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# Hydrogen explosion in ITER: Effect of nitrogen dilution on flame propagation of $H_2/O_2/N_2$ mixtures

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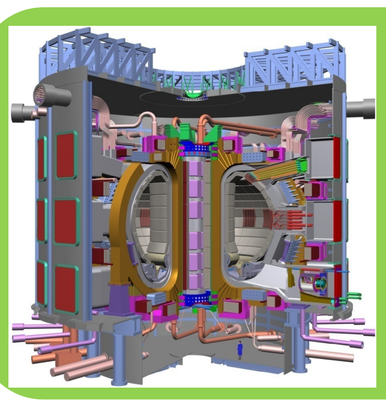
## Context



### Experimental Device: ITER

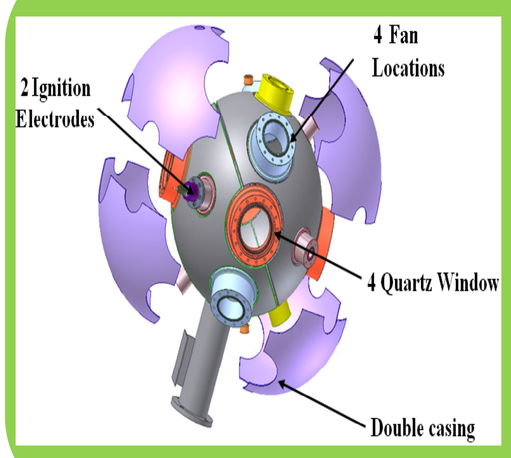
- ITER installation operating
- LOCA accident
- Water may enter in the Vacuum Vessel (VV)
- Safety procedure to evacuate the overpressure
- The water and the gases fill-in the suppression tank partially filled with cold water
- Molar Fraction in hydrogen increase in the environment
- Formation of a flammable atmosphere

RISK OF EXPLOSION

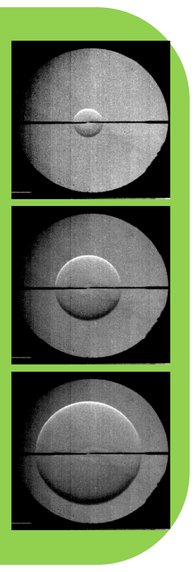
## Objectives

- Characterization of the laminar flame properties of $H_2/O_2/N_2$ flames
- Acquisition of an experimental database: $S_L°$; $L'$; $P_{max}$; $(dP/dt)_{max}$
- Validation of a detailed kinetic mechanism for $H_2/O_2/N_2$ combustion
- Determination of the activation energies of these mixtures

## Spherical Bomb




- Internal diameter = 476 mm
- Volume = 56 L
- Initial temperature ≤ 473 K
- Spherical bomb filled up by the partial pressure method
- Ignition using a high voltage discharge between two metallic electrodes
- Pressure recorded via a piezo-electric pressure transducer
- Flame observation with a schlieren optical system
- The unstretched flame speeds were deduced from the time evolution of the radius



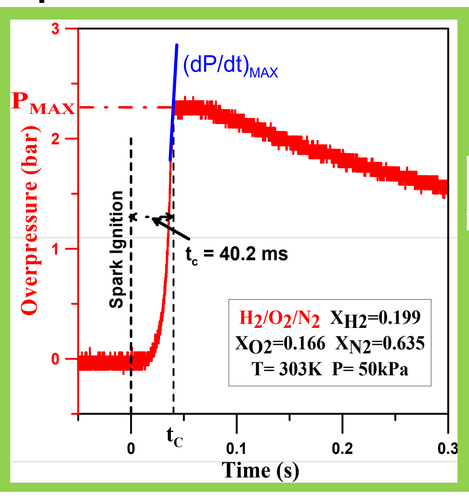
## Methodology

### Explosion parameters determination

Maximum pressure rise rate **$(dP/dt)_{MAX}$**

Maximum combustion pressure **$P_{MAX}$**

Combustion time **tc**




### Unstretched spatial velocity

$$r_f + 2L_b \ln(r_f) = V_S^0 t + cst$$

### From the spatial velocity to the laminar flame speed

*At the early stages of the flame, when the pressure is constant (dP/dt=0)*

$$S_L^0 = V_S^0 \big/ \sigma$$

## Results

### Experimental Conditions

- Molar fraction of hydrogen: 0.1 to 0.6
- $N_2/O_2$ ratio: 0.66 to 9 (0.66, 1, 1.5, 2.33, 3.76 and 9)
- Temperature: 303 and 343K
- Pressure: 50 and 100 kPa

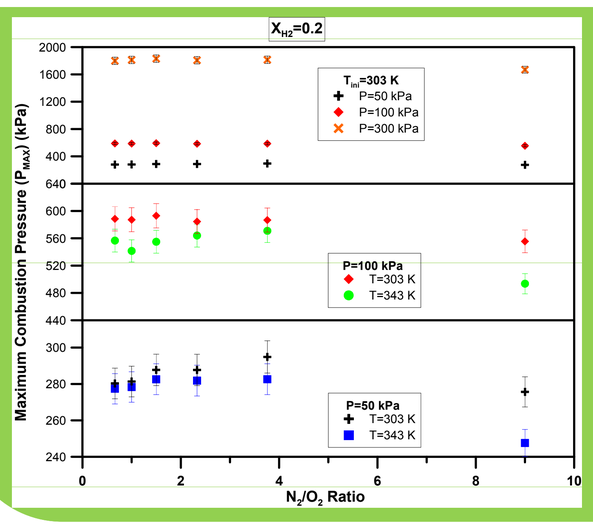
### Detailed Kinetic Models

**Wang Model[1] (USC)**
- 8 species and 28 reactions
- Excluding nitrogen species

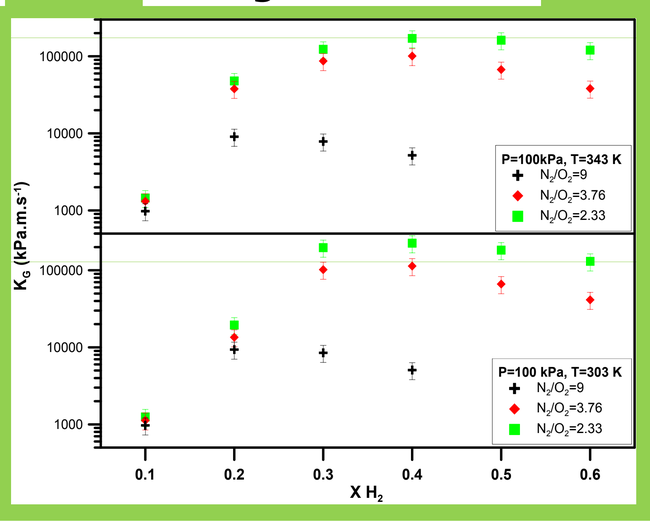
**Hong Model[2] (Stanford)**
- 10 species and 31 reactions
- Excluding nitrogen species

**Mével Model[3] (ICARE)**
- 32 species and 203 reactions
- Including nitrogen species

### Maximum Combustion Pressure




### Deflagration index

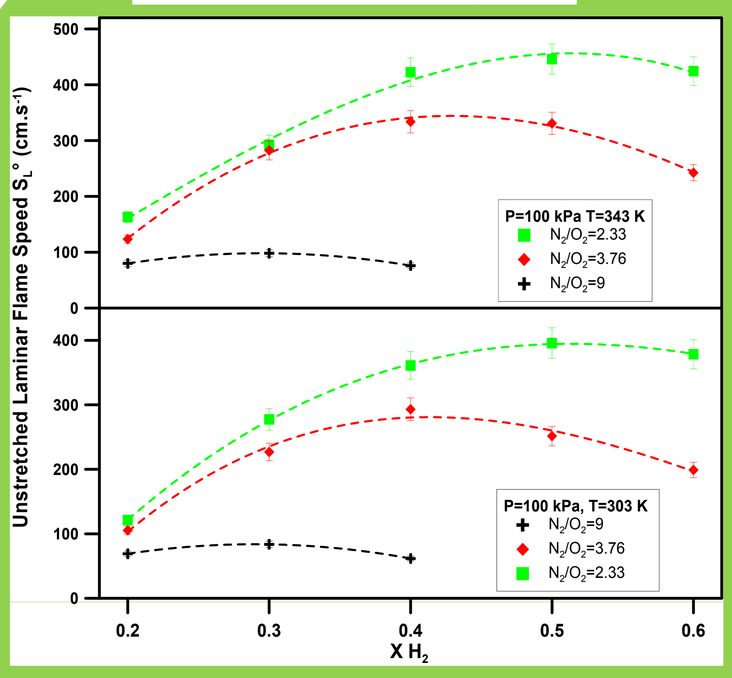


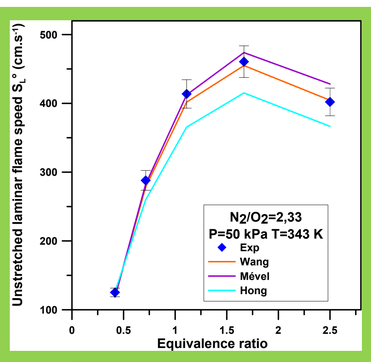

Normalization of the maximum pressure rise rate $(dP/dt)_{MAX}$

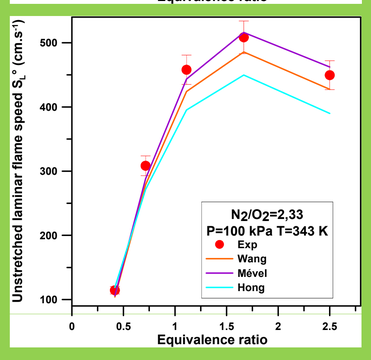
$$K_G = \left(\frac{dP}{dt}\right)_{MAX} * V^{\frac{1}{3}}$$

- Bell-shaped evolution
- Different maxima for each $N_2/O_2$ ratio
- $K_G$ increases when the $N_2/O_2$ ratio decrease

### Laminar Flame Speed




- Bell shaped evolution of the laminar flame speed as a function of the molar fraction in hydrogen
- Laminar flame speed increases with the increase of pressure and temperature

| | Wang Model | Mével Model | Hong Model |
|---|---|---|---|
| Average Error | 8.4% | 7.1% | 12.5% |

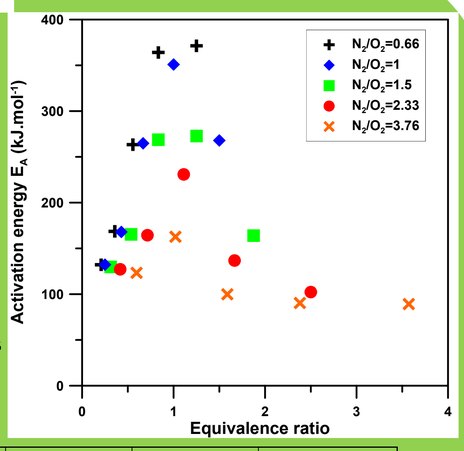
### Activation energies

Using the Mével mechanism:

Zel'dovich Analysis: $S_L^0 \approx \left[\exp\left(\frac{-E_A}{R \cdot T_B}\right)\right]^{\frac{1}{2}}$

Then: $2 \cdot Ln S_L^0 \approx LnA - \frac{E_A}{R} \cdot \frac{1}{T_B}$

$$E_A(\phi, T_{ini}, P_{ini}) = \left(a_1\phi^3 + a_2\phi^2 + a_3\phi + a_4\right)\left(\frac{P_{ini}}{P_{ref}}\right)^{a_5}\left(\frac{T_{ini}}{T_{ref}}\right)^{a_6}$$




| $N_2/O_2$ ratio | Domain of validation Φ | $a_1$ | $a_2$ | $a_3$ | $a_4$ | $a_5$ | $a_6$ |
|---|---|---|---|---|---|---|---|
| 0.66 | [0.21-1.25] | -610.3 | 1048 | -171.2 | 130.4 | 0.0 | -0.10 |
| 1 | [0.25-1.5] | -435.8 | 833.2 | -178.7 | 132.9 | -0.013 | 0.015 |
| 1.5 | [0.31-1.88] | -60.4 | -17.04 | 314.9 | 32.47 | -0.003 | 0.037 |
| 2.33 | [0.42-2.5] | 104.9 | -516.2 | 713.0 | -90.39 | 0.024 | 0.024 |
| 3.76 | [0.60-3.58] | 16.9 | -97.3 | 132.1 | 96.25 | 0.093 | -0.076 |

Zel'dovich Number: $\beta = \frac{E_a}{R \cdot T_B^2}(T_B - T_0)$

## Conclusion

- Acquisition of explosion parameters data for mixtures composed by $H_2/O_2/N_2$ for different experimental conditions
- The Mével Mechanism is the closest to the experimental results and it has been chosen for the activation energies determination

## Future Work

- Complete the activation energies study
- Study the laminar propagation and the explosion parameters of C-W-$H_2$-$O_2$-$N_2$ two-phase mixtures taking into account the temperature and pressure effects, C/W ratio and $N_2/O_2$ ratio.

**Acknowledgment**
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**References**

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[2]Hong Z et al.. (2011), Combust. Flame 158, 633-644
[3]Mével R., et al., Proceedings of the Combustion Institute 2009:32:359-366.