CHARACTERIZATION OF BACKFIRE AND POSTFIRE IN A HYDROGEN FUELLED SPARK IGNITION ENGINE

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by

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Certificate

This is to certify that the thesis entitled **"Characterization of Backfire and Postfire in a Hydrogen fuelled Spark Ignition Engine"**, being submitted by **Akshey Marwaha** to the **Indian Institute of Technology Delhi** for the award of the degree of Doctor of Philosophy is a record of the bonafide research carried out by him which has been prepared under my supervision in conformity with the rules and regulations of the Indian Institute of Technology Delhi. He has fulfilled all requirements for the submission of his thesis, which has attained the standard required for a Ph.D. degree of the Institute. The research reports and results presented in the thesis have not been submitted for any degree in any other university or institute.

Place: New Delhi

Date:

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Abstract

Backfire is an abnormal combustion phenomenon occurring during the suction stroke of a manifold hydrogen injection-based spark ignition engine due to mainly external ignition sources including residual gas temperature, hot spots, partially burned lubricating oil, hot engine components, misfire and postfire. Backfire results in an audible high-pitched sound with speed drop, decrease in mean effective pressure, stalling the engine operation, and damaging of engine components. This present work is aimed at investigation of backfire occurrence and its propagation in an automotive spark ignition engine fuelled with hydrogen.

A gasoline automotive four-stroke spark ignition engine (15 kW) was modified to a hydrogen engine by incorporating mainly a timed manifold hydrogen injection system. A transparent intake manifold system was developed and attached to the engine to visualize the propagation of backfire. A high-speed camera was used to capture the real-time backfire images during the engine running. The engine was run with varied speeds and torque. The experimental results indicate that backfire occurrence probability increases with the increase in torque at constant speed, the increase in speed (at constant torque), high equivalence ratio and the increase in torque with the decrease in speed (at constant brake power).

It is practically observed that the residual (exhaust) gas temperature plays a critical role in acting as one of the external ignition sources to initiate backfire when a fresh air-hydrogen mixture interacts with the residual gas inside the cylinder during the engine's suction stroke. The critical exhaust gas temperatures (EGT) identified for the backfire initiation are in the range of 765 °C to 955 °C for speeds from 2000 rpm to 4900 rpm. A dimensionless backfire occurrence number (BON) was developed using the experimental results to predict backfire occurrence, where BON

greater than or equal to zero denotes backfire occurrence. Backfire occurrence is strongly linked to other abnormal combustion phenomena called misfire and postfire.

Misfire occurs during engine cranking due to too low spark duration, low in-cylinder temperature, fouled spark plug and too much advanced spark timing and the accumulation of the unburnt hydrogen during misfire burns in subsequent cycle leading to Postfire occurrence during exhaust stroke resulting in backfire. The Indicated Mean Effective Pressure based coefficient of variation during backfire, postfire and misfire was above 5% resulting in combustion instability of the engine. The CFD results indicate about 13% unburnt hydrogen as a scavenging loss leaves the exhaust manifold during the misfire cycle and the charge temperature is in the range of 1300 to 1500 K near the intake valve during backfire propagation. The pressure rise in the exhaust manifold during postfire was observed beyond 2 bar. The backfire is characterized using backfire ignition delay, expansion, convergence and termination. The average backfire propagation velocity calculated using high-speed camera images is found to be 179.3 m/s corresponding to a Mach number of 0.52 at an equivalence ratio of 0.5 and hence, backfire under varied engine speed can be characterized as deflagration (subsonic). Simultaneous acquiring of the intake manifold and in-cylinder pressure was found a reliable approach for estimating backfire propagation velocity.

The notable findings that emerged from the study are that backfire is strongly linked with misfire and postfire occurrence. The probability of backfire could be reduced by retardation of hydrogen injection timing, optimization of spark timing, high reactant velocity, and elimination of misfire and postfire.

सार

बैकफायर एक असामान्य दहन घटना है जो मैनिफोल्ड हाइड्रोजन इंजेक्शन-आधारित स्पार्क इग्निशन इंजन के सक्शन स्ट्रोक के दौरान मुख्य रूप से बाहरी इग्निशन स्रोतों के कारण होती है, जिसमें अवशिष्ट गैस तापमान, हॉट स्पॉट, आंशिक रूप से जला हुआ चिकनाई तेल, गर्म इंजन घटक, मिसफायर और पोस्टफायर शामिल हैं। बैकफ़ायर के परिणामस्वरूप गति में गिरावट, औसत प्रभावी दबाव में कमी, इंजन संचालन में रुकावट और इंजन घटकों को नुकसान के साथ उच्च-तीक्ष्ण ध्वनि सुनाई देती है। इस वर्तमान कार्य का उद्देश्य हाइड्रोजन से संचालित ऑटोमोटिव स्पार्क इग्निशन इंजन में बैकफ़ायर घटना और इसके प्रसार की जांच करना है।

एक गैसोलीन ऑटोमोटिव फोर-स्ट्रोक स्पार्क इग्निशन इंजन (15 किलोवाट) को मुख्य रूप से टाइम्ड मैनिफोल्ड हाइड्रोजन इंजेक्शन प्रणाली को शामिल करके हाइड्रोजन इंजन में संशोधित किया गया था। बैकफ़ायर के प्रसार को देखने के लिए एक पारदर्शी इनटेक मैनिफोल्ड सिस्टम विकसित किया गया और इंजन से जोड़ा गया। इंजन चलने के दौरान वास्तविक समय की बैकफ़ायर छवियों को कैप्चर करने के लिए एक हाई-स्पीड कैमरे का उपयोग किया गया था। इंजन को विभिन्न गति और टॉर्क के साथ चलाया गया। प्रयोगात्मक परिणामों से संकेत मिलता है कि स्थिर गति पर टॉर्क में वृद्धि, गति में वृद्धि (स्थिर टॉर्क पर), उच्च तुल्यता अनुपात और गति में कमी (निरंतर ब्रेक पावर पर) के साथ टॉर्क में वृद्धि के साथ बैकफ़ायर घटना की संभावना बढ़ जाती है।

यह व्यावहारिक रूप से देखा गया है कि जब ताजी हवा-हाइड्रोजन मिश्रण इंजन के सक्शन स्ट्रोक के दौरान सिलेंडर के अंदर अवशिष्ट गैस के साथ संपर्क करता है, तो अवशिष्ट (निकास) गैस का तापमान बैकफ़ायर शुरू करने के लिए बाहरी इग्निशन स्रोतों में से एक के रूप में कार्य करने में महत्वपूर्ण भूमिका निभाता है। बैकफ़ायर आरंभ के लिए पहचाने जाने वाले महत्वपूर्ण निकास गैस तापमान (ईजीटी) 2000 आरपीएम से

4900 आरपीएम तक की गति के लिए 765 डिग्री सेल्सियस से 955 डिग्री सेल्सियस की सीमा में हैं। बैकफ़ायर घटना की भविष्यवाणी करने के लिए प्रयोगात्मक परिणामों का उपयोग करके एक आयाम रहित बैकफ़ायर घटना संख्या (बीओएन) विकसित किया गया था, जहां शून्य से अधिक या उसके बराबर बीओएन बैकफ़ायर घटना को दर्शाता है। बैकफायर की घटना अन्य असामान्य दहन घटनाओं से दृढ़ता से जुड़ी हुई है जिन्हें मिसफायर और पोस्टफायर कहा जाता है।

बहुत कम स्पार्क अवधि, कम इन-सिलेंडर तापमान, खराब स्पार्क प्लग और बहुत अधिक उन्नत स्पार्क टाइमिंग के कारण इंजन क्रैंकिंग के दौरान मिसफायर होता है और बाद के चक्र में मिसफायर जलने के दौरान बिना जले हाइड्रोजन का संचय होता है, जिससे एग्जॉस्ट स्ट्रोक के दौरान पोस्टफायर की घटना होती है, जिसके परिणामस्वरूप बैकफायर होता है। . बैकफ़ायर, पोस्टफ़ायर और मिसफ़ायर के दौरान भिन्नता का संकेतित औसत प्रभावी दबाव आधारित गुणांक 5% से ऊपर था जिसके परिणामस्वरूप इंजन की दहन अस्थिरता हुई। सीएफडी परिणामों से संकेत मिलता है कि मिसफायर चक्र के दौरान निकास में होने वाली हानि के कारण लगभग 13% अधजला हाइड्रोजन निकलता है और बैकफायर प्रसार के दौरान इनटेक वाल्व के पास चार्ज तापमान 1300 से 1500 K की सीमा में होता है। पोस्टफायर के दौरान एग्जॉस्ट मैनिफोल्ड में दबाव 2 बार से अधिक बढ़ गया। बैकफ़ायर को बैकफ़ायर इग्निशन विलंब, विस्तार, अभिसरण और समाप्ति का उपयोग करके चित्रित किया गया है। हाई-स्पीड कैमरा छवियों का उपयोग करके गणना की गई औसत बैकफ़ायर प्रसार वेग 0.5 के समतुल्य अनुपात पर 0.52 की मच संख्या के अनुरूप 179.3 मीटर/सेकेंड पाया गया है और इसलिए, विभिन्न इंजन गति के तहत बैकफ़ायर को अपस्फीति (सबसोनिक) के रूप में वर्णित किया जा सकता है। इनटेक मैनिफोल्ड और इन-सिलेंडर दबाव को एक साथ प्राप्त करने से बैकफ़ायर प्रसार वेग का अनुमान लगाने के लिए एक विश्वसनीय दृष्टिकोण पाया गया।

अध्ययन से जो उल्लेखनीय निष्कर्ष सामने आए, वे यह हैं कि बैकफ़ायर का मिसफायर और पोस्टफ़ायर घटना से गहरा संबंध है। हाइड्रोजन इंजेक्शन समय की मंदता, स्पार्क टाइमिंग का अनुकूलन, उच्च प्रतिक्रियाशील वेग, और मिसफायर और पोस्टफायर को खत्म करके बैकफ़ायर की संभावना को कम किया जा सकता है।

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Nomenclatures

Abbreviations

aBDC	after bottom dead center
AMR	adaptive mesh refinement
Ar	argon
aTDC	after top dead center
bBDC	before bottom dead center
BI	backfire intensity
BLER	backfire limiting equivalence ratio
BLIT	backfire limiting injection timing
BLST	backfire limiting spark timing
BON	backfire occurrence number
BP	brake power
bTDC	before top dead center
BTE	brake thermal efficiency
CA	crank angle
CCUS	carbon capture utilization and storage
CFD	computational fluid dynamics

CFL	Courant-Friedrichs-Lewy
COV IMEP	coefficient of variation in indicated mean effective pressure
DC	direct current
ECU	electronic control unit
EGR	exhaust gas recirculation
EGT	exhaust gas temperature
$EGT_{critical}$	critical exhaust gas temperature
EOC	end of combustion
EVO	exhaust valve opening
FVM	finite volume method
GHG	greenhouse gas
GW	gigawatt
H	hydrogen radical
H_2	hydrogen
H_2O	water
H_2O_2	hydrogen peroxide
HO_2	hydroperoxyl radical
HRR	heat release rate

Hz	hertz
IC	internal combustion
IL_i	intake valve lift at crank angle i in meters
IL_{max}	maximum intake valve lift in meters
IMEP	indicated mean effective pressure
IVO	intake valve opening
kg	kilogram
kHz	kilohertz
kPa	kilopascal
kW	kilowatt
LBV	laminar burning velocity
µs	microsecond
MBT ST	maximum brake torque spark timing
MJ	megajoule
ms	millisecond
MT	megaton
MW	megawatt
N_2	nitrogen

NOx	oxides of nitrogen
O	oxygen radical
O_2	oxygen
OH	hydroxyl radical
PCC	phantom camera control
PMEP	pumping mean effective pressure
ppm	parts per million
RGT	residual gas temperature
RTV	room-temperature-vulcanizing silicone
SD	standard deviation
SE_m	standard error of the mean
SI	spark ignition
SOC	start of combustion
ST	spark timing
TDC	top dead center
TWh	terawatt hour
URANS	unsteady Reynolds Averaged Navier-Stokes
UV	ultraviolet

Symbols

a_c	crank radius (m)
B	bore (m)
CA_{bo}	crank angle location marking backfire origin
CA_{incyl}	crank angle marking a rise in the in-cylinder pressure
CA_{intm}	crank angle marking a rise in the intake manifold pressure
CA_{IVC}	crank angle corresponding to intake valve closing
CA_{SOI}	crank angle corresponding to start of hydrogen injection
C_D	combustion duration
$c_p{}'$	specific heat at constant pressure (kJ/kmol K)
c_p	specific heat at constant pressure (kJ/kgK)
c_{p_a}	specific heat of air at constant pressure (kJ/kgK)
$c_{p_{ch}}$	specific heat of hydrogen-air charge at constant pressure (kJ/kgK)
$c_{p_{H_2}}$	specific heat of hydrogen at constant pressure (kJ/kgK)
CV_{H_2}	calorific value of hydrogen (MJ/kg)
$\frac{dA}{d\theta}$	instantaneous surface area of the cylinder (m^2)
$\frac{dp_i}{d\theta}$	rate of pressure rise (bar/degree)

$\frac{dQ}{d\theta}$	gross heat release rate with heat losses (J/degree)
$\frac{dQ_h}{d\theta}$	rate of instantaneous heat transfer (W)
$\frac{dV_i}{d\theta}$	rate of change in cylinder volume (m^3)
h	convective heat transfer coefficient (W/m^2 K)
$IMEP_n$	net indicated mean effective pressure (Pa)
$IMEP_{gr}$	gross indicated mean effective pressure (Pa)
L	engine stroke (m)
l_c	length of the connecting rod (m)
M	molecular weight (kg/kmol)
$\dot{m}_a$	mass flow rate of air (kg/s)
m_{a_i}	mass of air at crank angle i in (g/crank angle)
m_{f_i}	mass of hydrogen at crank angle i in (g/crank angle)
$\dot{m}_{H_2}$	mass flow rate of hydrogen (kg/s)
n	total number of measurements
N	engine speed (rpm)
p	in-cylinder pressure (kPa)
p_i	instantaneous in-cylinder pressure (bar)

$p_i(\theta)$	in-cylinder pressure (Pa)
p_m	motoring pressure of cylinder (bar)
p_r	pressure at the intake valve opening ()
$Q_{c_i}(\theta)$	cumulative heat release at a crank angle (J)
r	engine compression ratio
R	universal gas constant (J/mol K)
R_a	gas constant of air (J/kg K)
R_c	gas constant of hydrogen-air charge (J/kg K)
R_{H_2}	gas constant of hydrogen (J/kg K)
s_{mp}	mean piston speed (m/s)
t	time period of frame (s)
T	reactant temperature (K)
t_{bd}	crank angle between backfire origin and start of hydrogen injection
t_{bo}	time required for the initiation of backfire origin (ms)
t_{bpd}	crank angle difference marking rise in in-cylinder and intake pressure
t_{bp_s}	backfire propagation time (s)
t_c	cycle time (ms)
T_{exh}	exhaust gas temperature (°C)

T_{exh_c}	critical exhaust gas temperature (°C)
t_i	induction time (ms)
T_i	intake air temperature (°C)
T_{i_g}	in-cylinder mean gas temperature (K)
$T_{ig_{EVO}}$	in-cylinder mean gas temperature at EVO
t_R	reaction time (ms)
T_r	temperature at intake valve opening (K)
T_{rsg}	residual gas temperature (K)
T_w	average cylinder wall temperature (K)
$V_{avg_{bp}}$	averaged backfire propagation velocity (m/s)
V_{cc}	cylinder clearance volume (m^3)
V_d	cylinder displaced volume (m^3)
$V_i(\theta)$	instantaneous cylinder volume (m^3)
V_r	volume at intake valve opening
w_{av}	mean gas velocity (m/s)
WD_{gr}	gross indicated work done per cycle (J)
WD_n	net indicated work done per cycle (J)
x_{H_2}	mole fraction of hydrogen

y	relative distance between in-cylinder and intake pressure sensor (m)
z_1	distance covered by flame front in the first frame (m)
η_{brake}	brake thermal efficiency (%)
γ	ratio of specific heat of hydrogen-air charge
λ	air-fuel ratio
μ	mean of measurements
μ_{IMEP_n}	mean of measurements of net IMEP
Φ	equivalence ratio
$\frac{\phi}{cycle}$	equivalence ratio per cycle
ϕ_l	localized equivalence ratio
σ_{IMEP_n}	standard deviation in measurements of net IMEP
τ_{H_2}	induction time of hydrogen
θ_r	crank angle in radians