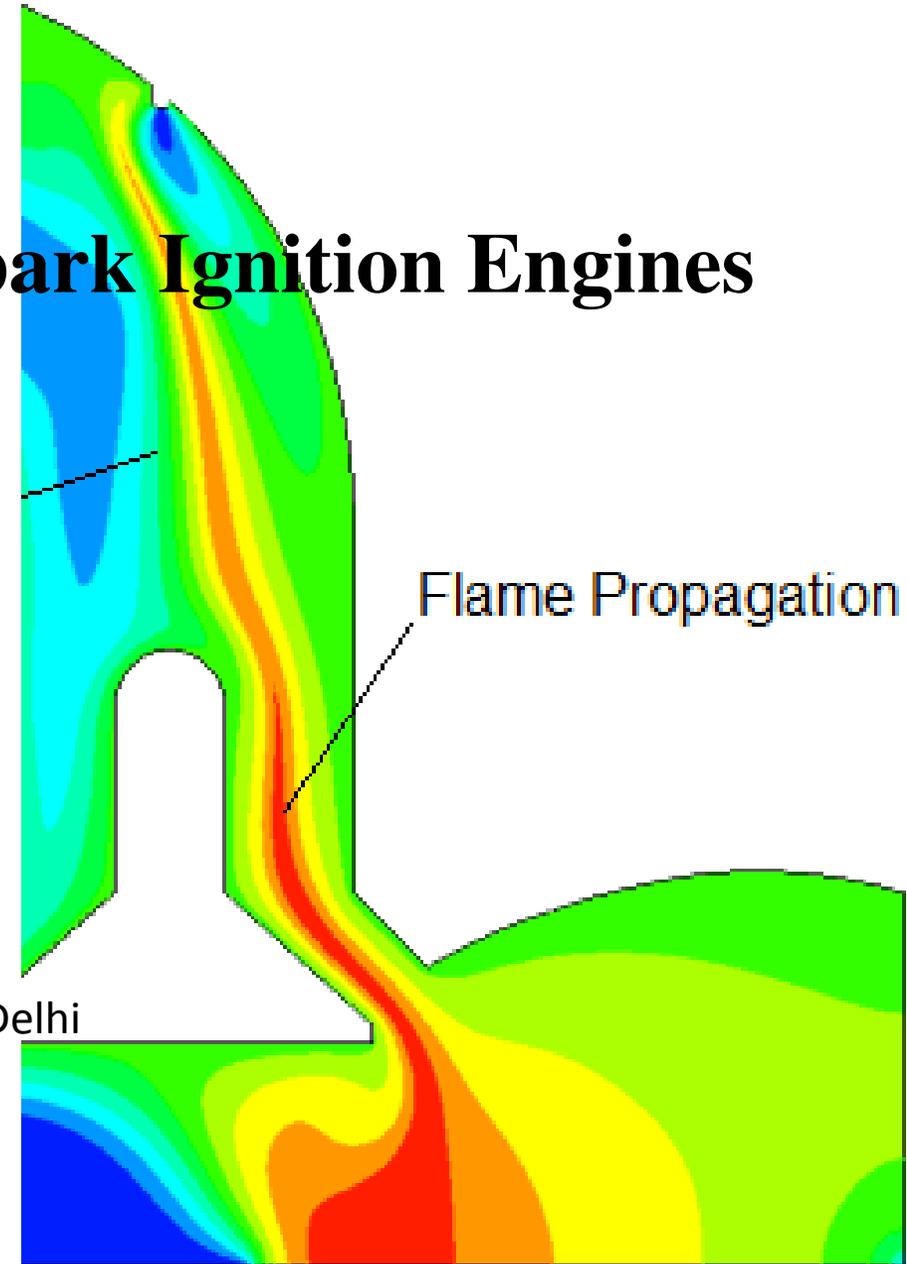


Presentation  
on  
**Control of Backfire in Hydrogen Fueled Spark Ignition Engines**

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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.

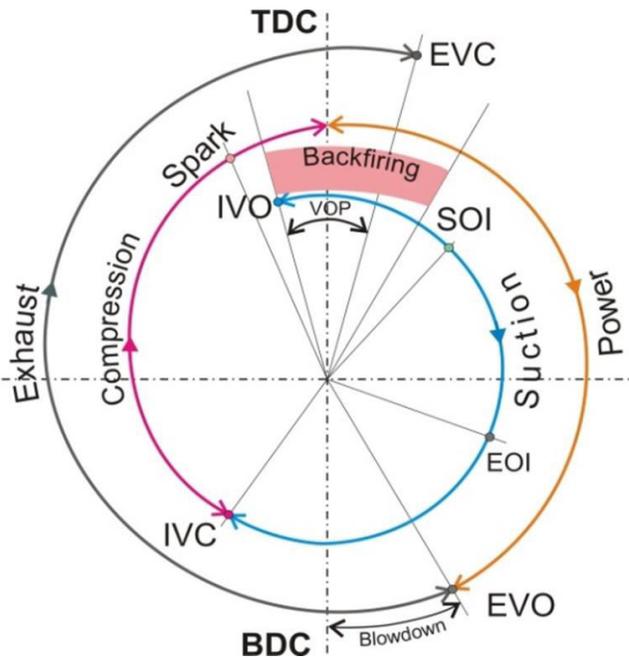


Figure: Valve timing diagram with backfire

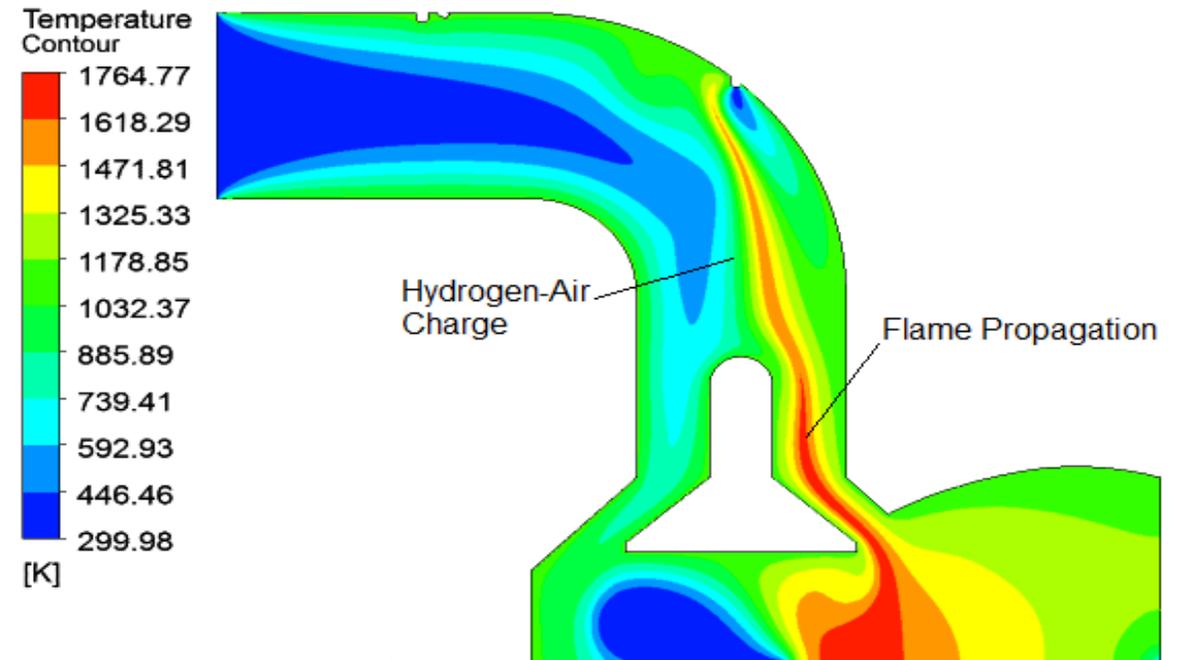


Figure: Propagation of Backfire

# 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

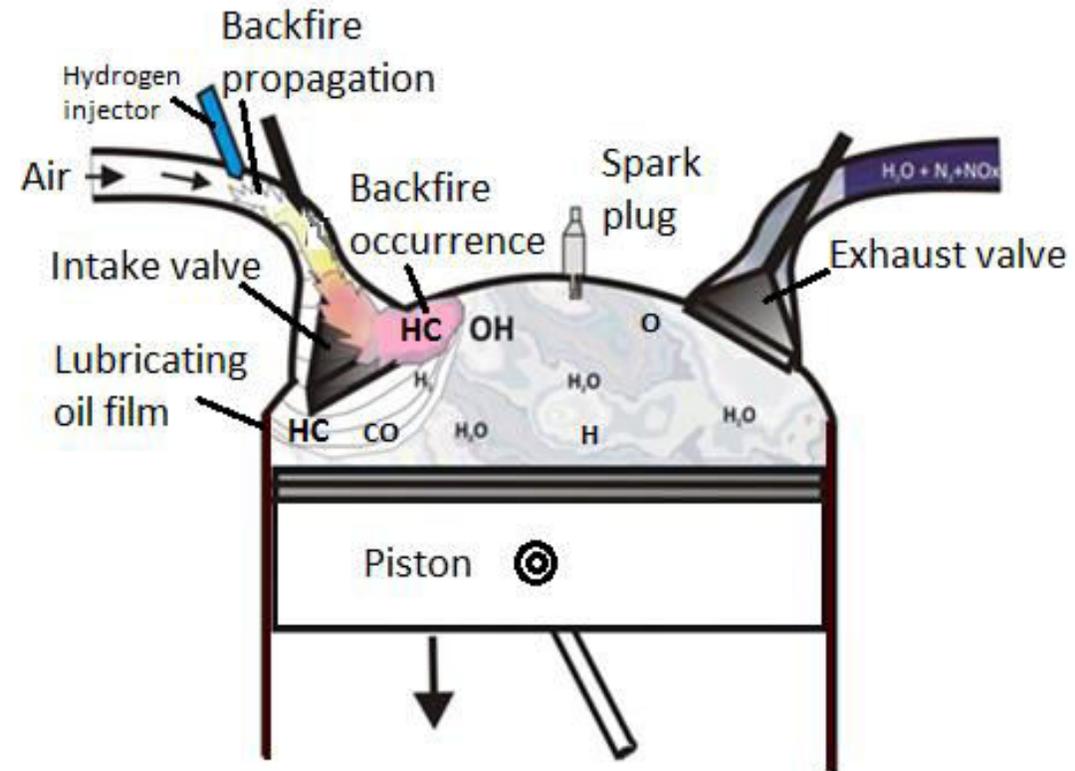


Figure: Backfire occurrence and propagation in the intake manifold

# 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

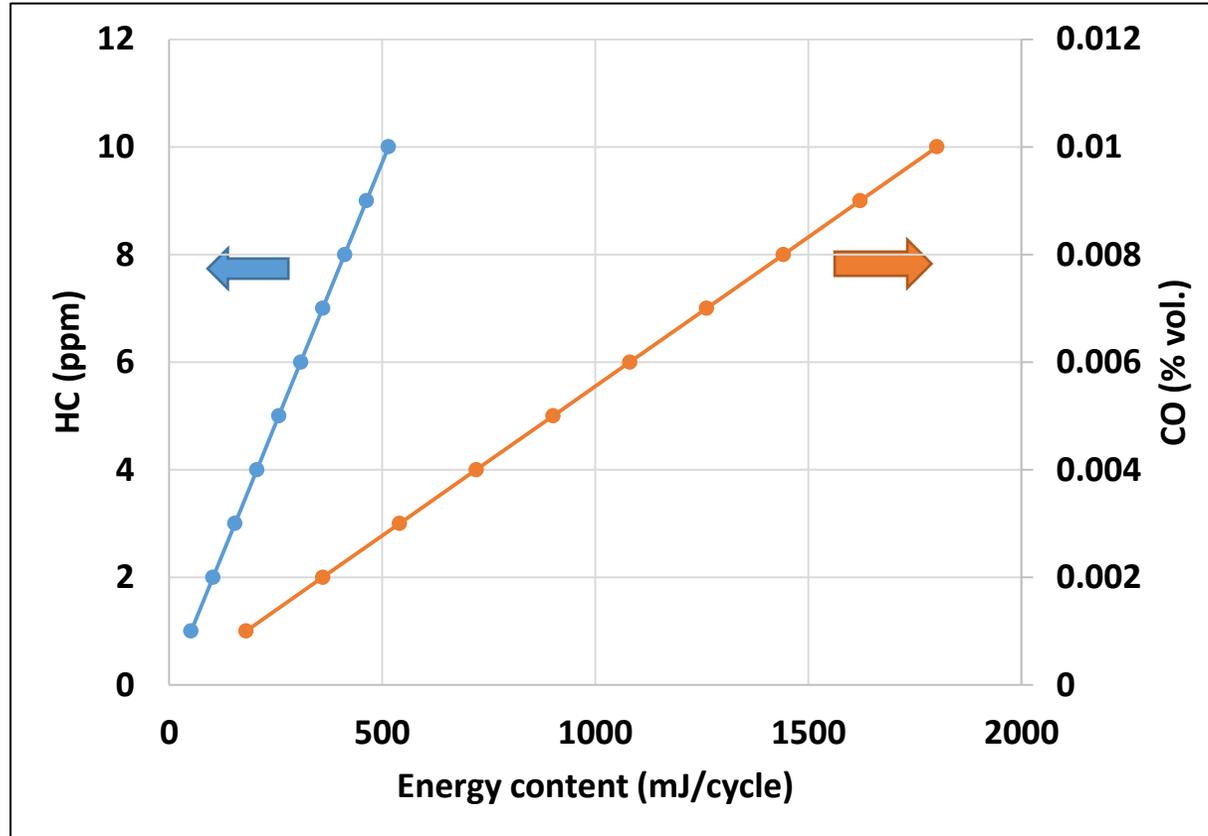


Fig. 7 Energy content of HC and CO emissions

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<sub>2</sub> (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

$\rho$  = Density of reactant (kg/ m<sup>3</sup>)

$C$  = specific heat (kJ/kg K)

$V$  = Volume of reactant (air+fuel) in spark plug's electrode zone (m<sup>3</sup>)

$d_{opt}$  = 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<sub>2</sub> - 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

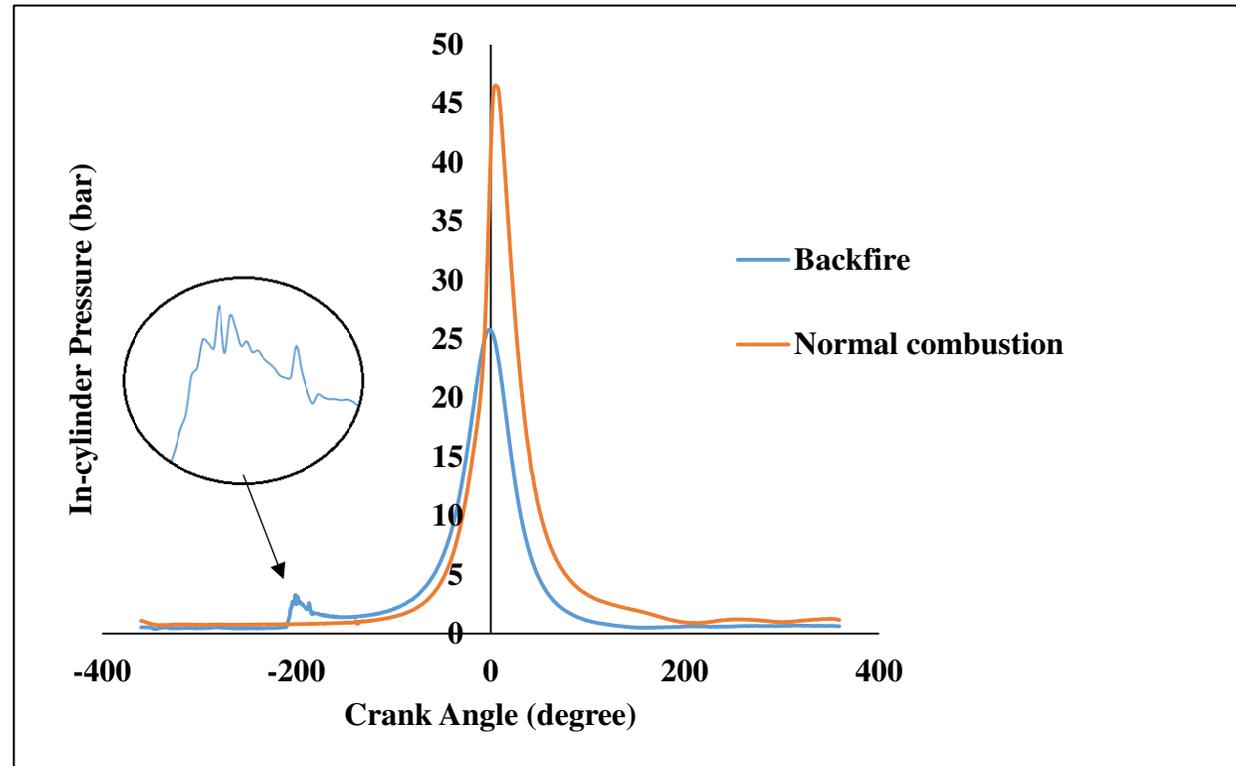


Figure: In-cylinder pressure during normal combustion and backfire

# Backfire region

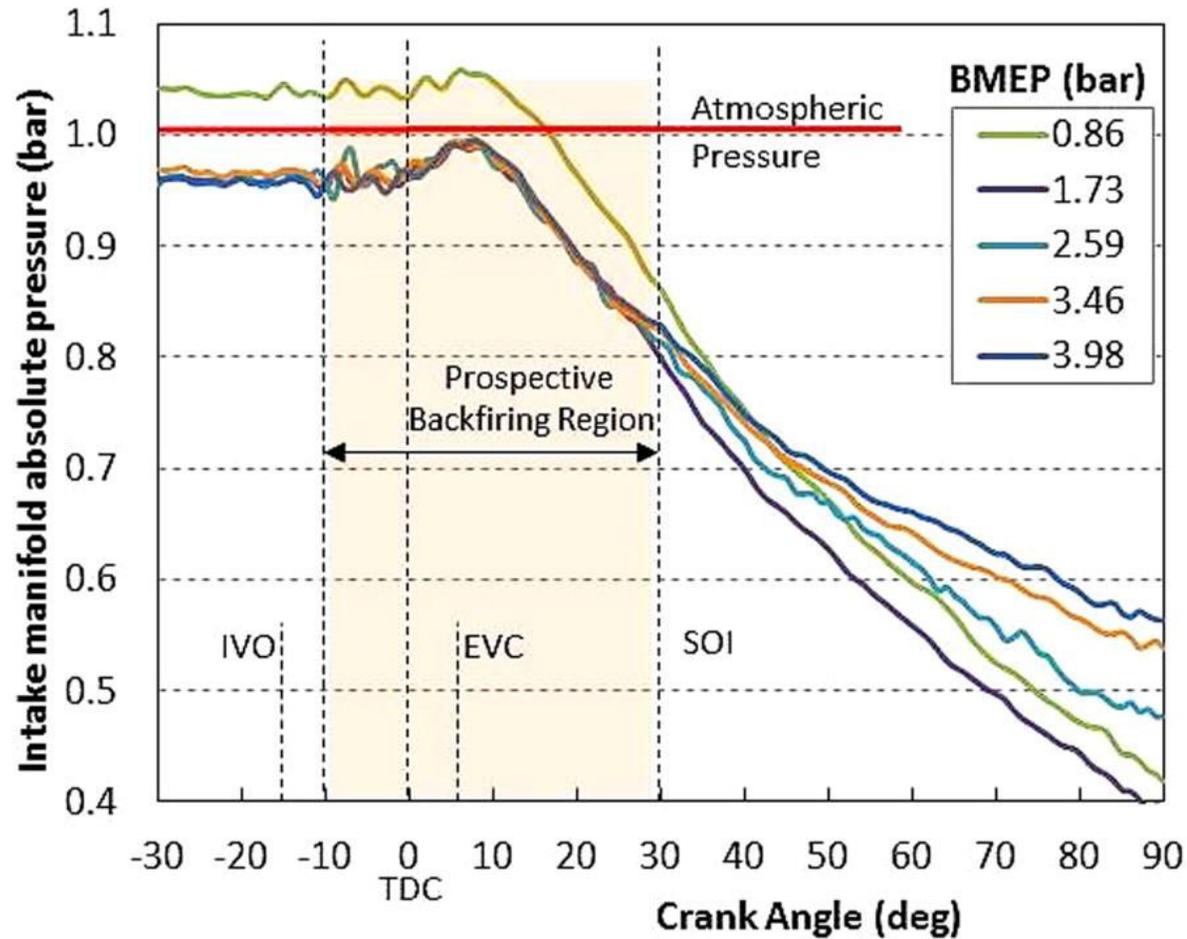


Figure: Variation in intake manifold pressure with respect to crank angle

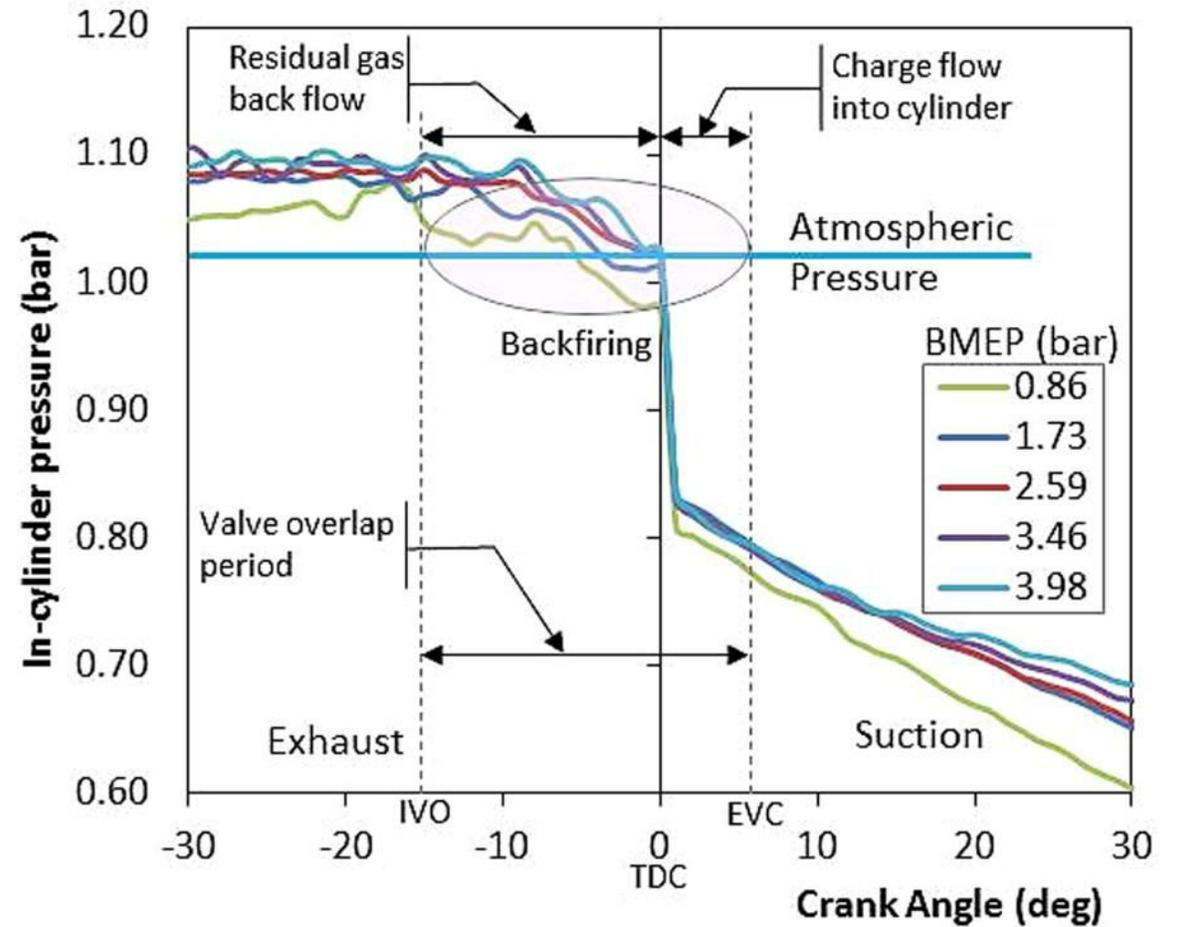


Figure: Indicative diagram of backfire zone during gas exchange process

# Effect of knocking on backfire

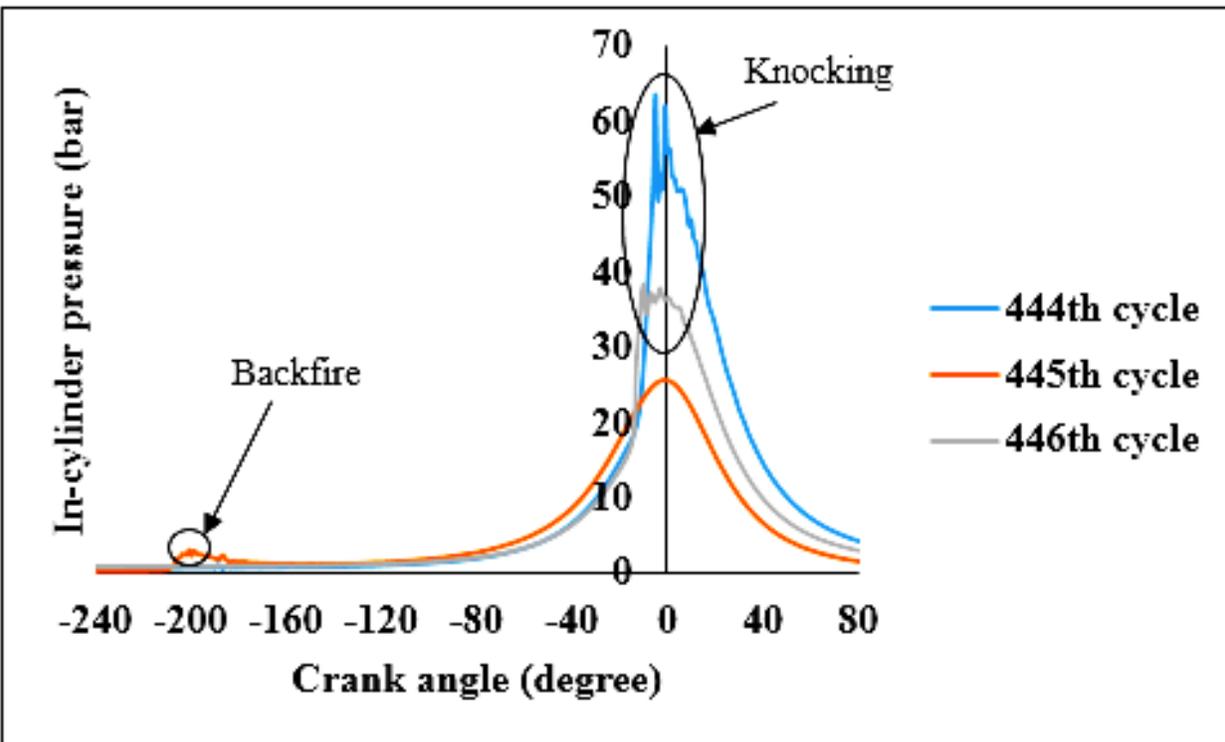


Figure: Occurrence of backfire and knocking

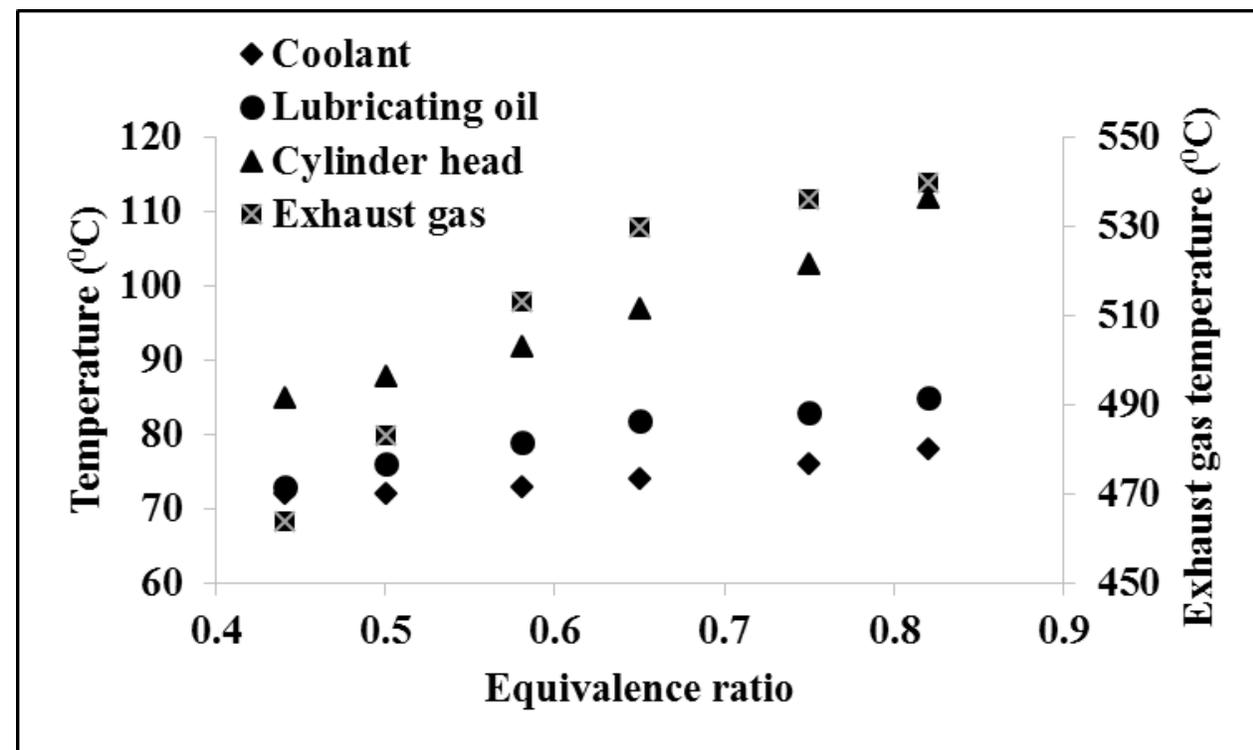


Figure: Variation of various temperatures with equivalence ratio

# 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

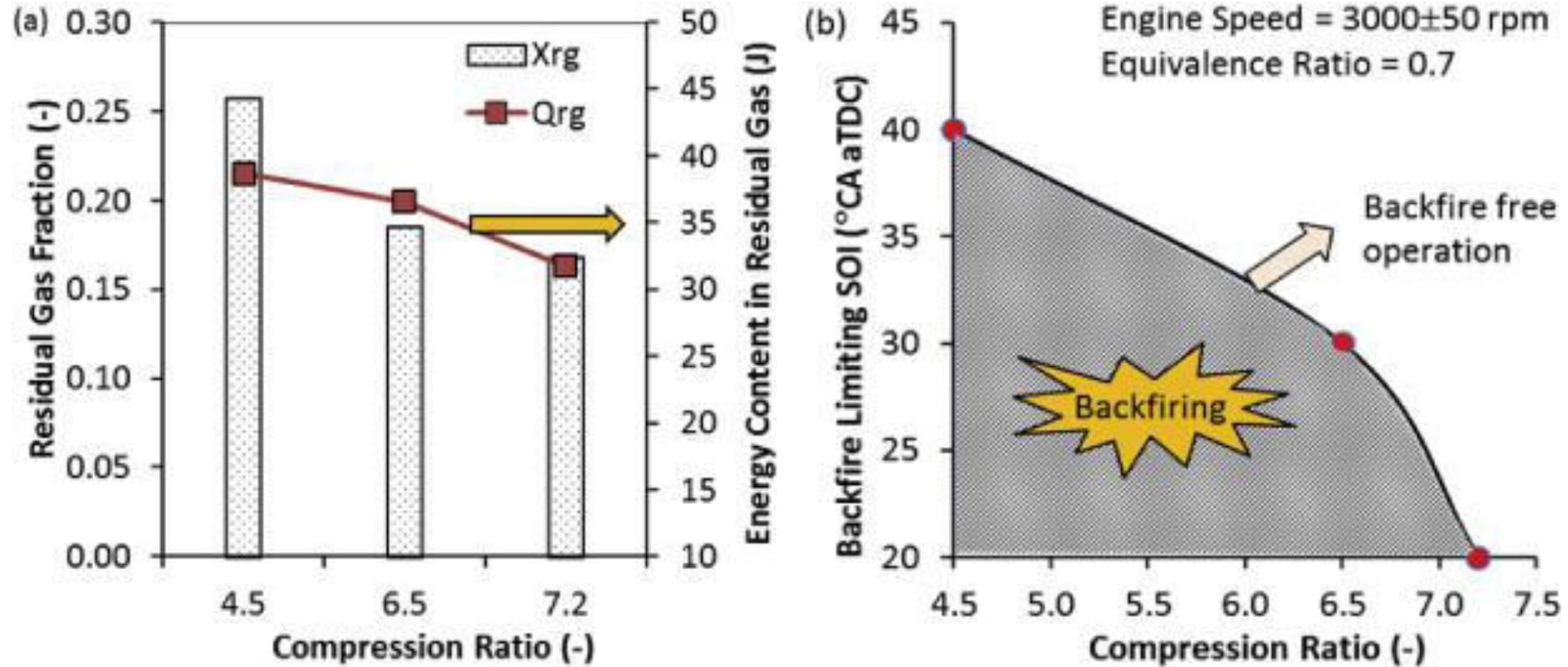


Figure: Residual gas fraction and energy contained in it, and experimental observations on backfire limiting start of injection at various compression ratios.

# Optimization of hydrogen injection timing for backfire control

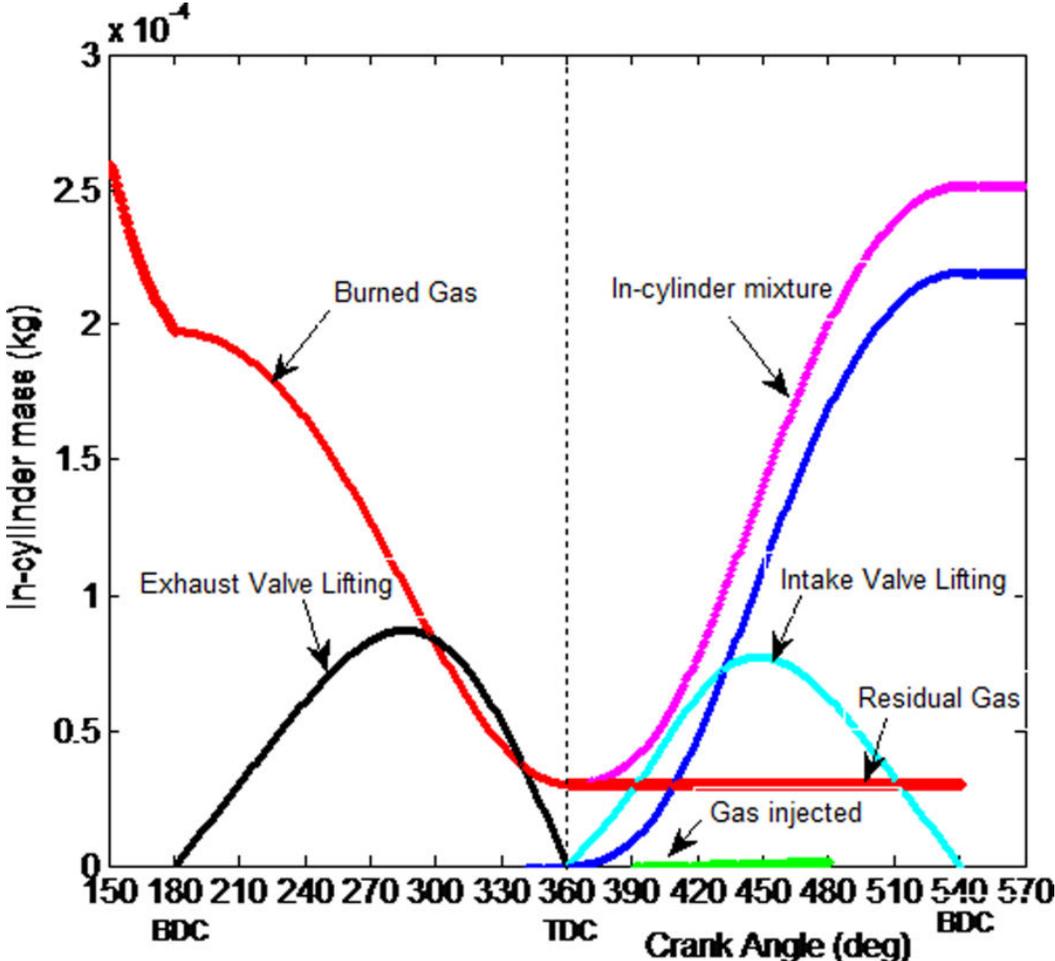


Figure: Instantaneous in-cylinder mass and valves lifting profile with respect to crank angle during gas exchange process

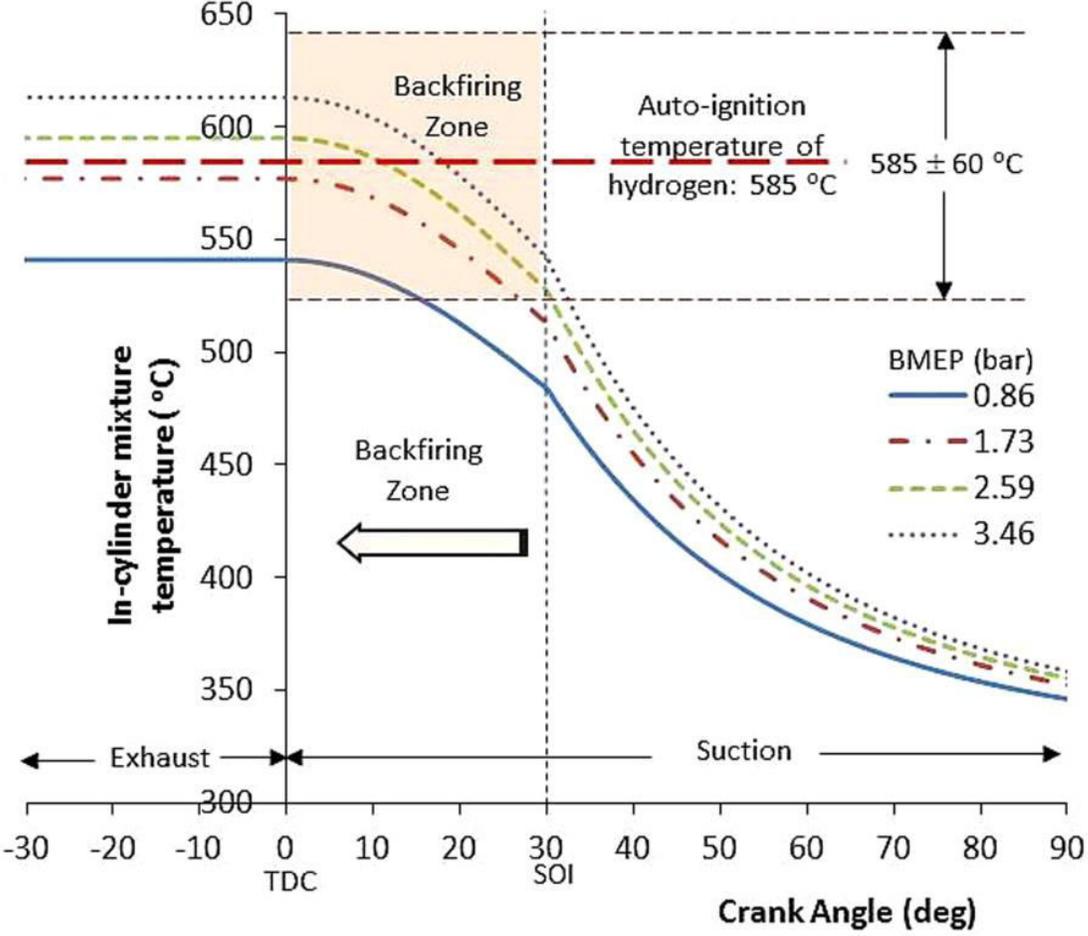
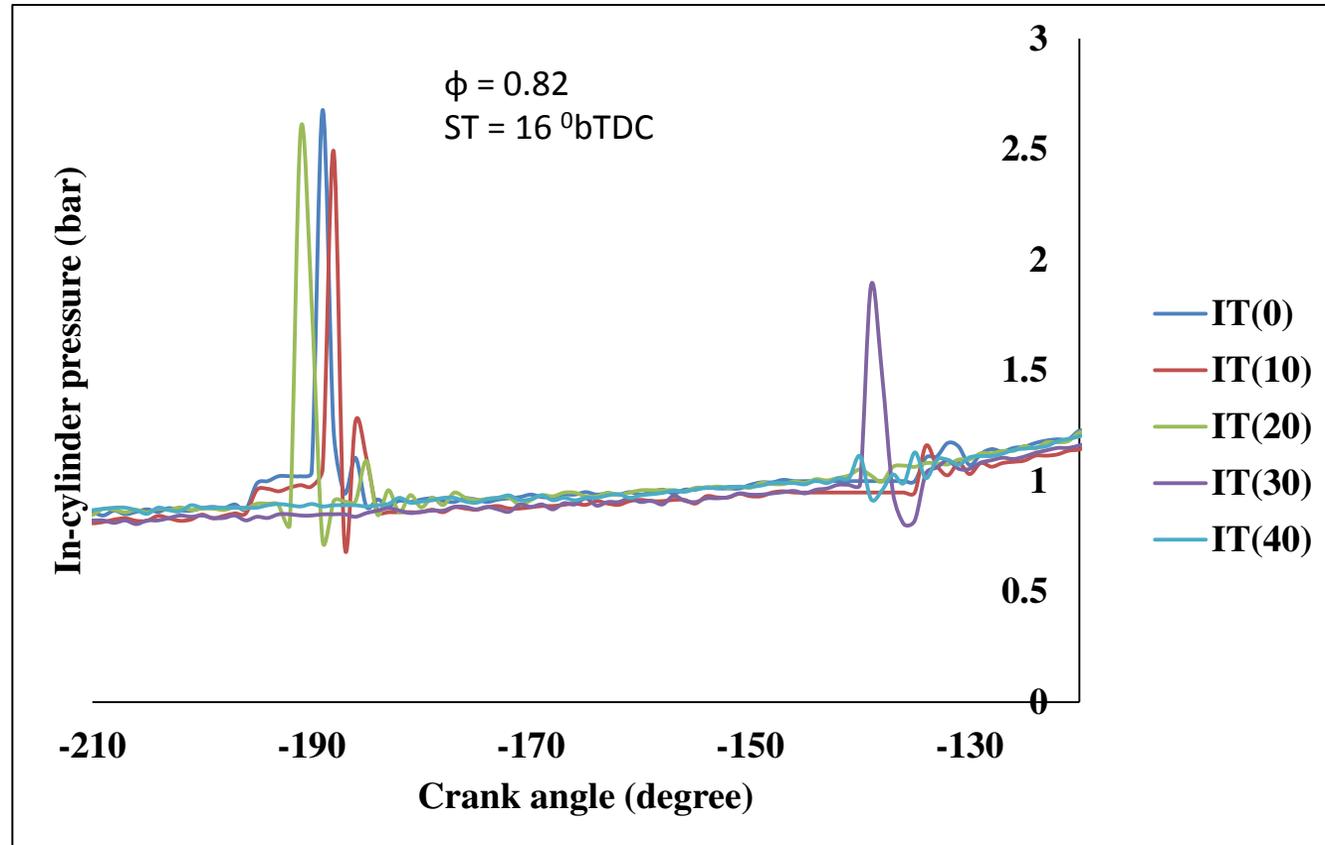


Figure: In-cylinder mixture temperature with respect to crank angle during suction stroke

# Optimization of hydrogen injection timing for backfire control



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

Figure: Occurrence of backfire with various injection timings

# Backfire propagation

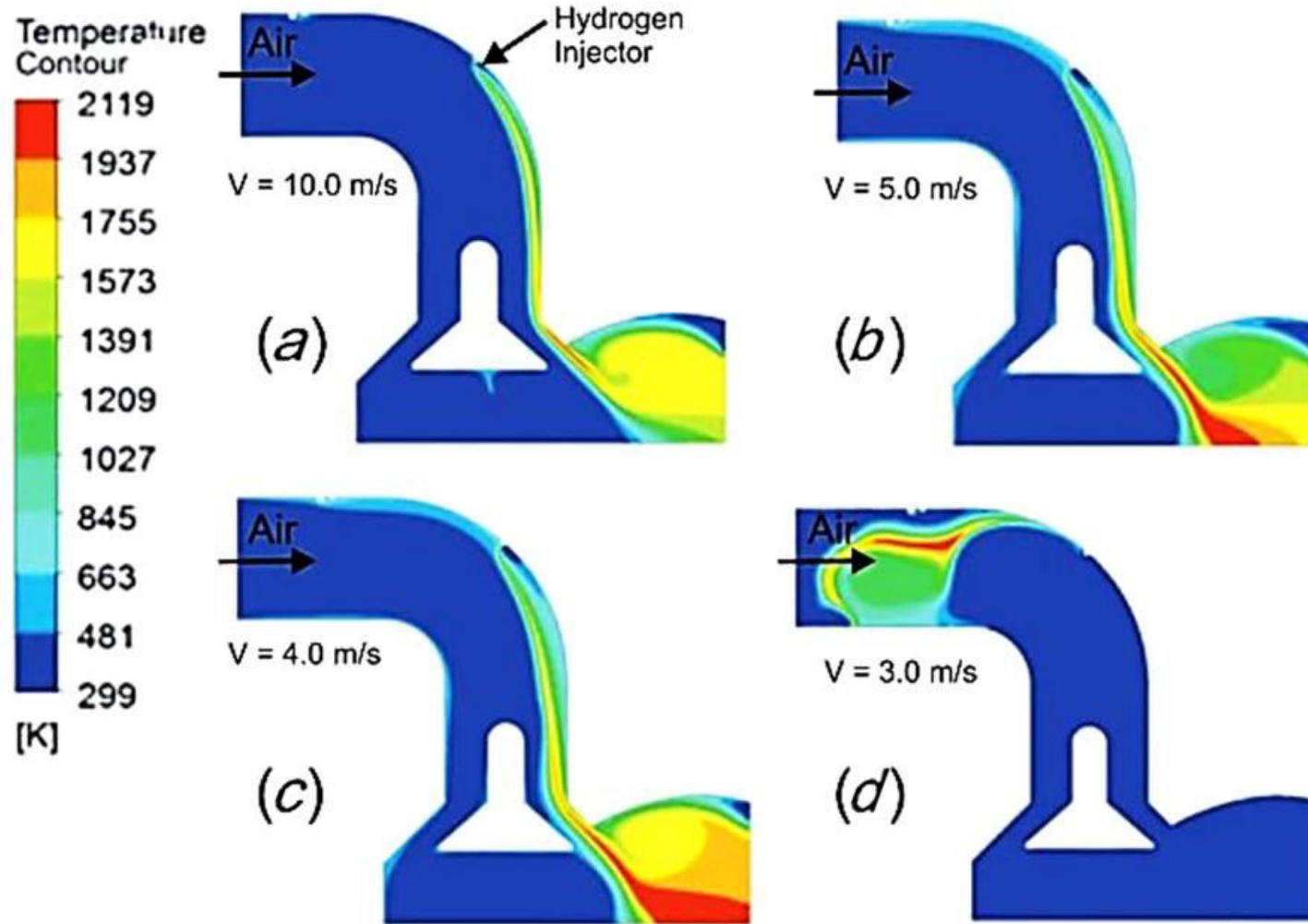


Figure: Propagation of backfire with different velocity of reactant

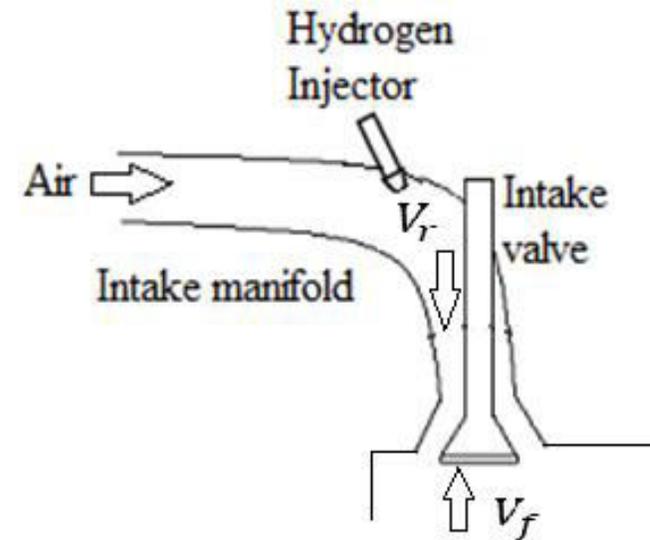
# Backfire propagation

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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- 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

