITION ENGINE**

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**CENTRE FOR ENERGY STUDIES
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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EMISSIONS CHARACTERISTICS OF A
HYDROGEN FUELLED SPARK IGNITION ENGINE**

by

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Centre for Energy Studies

Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

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CERTIFICATE

The thesis entitled “*Study on Backfire, Performance and Emissions Characteristics of a Hydrogen Fuelled Spark Ignition Engine*” being submitted by **Mr. Bheru Lal Salvi** to the **Indian Institute of Technology Delhi** for the award of **Doctor of Philosophy** is a record of bonafied research work carried out by him. He has worked under my guidance and supervision, and has fulfilled the requirements for the submission of this thesis, which has attained the standard required for a Ph.D. degree of the institute. The results presented in the thesis have not been submitted, in part or full, elsewhere for the award of any degree or diploma.

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ABSTRACT

This research work was aimed for study of backfire, performance improvement and emissions reduction in a hydrogen fuelled spark ignition engine. For this study, a carburettor based gasoline fuelled spark ignition (SI) engine generator set with rated power output of 2.1 kVA at 50 Hz and 220 V was selected and then converted into hydrogen fuelled generator set using timed manifold injection. The experimental study was carried out at various compression ratios (4.5:1, 6.5:1(base) and 7.2:1), spark timings, delay in start of hydrogen gas injection and exhaust gas recirculation (EGR) up to 25 % by volume. The study at reduced compression ratio of 4.5:1 was also carried out for wide parametric study of backfire occurrence in a hydrogen fuelled SI engine.

Experimental results revealed that hydrogen fuelled SI engine operation at increased compression ratio of 7.2:1 improved the relative brake thermal efficiency (BTE) by 10 % as compared to base compression ratio of 6.5:1 at power output of 1 kW. The highest BTE of 15.3 % was observed at equivalence ratio of 0.5 and it decreased with respect to increase in equivalence ratio, while power output increased. The engine operation at higher equivalence ratio of 0.8 and above was observed with combustion knock and reduced BTE. However, the NO_x emission increased at increased compression ratio of 7.2:1 and also it increased with respect to increase in equivalence ratio.

The spark time variation and EGR were used for NO_x emission reduction at source level. The spark advancing from maximum brake torque (MBT) caused to increase in NO_x emission, while spark retarding up to 2° CA bTDC reduced the NO_x emission marginally, but power output and the thermal efficiency dropped significantly by 6 %. The EGR level up to 24 % by volume significantly reduced the NO_x emission up to 57 %. The spark time retarding is not a suitable option for NO_x emission reduction in hydrogen

fuelled SI engines, whereas the EGR level of 20 % by volume was chosen as optimum where the NO_x emission was reduced by 50 % with marginal effect on power drop as compared to NO_x emission without EGR.

The results of numerical analysis and experimental study on backfire occurrence indicate that backfire is mainly function of residual gas temperature and hot-spots. It was found from the numerical analysis of in-cylinder mixture temperature during suction stroke that delayed gas injection would reduce the probability of backfire occurrence due to cooling of residual gas and hot-spots. In addition to this the backfire occurrence phenomenon was explained using computational fluid dynamics (CFD) and found that backfire occurs due to hot-spot and flame propagate towards upstream of intake manifold. The probability of backfire occurrence reduced with respect to increase in intake charge velocity. The experimental observations for delay in start of injection (SOI) have shown that backfire limiting start of injection (BFL-SOI) reduced with increased compression ratio and the delay in SOI up to 50° CA aTDC eliminated the backfire occurrence and improved the engine performance also. It was found from the experimental results of flame kernel growth rate (FKGR) that higher FKGR for hydrogen with respect to equivalence ratio is responsible for reduced ignition lag and rapid flame propagation, while use of EGR with intake charge reduced the FKGR by charge dilution.

The notable findings emerged from this study are that the hydrogen fuelled SI engine with increased compression ratio of 7.2:1, MBT spark timing of 9° CA bTDC and EGR value of 20 % by volume will give better performance and reduced NO_x emission. The addition of EGR slows down the FKGR and delay in SOI allows to cool down the residual gas; therefore probability of backfire occurrence reduces with EGR and delay in SOI. On the whole, the hydrogen fuelled spark ignition engine with EGR could provide beneficial results of reduced NO_x emission and elimination of backfire.

TABLE OF CONTENTS

CERTIFICATE.....	i
ACKNOWLEDGEMENTS	iii
ABSTRACT.....	v
TABLE OF CONTENTS	vii
LIST OF FIGURES	xi
LIST OF TABLES	xvii
NOMENCLATURES	xix
Chapter – 1	1
INTRODUCTION.....	1
1.1 Background of the study	1
1.2 Motivation of the work	2
1.3 Problem statement and solution outline	3
1.4 Organizational frame work of research.....	4
Chapter – 2	7
LITERATURE SURVEY.....	7
2.1 Use of hydrogen as fuel for SI engines	7
2.2 Backfire in hydrogen fuelled SI engines.....	9
2.2.1 Chemical kinetics of hydrogen-oxygen reaction.....	10
2.2.2 Backfire control methods in hydrogen fuelled SI engines.....	10
2.2.3 Flame kernel growth rate in SI engines	11
2.2.4 Closure	12
2.3 Performance and emissions characteristics of hydrogen fuelled SI engines	13
2.3.1 Hydrogen fuelled SI engines operating at various compression ratios.....	13

2.3.2	Genesis of NO formation	14
2.3.3	Emission reduction in hydrogen fuelled SI engines.....	15
2.3.4	Closure	18
2.4	Energy and exergy study of hydrogen fuelled SI engines	18
2.5	Summary of literature survey	19
2.6	Research gaps.....	22
Chapter – 3		23
OBJECTIVES AND METHODOLOGY		23
3.1	Objectives.....	23
3.2	Phases in research work	24
3.3	Methodology	25
3.3.1	Change of compression ratio.....	25
3.3.2	Strategies for NO _x emission reduction in a hydrogen fuelled SI engine....	25
3.3.3	Analysis of backfire and its control in hydrogen fuelled SI engine	26
3.3.4	Calculation of flame kernel growth rate.....	33
Chapter – 4		35
DEVELOPMENT OF EXPERIMENTAL SETUP AND TEST PROCEDURE.....		35
4.1	Experimental setup.....	35
4.2	Development of engine management system.....	40
4.3	Modification of spark timing	45
4.4	Variation in engine's compression ratio	45
4.5	Instrumentation and data acquisition system	47
4.6	Exhaust gas recirculation and its flow rate calculation.....	48
4.7	Calculation of uncertainty	51
4.8	Calculation of combustion and performance parameters.....	52

4.9	Safety and handling of hydrogen	55
4.10	General test matrix and experimental test procedure	56
4.11	CFD simulation for study of backfire analysis	61
Chapter – 5		63
RESULTS AND DISCUSSION		63
5.1	Study of various compression ratios in a hydrogen fuelled SI engine.....	63
5.1.1	Effects of spark timing on combustion characteristics	63
5.1.2	Effects of spark timing on performance characteristics.....	68
5.1.3	Optimization of spark gap.....	71
5.1.4	Optimization of start of gas injection.....	73
5.1.5	Effects of compression ratios on combustion characteristics	78
5.1.6	Effects of compression ratios on engine performance	88
5.1.7	Effects of compression ratios on engine temperatures.....	93
5.1.8	Effects of compression ratios on volumetric efficiency.....	95
5.1.9	Effects of compression ratios on emissions characteristics	97
5.1.10	Closure	102
5.2	Emission reduction strategies in a hydrogen fuelled SI engine	103
5.2.1	Effects of spark time retarding on performance and NO _x emission.....	103
5.2.2	Effects of EGR on combustion, performance and NO _x emission	105
5.2.3	Closure	113
5.3	Backfire analysis in a hydrogen fuelled SI engine.....	114
5.3.1	Effects of BMEP on in-cylinder mixture temperature in suction stroke.....	116
5.3.2	Analysis of charge flow through intake manifold and backfire.....	119
5.3.3	Effects of start of gas injection and compression ratios on backfire.....	121
5.3.4	Backfire propagation.....	125

5.3.5 Effects of equivalence ratio and EGR on backfire occurrence	127
5.3.6 Experimental study of flame kernel growth rate in SI engine	128
5.3.7 Effect of inlet charge velocity on backfire occurrence	133
5.3.8 Strategies for backfire control in hydrogen fuelled SI engines.....	135
5.3.9 Closure	136
5.4 Energy and exergy analysis in a hydrogen fuelled SI engine	137
5.4.1 Closure	138
Chapter – 6	139
CONCLUSIONS AND RECOMMENDATIONS.....	139
6.1 Conclusions	139
6.1.1 Study on effects of various compression ratios	139
6.1.2. The NO _x emission reduction	141
6.1.3. Backfire analysis	141
6.2 Recommendations and scope for future study	143
REFERENCES.....	145
APPENDICES	155
Appendix – A: Electronic control unit and graphical user interface.....	155
Appendix – B: Gas injector and its specifications	157
Appendix – C: Modification and calculation of engine’s compression ratio.....	159
Appendix – D: Measuring instruments and specifications.....	161
Appendix – E: Flashback arrestor	163
PUBLICATIONS FROM THIS THESIS.....	165
AUTHOR’S BIOGRAPHY	169

LIST OF FIGURES

Fig. No.	Title	Page No.
Fig. 2.1.	Backfire occurrence in the intake manifold [9]	9
Fig. 3.1:	Intake manifold geometry.....	28
Fig. 3.2:	Intake manifold and combustion chamber 3D geometry with meshing.....	30
Fig. 3.3:	Intake manifold, valve geometry and backfire during charge flow.....	31
Fig. 3.4:	(a) AVL Visio FEM sensors integrated with spark plug and (b) flame detection signals with respect to crank angle	34
Fig. 4.1:	Schematic diagram of the experimental setup.....	38
Fig. 4.2:	Photographic view of developed experimental setup (Plate – 1)	39
Fig. 4.3:	Photographic view of developed experimental setup (Plate – 2)	39
Fig. 4.4:	Block diagram of engine management system (EMS).....	40
Fig. 4.5:	Parts and sensors used in engine management system.....	41
Fig. 4.6:	Developed mechanism (a) Teethed wheel and speed sensor, (b) TMAP sensor and gas injector, and (c) throttle position sensor mounting	42
Fig. 4.7:	Hydrogen gas supply line with (a) gas injector and (b) flashback arrestor	44
Fig. 4.8:	Modified ignition system (a) spark time simulation test bench, (b) ignition system mounted on engine and (c) online monitoring of spark timing	44
Fig. 4.9:	(a) Schematic diagram of engine, (b) cylinder head with proposed area for metal removal and filling, (c) cylinder head with reduced $CR_1 = 4.5:1$, (d) base cylinder head with $CR_2 = 6.5:1$, and (e) cylinder head with increased $CR_3 = 7.2:1$	46
Fig. 4.10:	Visio FEM and Visio Flame sensor integrated with engine.....	49
Fig. 4.11:	Visio Flame sensor mounted on the engine cylinder head.....	49

Fig. 4.12: Determining the start of combustion and duration of combustion	54
Fig. 4.13: Selection of start of injection and duration of injection	58
Fig. 4.14: Valve timing diagram with backfire period and safe start of injection.....	58
Fig. 5.1: In-cylinder pressure with respect to crank angle at various spark timings.....	65
Fig. 5.2: In-cylinder pressure with respect to volume at various spark timings	65
Fig. 5.3: Variation in heat release rate w.r.t. crank angle at various spark timings.....	67
Fig. 5.4: Mass fraction burnt with respect to crank angle at various spark timings.....	67
Fig. 5.5: Variation in IMEP w.r.t. spark timing and compression ratio.....	68
Fig. 5.6: Variation in COV of IMEP w.r.t. spark timing and compression ratio.....	69
Fig. 5.7: Variation in brake torque and BTE w.r.t. spark timing and compression ratios .	70
Fig. 5.8: Variation in IMEP and COV of IMEP with respect to spark gap	72
Fig. 5.9: Effects of start of injection on in-cylinder pressure	74
Fig. 5.10: Effects of start of injection on rate of pressure rise.....	74
Fig. 5.11: Variation in peak HRR and cumulative heat released w.r.t. delay in SOI	75
Fig. 5.12: Effects of start of injection on IMEP and COV of IMEP.....	76
Fig. 5.13: Effects of start of injection on equivalence ratio and volumetric efficiency.....	77
Fig. 5.14: Effects of start of injection on BMEP and brake thermal efficiency	78
Fig. 5.15: In-cylinder pressure with respect to crank angle at various compression ratios and equivalence ratios.....	79
Fig. 5.16: Variation in HRR with respect to crank angle at various compression ratios and equivalence ratios.....	80
Fig. 5.17: Effects of compression ratios on peak heat release rate at various equivalence ratios.....	81
Fig. 5.18: Mass fraction burnt with respect to crank angle at various compression ratios and equivalence ratios.....	82

Fig. 5.19: Effects of compression ratios on (a) ignition lag and (b) duration of combustion	83
Fig. 5.20: In-cylinder average gas temperature with respect to crank angle	84
Fig. 5.21: In-cylinder average peak temperature with respect to compression ratio	84
Fig. 5.22: In-cylinder pressure during normal cycle and knock cycle at compression ratios of 6.5:1 (base) and 7.2:1	85
Fig. 5.23: Apparent heat release rate of normal cycles and knocking cycles	86
Fig. 5.24: Knock peaks with respect to number of engine cycles at compression ratios of 6.5:1 (base) and 7.2:1	87
Fig. 5.25: High knock peaks with respect to number of cycles at compression ratio of 6.5:1 (base) and equivalence ratio of 1.0	87
Fig. 5.26: Effects of compression ratios on indicated mean effective pressure.....	88
Fig. 5.27: Variation in COV of IMEP with respect to equivalence ratio at various compression ratios	89
Fig. 5.28: Effects of compression ratios on indicated thermal efficiency	90
Fig. 5.29: Brake specific energy consumption with respect to compression ratio	90
Fig. 5.30: Effects of compression ratios on BMEP at various equivalence ratios.....	92
Fig. 5.31: Effects of compression ratios on brake thermal efficiency	92
Fig. 5.32: Effects of compression ratios on exhaust gas temperature.....	94
Fig. 5.33: Effects of compression ratios on temperature of lubrication oil and cylinder fins at various equivalence ratios	94
Fig. 5.34: Clearance volume and residual gas fraction w.r.t. compression ratio	96
Fig. 5.35: Variation in volumetric efficiency w.r.t. compression ratio in a gasoline and hydrogen fuelled SI engine	96

Fig. 5.36: Effects of compression ratio on specific HC emission in gasoline and hydrogen fuelled SI engine	98
Fig. 5.37: Effects of compression ratios on specific CO ₂ emission.....	98
Fig. 5.38: Specific NO _x emission with respect to compression ratio in a hydrogen and gasoline fuelled SI engine	100
Fig. 5.39: Residual gas fraction and specific NO _x emission w.r.t. compression ratios ...	100
Fig. 5.40: Specific NO _x emission with respect to equivalence ratio at various compression ratios for hydrogen and gasoline fuelled SI engine	101
Fig. 5.41: Effects of spark timing on ignition lag and duration of combustion.....	104
Fig. 5.42: Effects of spark timing on BMEP, BTE and NO _x emission.....	104
Fig. 5.43: Relative change in BMEP, BTE and NO _x emission w.r.t. spark timing	105
Fig. 5.44: In-cylinder pressure with respect to crank angle at various EGR	106
Fig. 5.45: Cyclic variation of in-cylinder pressure at EGR of 23.5 % by volume.....	106
Fig. 5.46: Effects of EGR on peak heat release rate and ignition lag	107
Fig. 5.47: Effects of EGR on IMEP and COV of IMEP at compression ratio of 7.2:1 ...	109
Fig. 5.48: Effects of EGR on BMEP, BTE and specific NO _x emission	109
Fig. 5.49: Relative change in BMEP, BTE and NO _x emission with respect to EGR	110
Fig. 5.50: Effects of EGR on nitrogen and oxygen contents in in-cylinder charge and reduction in specific NO _x emission	110
Fig. 5.51: Relative change in nitrogen and oxygen contents in in-cylinder charge with respect to EGR and reduction in NO _x emission	111
Fig. 5.52: Comparative NO _x emission with respect to spark time retarding and exhaust gas recirculation.....	112
Fig. 5.53: Intake manifold and in-cylinder pressure, and intake and exhaust valve lift with respect to crank angle during gas-exchange process	115

Fig. 5.54: Instantaneous in-cylinder mass and valve lift profile with respect to crank angle during gas-exchange process	115
Fig. 5.55: Variation in in-cylinder mixture temperature with respect to crank angle during suction stroke	117
Fig. 5.56: CFD analysis of hydrogen-air mixture flow through intake manifold and in-cylinder hot-spot	119
Fig. 5.57: CFD analysis of backfire occurrence and its propagation in the intake manifold	120
Fig. 5.58: Effects of start of injection on IMEP and COV of IMEP.....	122
Fig. 5.59: Effects of start of injection on volumetric efficiency and equivalence ratio...	122
Fig. 5.60: Effects of compression ratios on residual gas fraction and energy content in residual gas	124
Fig. 5.61: Effects of compression ratio on backfire limiting start of injection.....	124
Fig. 5.62: Laminar burning velocity of gasoline, methane and hydrogen with respect to equivalence ratio	126
Fig. 5.63: Variation in laminar burning velocity with respect to EGR and ER.....	127
Fig. 5.64: Variation in FKGR with respect to BMEP in a gasoline fuelled SI engine	128
Fig. 5.65: Flame kernel growth rate with respect to equivalence ratio.....	130
Fig. 5.66: Flame kernel growth rate w.r.t. EGR in a hydrogen fuelled SI engine	130
Fig. 5.67: FKGR vs flame travelled when piston reached to TDC at the end of compression stroke	131
Fig. 5.68: Validation of correlation for FKGR with experimental results	132
Fig. 5.69: Variation in FKGR with respect to equivalence ratio and EGR	133
Fig. 5.70: Velocity of flame and reactants with respect to crank angle at intake valve ..	134
Fig. 5.71: Intake charge velocity and backfire occurrence in the intake manifold.....	135

Fig. 5.72: Fuel energy distribution in hydrogen fuelled SI engine 137

Fig. 5.73: Fuel exergy distribution in hydrogen fuelled SI engine 138

LIST OF TABLES

Table No.	Title	Page No.
Table – 2.1:	Properties of hydrogen, methane and gasoline [1,2,6]	8
Table – 2.2:	Summary of literature survey on backfire and its control in hydrogen fuelled SI engines.....	20
Table – 2.3:	Summary of literature survey on performance and emissions characteristics of hydrogen fuelled SI engines	21
Table – 4.1:	Specifications of engine and alternator.....	36
Table – 4.2:	Valve timings and spark timing of the engine	37
Table – 4.3:	Summary of uncertainty of measurement for various parameters.....	51
Table – 4.4:	General test matrix for experimental work.....	57
Table – 5.1:	Summary of engine performance w.r.t. spark timing and compression ratios	71
Table – 5.2:	Summary of effects of compression ratios on performance and emission characteristics.....	102
Table – 5.3:	Summary of effects of EGR on BMEP, BTE and NO _x emission.....	113
Table – 5.4:	In-cylinder mixture temperature w.r.t. crank angle during suction	118
Table – 5.5:	Summary of effects of start of gas injection on IMEP, COV of IMEP and volumetric efficiency at compression ratio of 7.2:1	125
Table – 5.6:	Summary of factors affecting the backfire and its control strategies	136

NOMENCLATURES

Abbreviations

aBDC	=	After bottom dead centre	HC	=	Hydrocarbon
AC	=	Alternative current	HRR	=	Heat release rate
aTDC	=	After top dead centre	ICE	=	Internal combustion engine
bBDC	=	Before bottom dead centre	IMEP	=	Indicated mean effective pressure
BDC	=	Bottom dead centre	IPC	=	Inlet port cooling
BMEP	=	Brake mean effective pressure	IR	=	Infra-red
BP	=	Brake power	ITE	=	Indicated thermal efficiency
BSEC	=	Brake specific energy consumption	LHV	=	Lower heating value
BSFC	=	Brake specific fuel consumption	MBT	=	Maximum brake torque
bTDC	=	Before top dead centre	MFI	=	Manifold fuel injection
BTE	=	Brake thermal efficiency	NO _x	=	Nitrogen oxides
CA	=	Crank angle	NRV	=	Non-return valve
CFD	=	Computational fluid dynamics	NTP	=	Normal temperature and pressure (25° C and 1.013 bar)
CHR	=	Cumulative heat released	PCV	=	Positive crankcase ventilation
CNG	=	Compressed natural gas	PFI	=	Port fuel injection
CR	=	Compression ratio	rpm	=	Revolution per minute
CT	=	Coolant temperature	SC	=	Supercharging
DOC	=	Duration of combustion	SIE	=	Spark ignition engine
ECU	=	Electronic control unit	SOC	=	Start of combustion
EGR	=	Exhaust gas recirculation	SOI	=	Start of injection
EMS	=	Engine management system	ST	=	Spark timing
EOC	=	End of combustion	STA	=	Spark time advance
ER	=	Equivalence ratio	STMIS	=	Sequential timed manifold injection system
FKGR	=	Flame kernel growth rate			

TDC = Top dead centre
 TMI = Timed manifold injection
 TPS = Throttle position sensor
 VC = Valve close
 Vol.Eff. = Volumetric efficiency
 VOP = Valve overlap period
 w.r.t = With respect to
 WI = Water injection
 WOT = Wide open throttle

Symbols

h = Enthalpy (J/kg)
 m_{mix} = Mass of in-cylinder charge
 N = Engine speed (rpm)
 p = Pressure (N/m²)

s = Entropy (J/kgK)
 T = Temperature (K)
 \dot{R}_{FKG} = Flame kernel growth rate
 (m/s)
 r_c = Compression ratio

Greek symbols

ϕ = Fuel-air equivalence ratio
 γ = Ratio of specific heats
 ρ = Density (kg/m³)
 η_{ith} = Indicated thermal efficiency
 θ = Crank angle
 χ = Residual gas fraction