6th International Hydrogen and Fuel Cell Conference (IHFC-2017)

Presentation
on

Control of Backfire in Hydrogen Fueled Spark Ignition Engines

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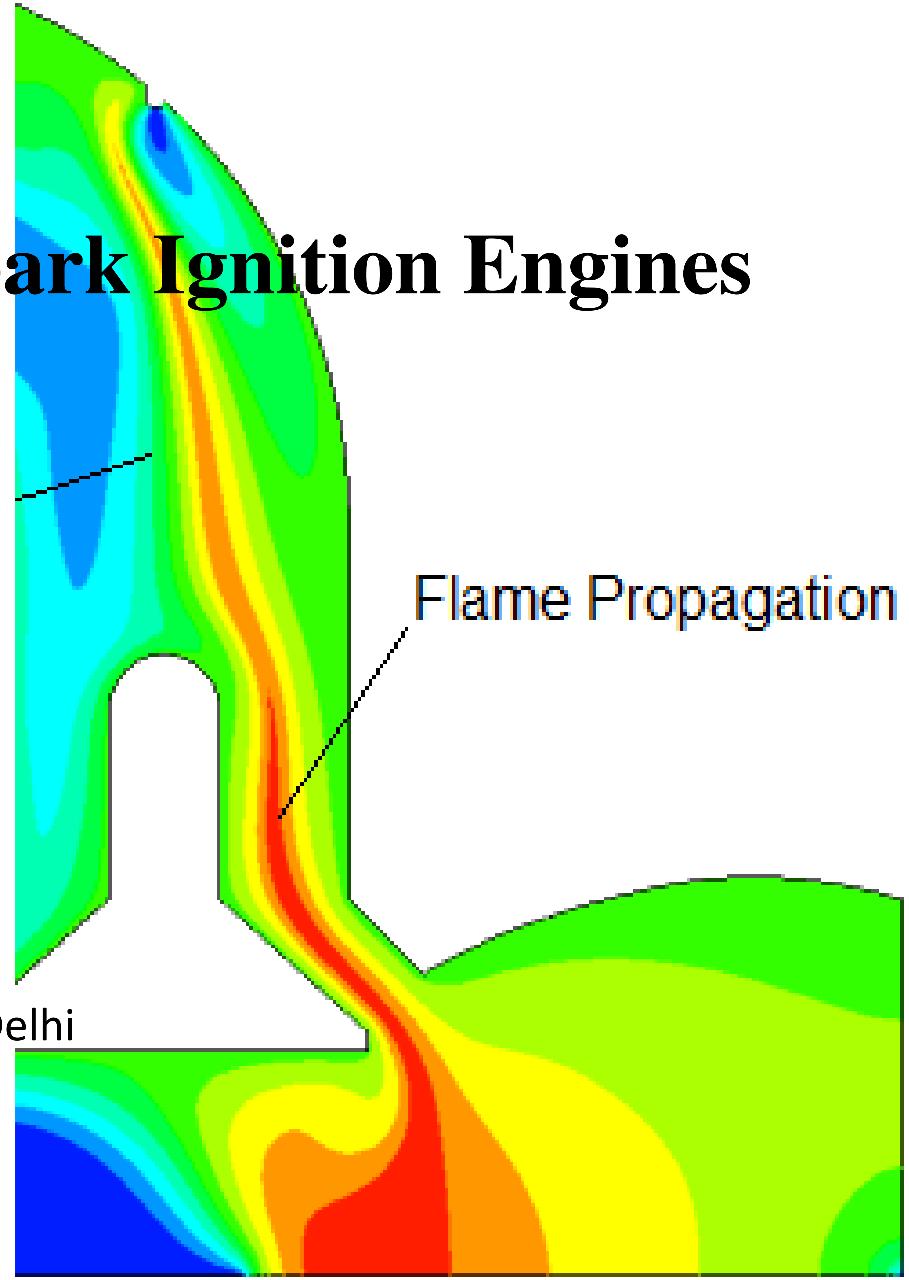


Introduction

- Backfire is a pre-ignition phenomenon that occurs during suction stroke of hydrogen fueled spark ignition engines.
- During backfire, the flame propagates towards upstream of the intake manifold of the engine resulting in stalling of engine operation and arising engine's safety problem.

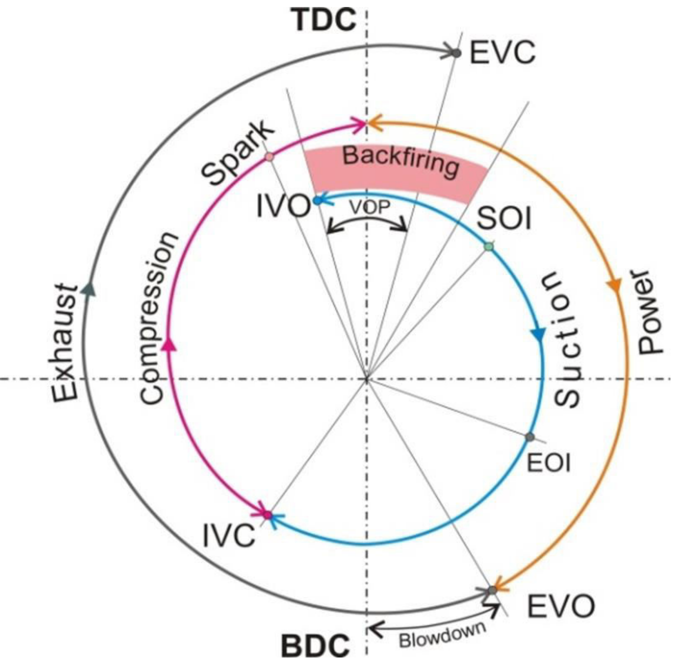


Figure: Valve timing diagram with backfire

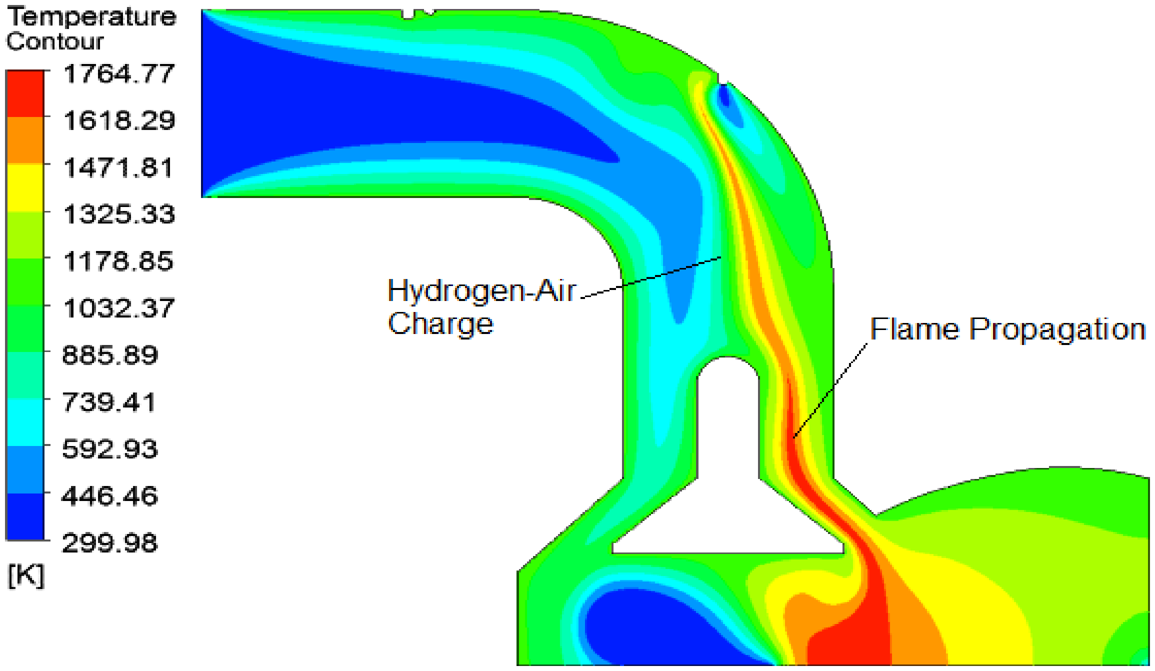


Figure: Propagation of Backfire

Occurrence of Backfire :

➢The backfire occurs due to:

- Hot residual gas
- Hot engine's components
- Oxidation of traces of lubricating oil
- Unburned hydrogen
- Radicals
- Minimum ignition energy (0.02 mJ)
- High flame velocity (2.65 to 3.25 m/s)
- Minimum quenching distance (0.64 mm)
- Wider flammability limits (4 to 75% of air volume)

Chemical Kinetics of H_2–O_2 Reaction Mechanism

$H_2 + OH \rightarrow H_2O + H$

$H + O_2 \rightarrow OH + O$

$O + H_2 \rightarrow OH + H$

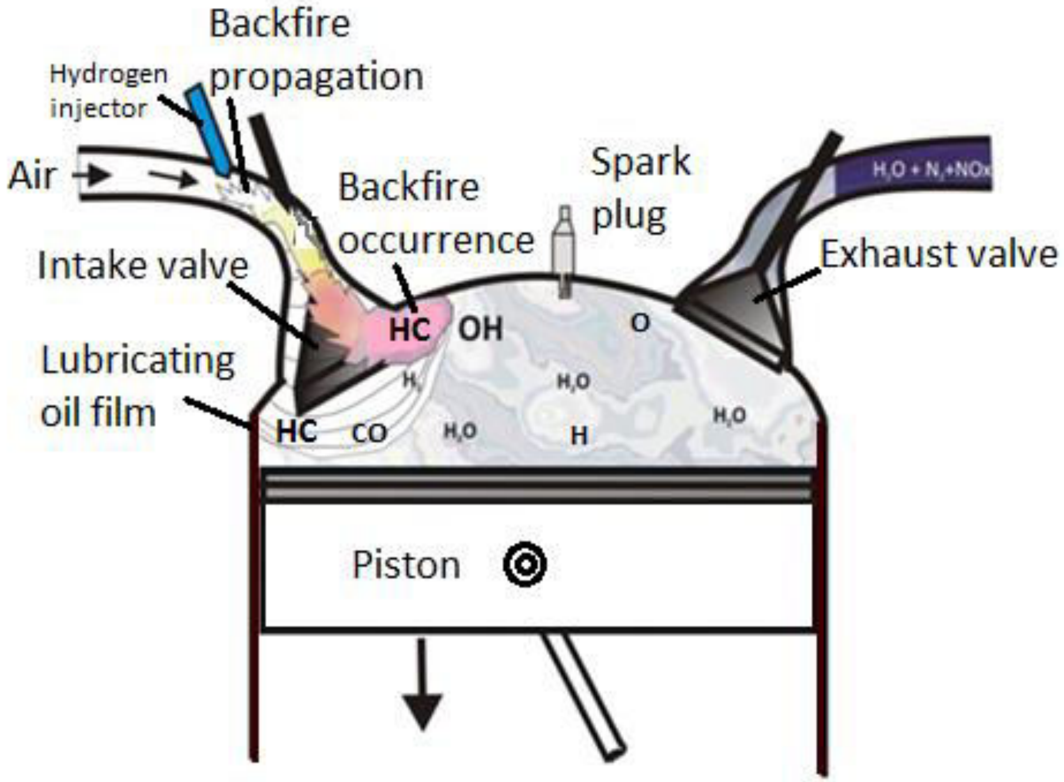


Figure: Backfire occurrence and propagation in the intake manifold

Cause of Backfire in Hydrogen Fuelled Spark Ignition Engines

- Decrease in fuel flow rate due to pressure rise in intake manifold
- Increase in Pumping and Compression work
- Decrease in indicated power
- Rapid decrease in speed and some extend to stall engine operation
- Damaging of intake manifold and fuel supply system
- High pitch noise

External Source of Ignition Energy in SI Engines

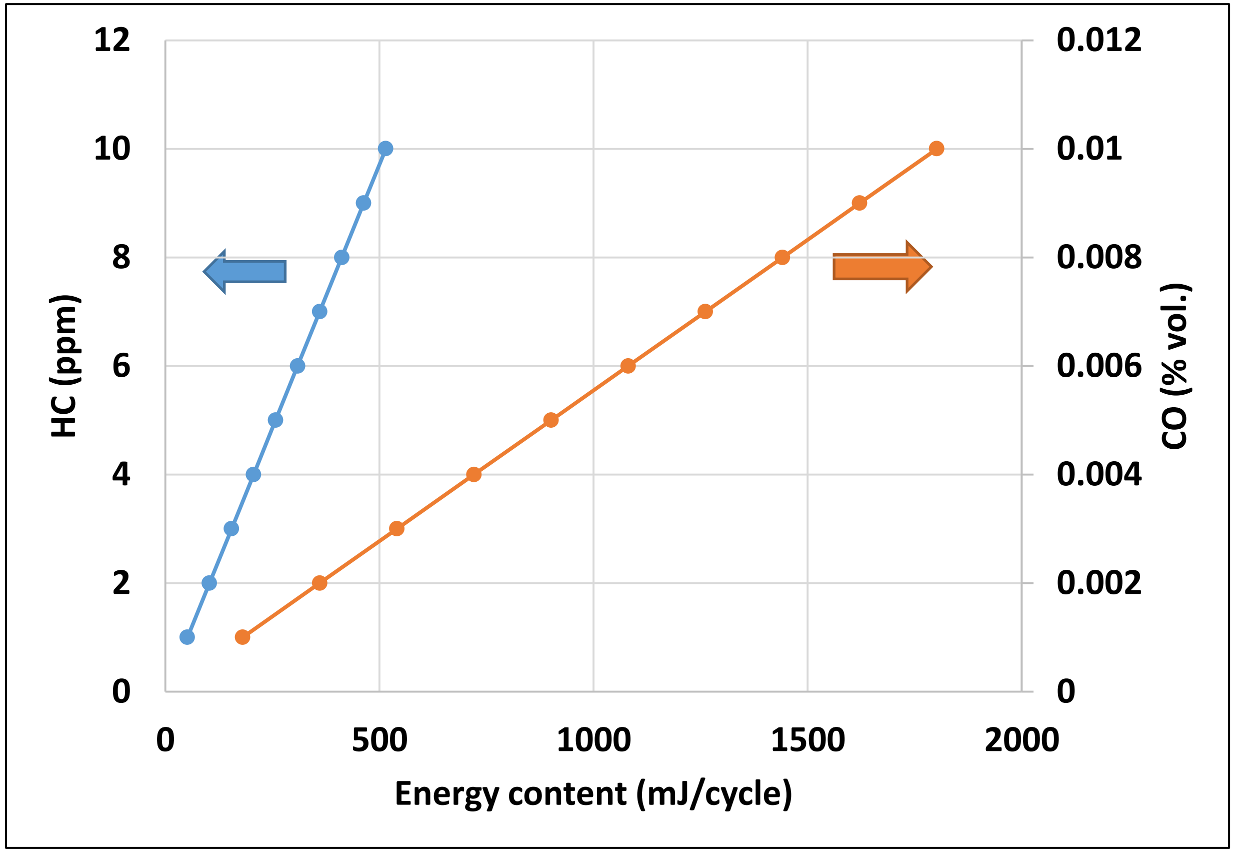


Fig. 7 Energy content of HC and CO emissions

Energy content of 1 ppm of HC = 50 mJ/cycle
Energy content of 0.001 % vol. of CO = 180 mJ/cycle
Energy content of unburned H_2 (100 ppm) = 1560 mJ/cycle
Energy content of residual gas = 20000 to 40000 mJ/cycle

$$MIE = \rho \times C \times \frac{\pi \times d_{opt}^3}{6} \times (T_f - T_r)$$

Where, MIE = minimum ignition energy

ρ = Density of reactant (kg/ m3)

C = specific heat (kJ/kg K)

V = Volume of reactant (air+fuel) in spark plug's electrode zone (m3)

d_{opt}= optimum diameter of sphere in spark plug electrode zone (m)

T_f = flame temperature (K)

T_r = Initial temperature of reactant (air+fuel) (K)

The MIE of H_2 - air charge = 0.02 mJ

Identification of backfire

- Backfire is identified by high pitched sound, sudden rise of intake manifold pressure/ or in-cylinder pressure during suction stroke of the engine

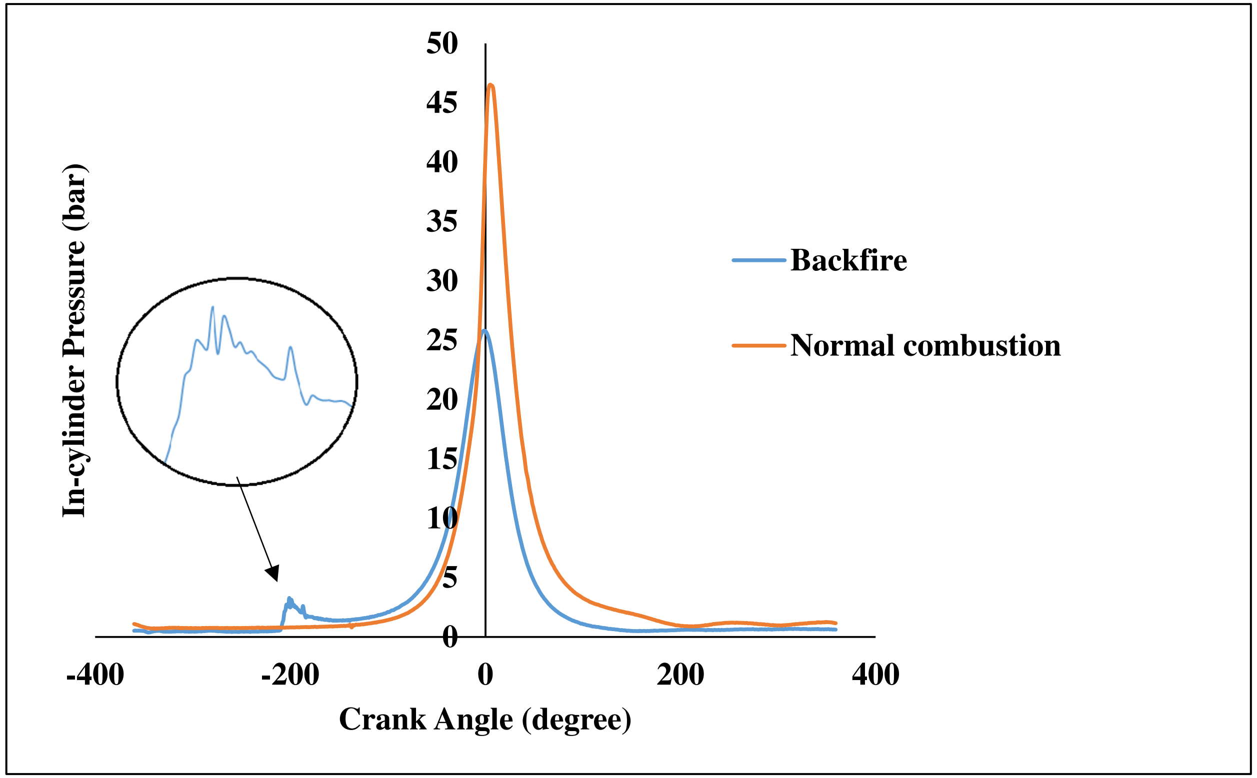


Figure: In-cylinder pressure during normal combustion and backfire

Backfire region

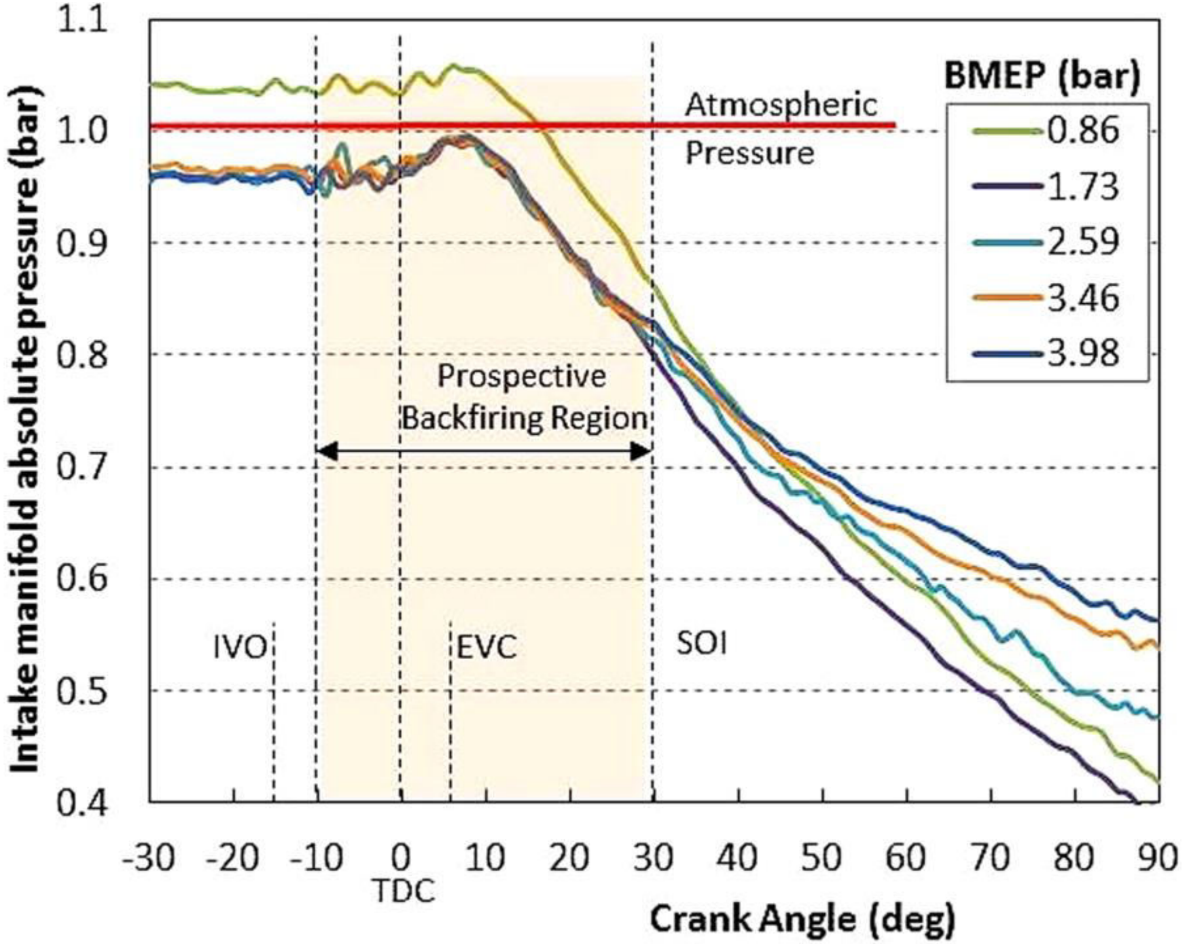


Figure: Variation in intake manifold pressure with respect to crank angle

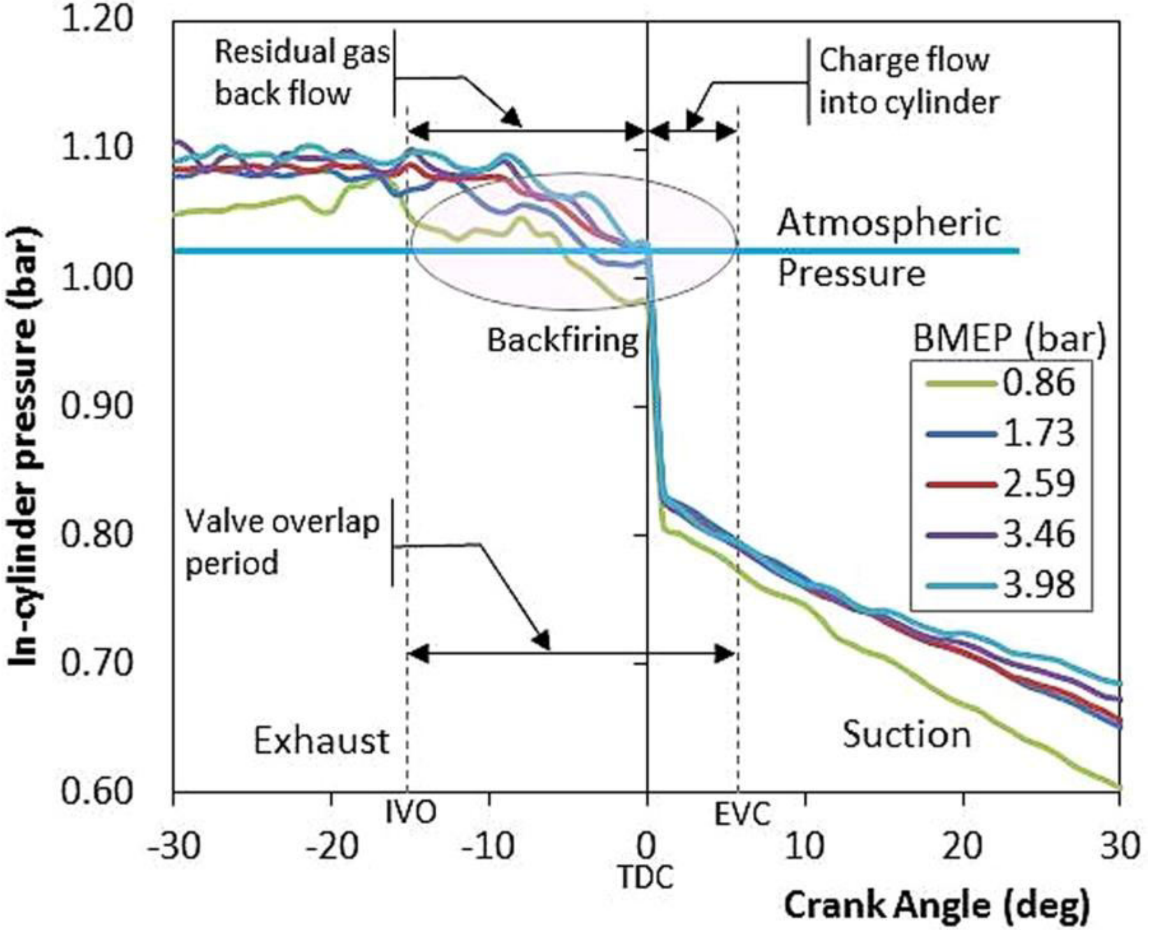


Figure: Indicative diagram of backfire zone during gas exchange process

Effect of knocking on backfire

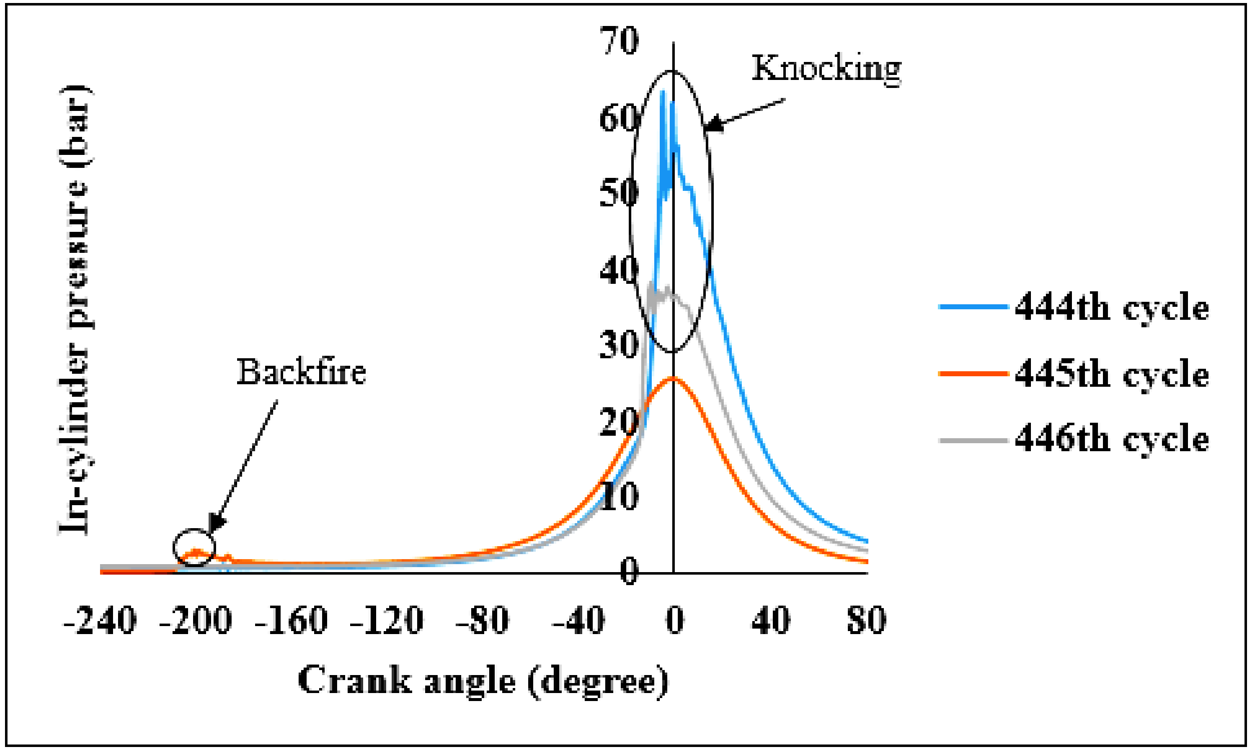


Figure: Occurrence of backfire and knocking

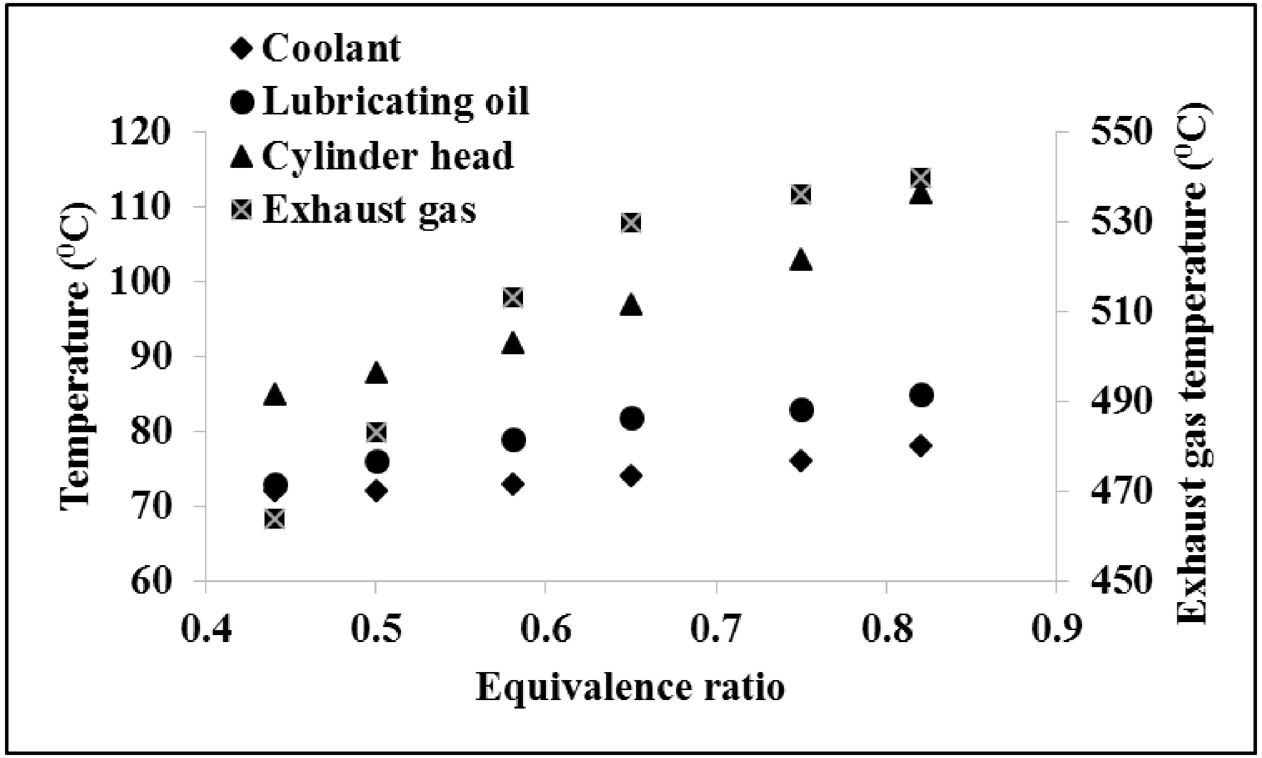


Figure: Variation of various temperatures with equivalence ratio

Control strategies for backfire

- Delay in hydrogen fuel injection
- Retarding spark timing
- Direct hydrogen injection
- Using Exhaust gas recirculation
- Using water injection in intake manifold
- Charge boosting
- Dedicated lubricating oil
- Specific design of intake manifold

Effect of compression ratio on backfire limiting start of injection

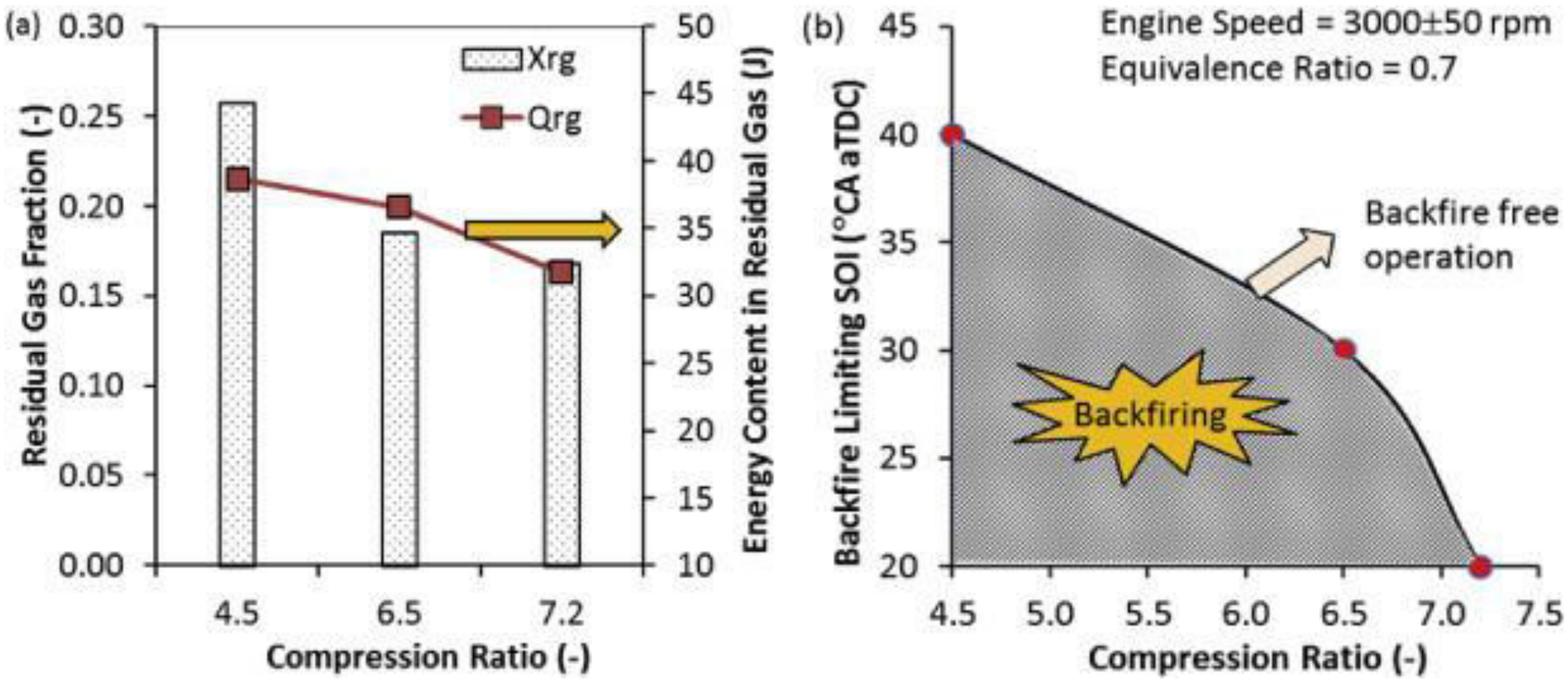


Figure: Residual gas fraction and energy contained in it, and experimental observations on backfire limiting start of injection at various compression ratios.

Optimization of hydrogen injection timing for backfire control

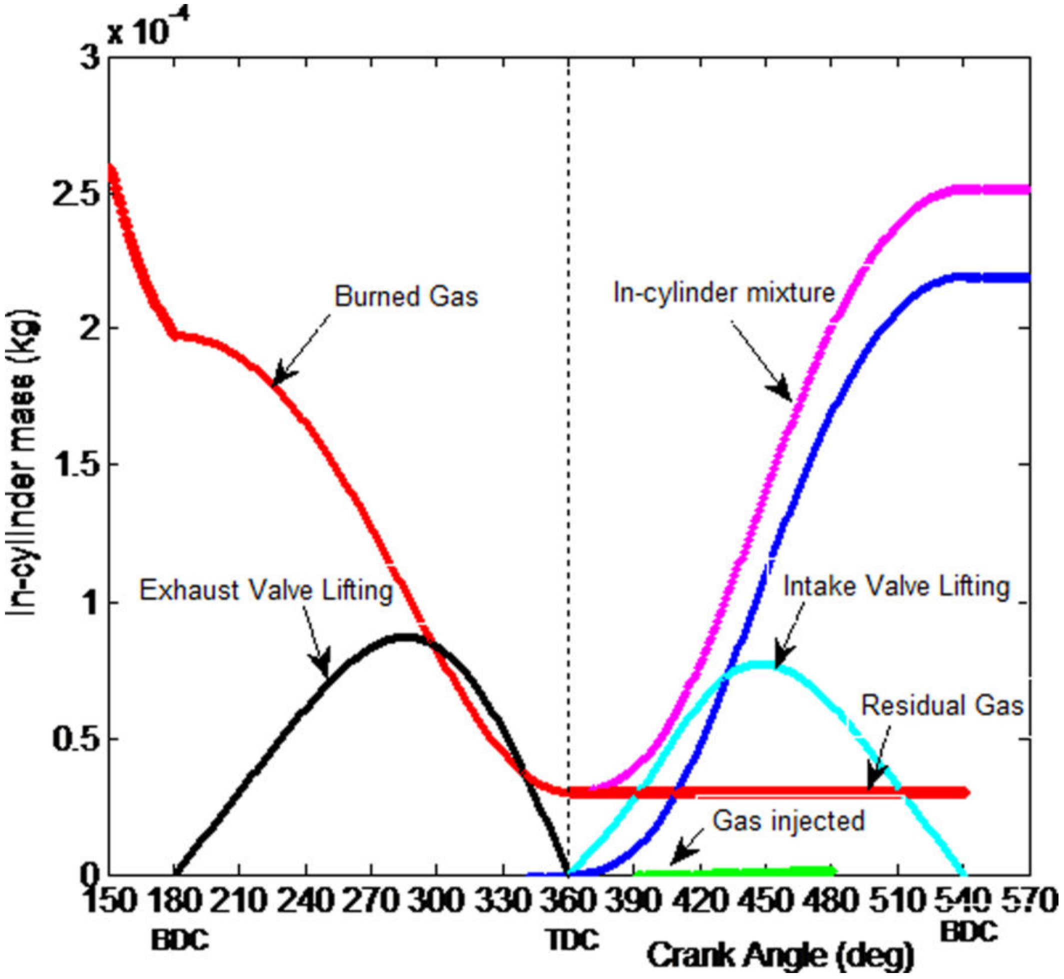


Figure: Instantaneous in-cylinder mass and valves lifting profile with respect to crank angle during gas exchange process

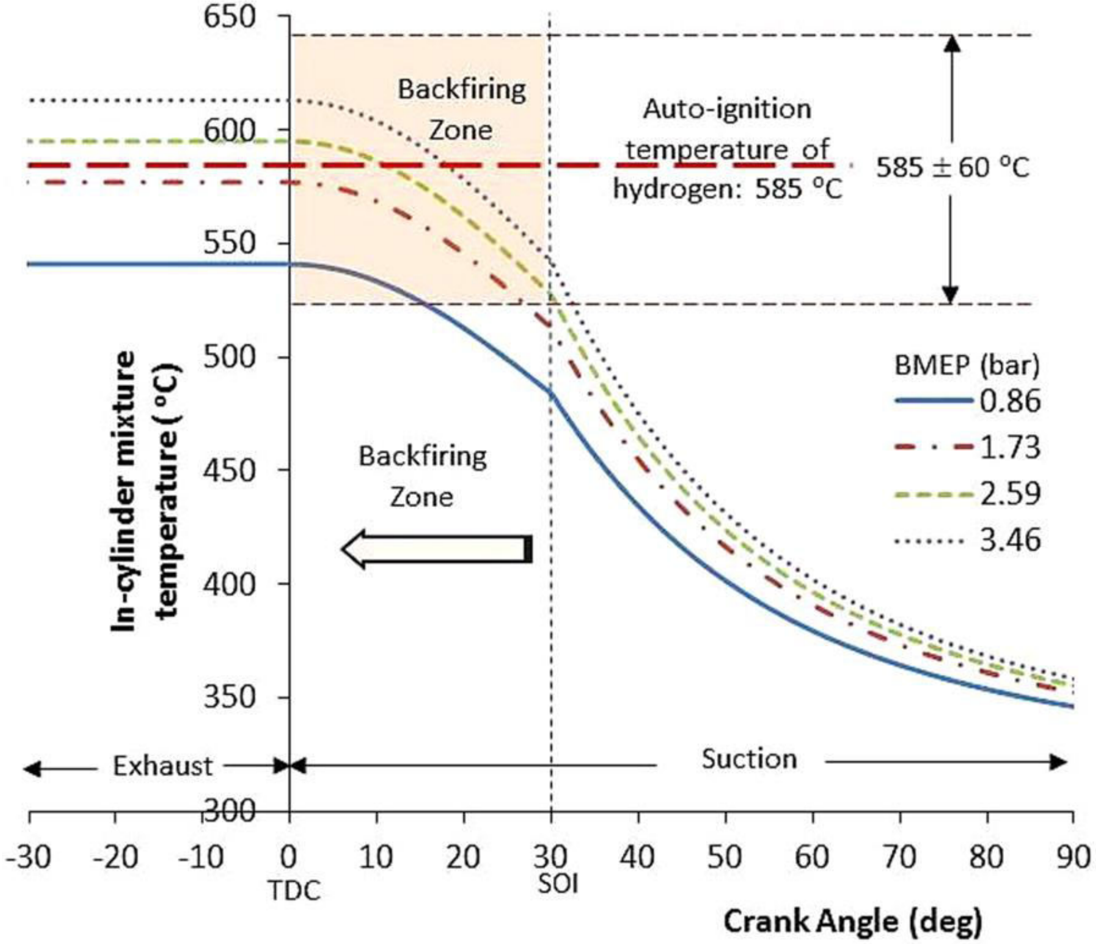


Figure: In-cylinder mixture temperature with respect to crank angle during suction stroke

Optimization of hydrogen injection timing for backfire control

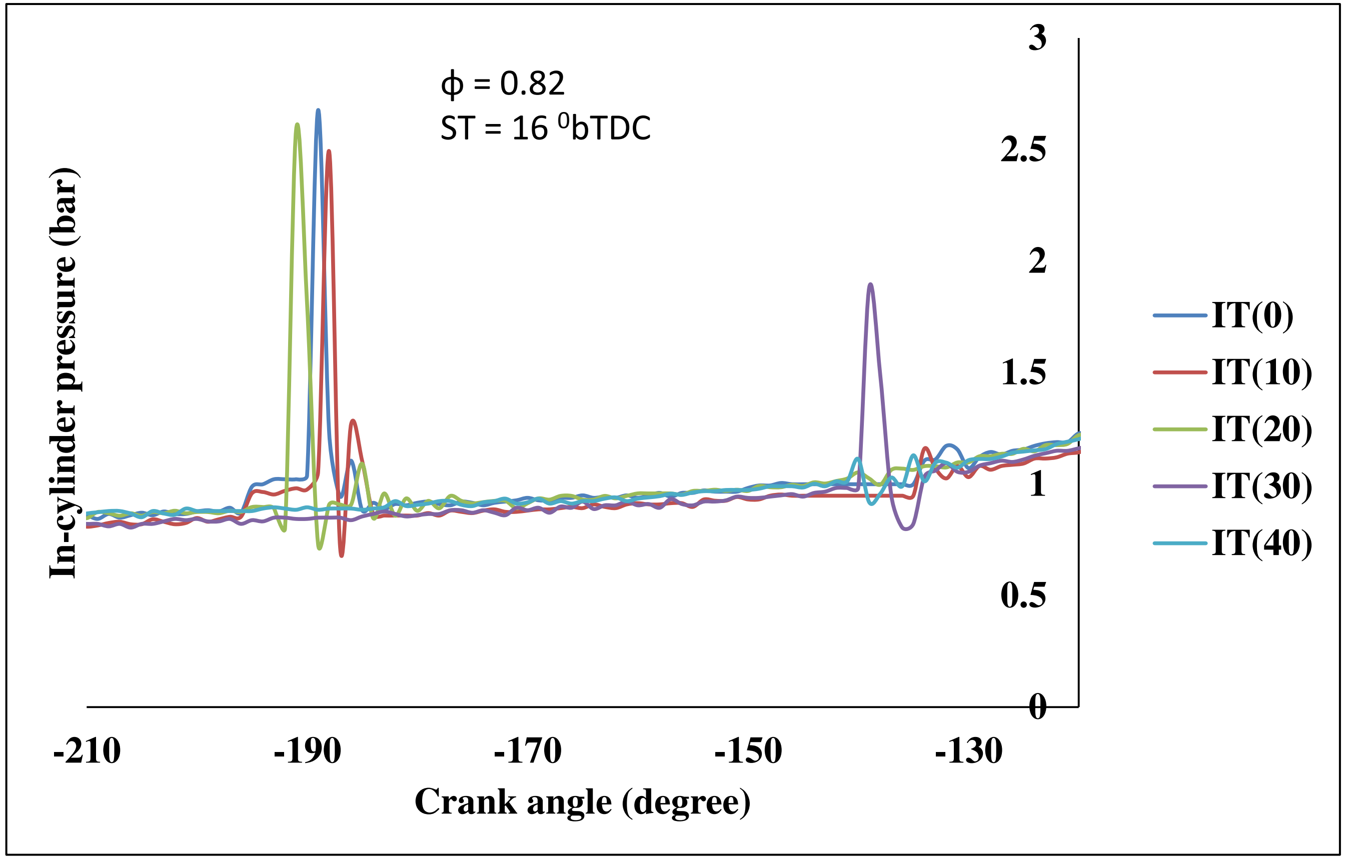


Figure: Occurrence of backfire with various injection timings

- **The backfire limiting injection timing was 30^0 aTDC and 40^0 aTDC for single cylinder and multi-cylinder spark ignition engine respectively.**

Backfire propagation

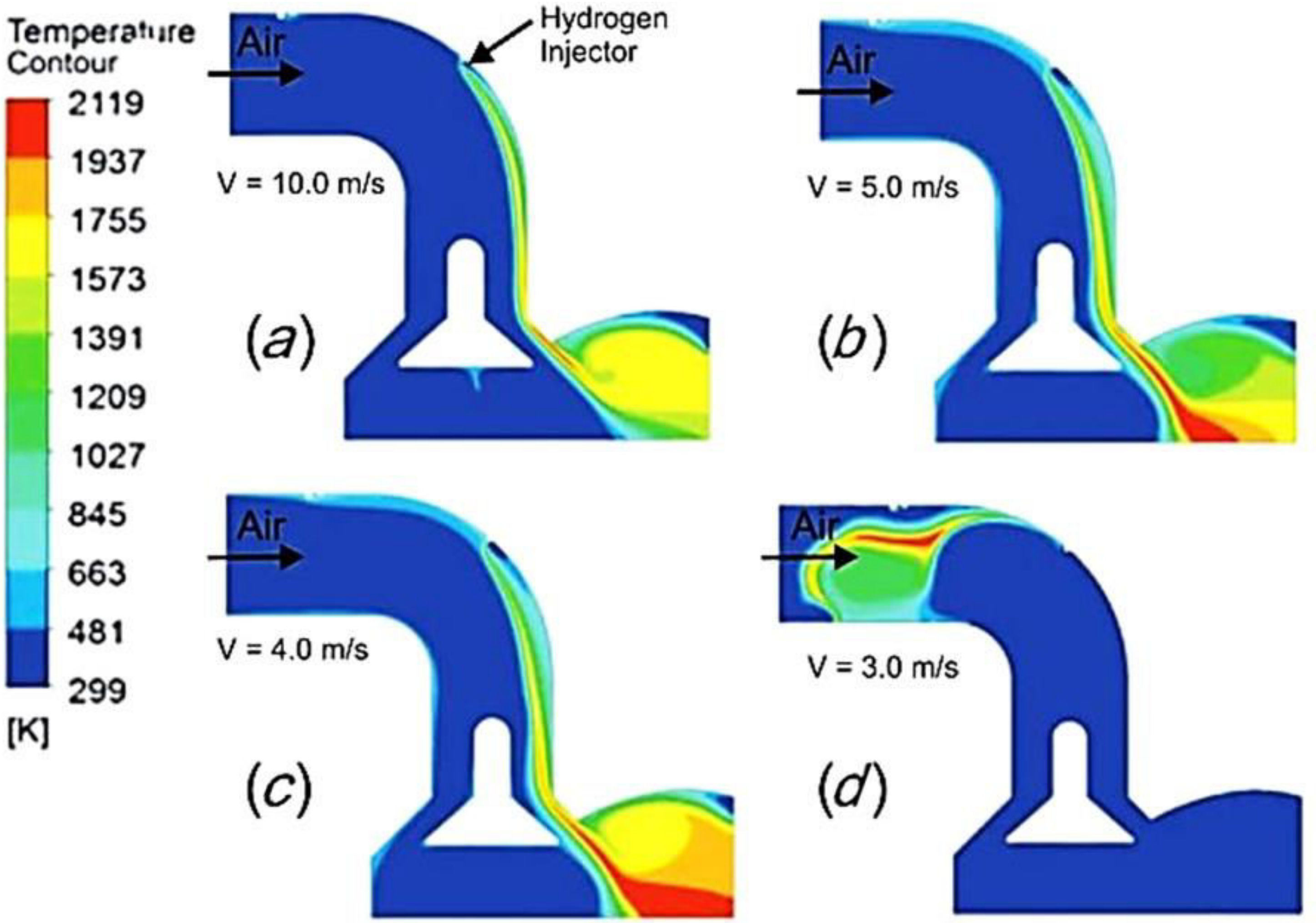


Figure: Propagation of backfire with different velocity of reactant

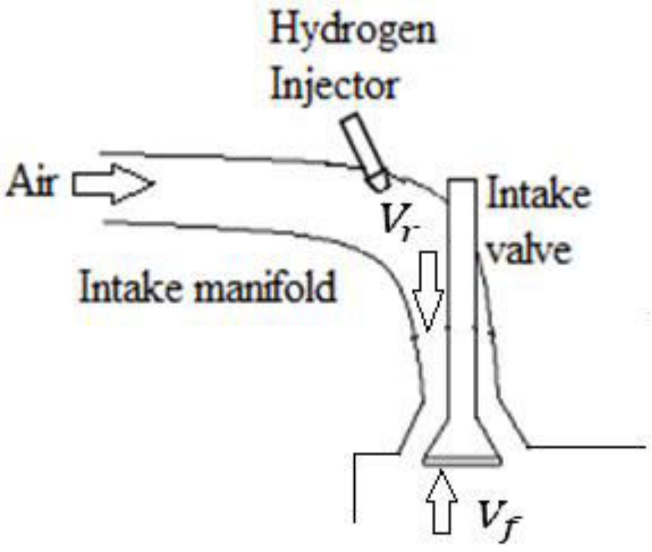
Backfire propagation

The reactant velocity is given as

$$V_r = \sqrt{\left\{\frac{2\gamma}{\gamma-1}\frac{p_0^{\frac{\gamma-2}{\gamma}}}{\rho}p_c^{\frac{2}{\gamma}}\left[1-\left(\frac{p_c}{p_0}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}}$$

The turbulent flame velocity is given as [4]

$$V_f = A\left[\frac{NDLP}{T_b^{1.67}}\right]^{0.4} T_b^{0.41}T_u^{1.25}\left[\frac{X_f F(\phi)}{\phi}\right]^{0.5}\frac{R}{E_a}exp\left(-\frac{E_a}{2RT_b}\right)$$



If V_r < V_f (backfire will take place)

If V_r > V_f (backfire will not take place)

Conclusions:

- The residual gas temperature and combustion with knock are the key parameter for backfire occurrence.

- The hot-spots (due to partial burnt lubrication oil, spark plug tip, etc.) at high residual gas temperature could lead to pre-ignition of hydrogen-air charge during suction stroke resulting in more probability of backfire.

- The backfire can be eliminated by delayed (retarded) start of hydrogen injection timing preferably after 30° CA TDC during suction stroke, Retarding spark timing, water injection and EGR.

References

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2. B.L. Salvi, K.A. Subramanian, Experimental investigation on effects of compression ratio and exhaust gas recirculation on backfire, performance and emission characteristics in a hydrogen fuelled spark ignition engine, In International Journal of Hydrogen Energy, Volume 41, Issue 13, 2016, pp. 5842-5855.

3. B.L. Salvi, K.A. Subramanian, Experimental investigation on effects of exhaust gas recirculation on flame kernel growth rate in a hydrogen fuelled spark ignition engine, In Applied Thermal Engineering, Volume 107, 2016, pp. 48-54.

4. Fagelson J. J., Mclean W. J. and Boer P. C. T. de, Performance and NOx Emissions of Spark Ignited Combustion Engines Using Alternative Fuels—Quasi One-Dimensional Modeling I. Hydrogen Fueled Engines, Combustion Science and Technology Volume 18 ,1978, pp. 47-57.

Thank you