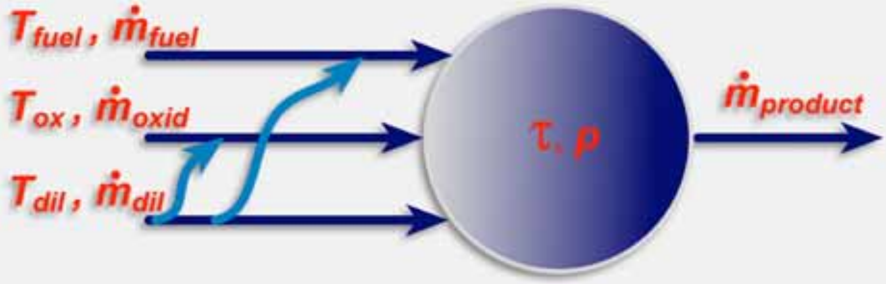
Mild Combustion

Una lezione nell'atelier di un "nuovo" processo di combustione

Antonio Cavaliere
Università Federico II
Dipartimento di Ingegneria Chimica

Mara de Joannon
C.N.R.
Istituto di Ricerche sulla Combustione
Napoli, Italy

Schema di principio del reattore



Definizioni

- **Frazione di miscelamento**

$$Z = \frac{\beta - \beta_{ox}}{\beta_{fuel} - \beta_{ox}}$$

- **Temperature**

frozen temperature	$T_{froz}(Z)$
maximum temperature	$T_{max}(Z)$
equilibrium temperature	$T_{eq}(Z)$
ignition temperature	$T_{ign}(Z)$

$$Z = \frac{\beta - \beta_2}{\beta_1 - \beta_2}$$

Frazione di miscelamento

- β *é una qualsiasi variabile "conservativa"*
- *i pedici 1 e 2 si riferiscono rispettivamente al valore di nel getto che trasporta prevalentemente il combustibile e l'ossidante*

$$Y_{(C,H)} = \sum a_{C,i} \frac{m_C}{m_i} Y_i + \sum a_{H,i} \frac{m_H}{m_i} Y_i$$ ***Frazione di massa del combustibile***

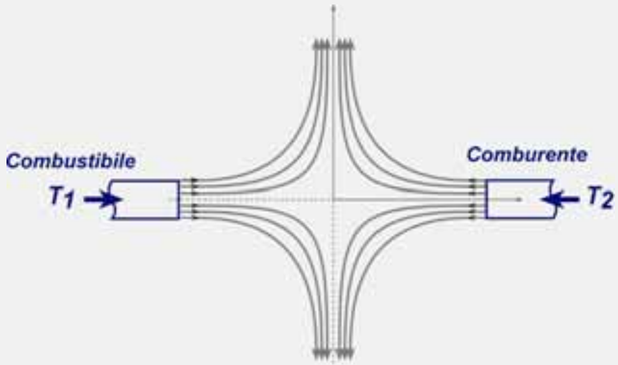
$$Y_{(O)} = \sum a_{O,i} \frac{m_O}{m_i} Y_i$$ ***Frazione di massa del comburente***

$$Z_f = \xi_f = \frac{Y_{(C,H)} - Y_{(C,H)2}}{Y_{(C,H)1} - Y_{(C,H)2}} = \frac{Y_{(C,H)}}{Y_{(C,H)1}}$$ ***Frazione di miscelamento per*** $Y_{(C,H)}$

$$Z_O = x_O = \frac{Y_{(O)} - Y_{(O)2}}{Y_{(O)1} - Y_{(O)2}} = 1 - \frac{Y_{(O)}}{Y_{(O)2}}$$ ***Frazione di miscelamento per*** $Y_{(O)}$

Risulta che:

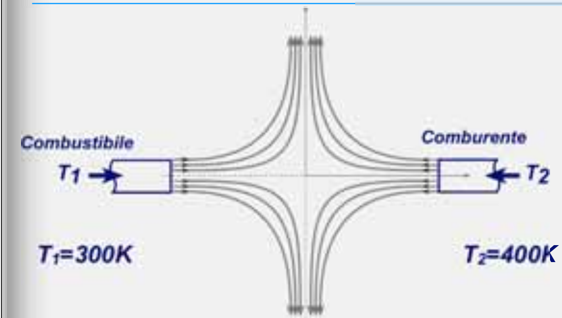
$$\frac{Y_{(C,H)}}{Y_{(C,H)_1}} = 1 - \frac{Y_{(O)}}{Y_{(O)_2}}$$



$$Z_{st} = \xi_{st} = \left(1 + \nu_s \frac{Y_{(C,H)_1}}{Y_{(O)_2}}\right)^{-1}$$

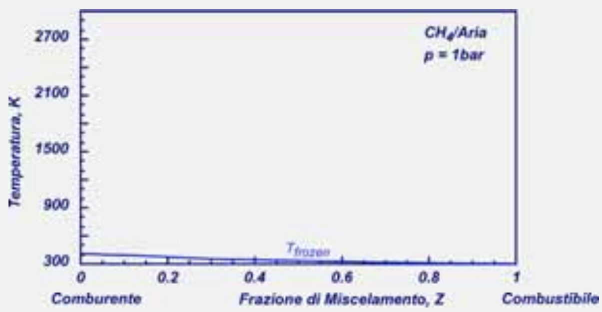
Frazione di miscelamento in corrispondenza del rapporto stechiometrico ν_s

Definizione di T_{frozen}



T_1=300K ***T_2=400K***

$$T_{frozen} = \frac{\bar{c}_p\big|_2}{\bar{c}_p\big|_{mix}} Y_{ox}\big|_2 (1-Z)\,T_2 + \frac{\bar{c}_p\big|_1}{\bar{c}_p\big|_{mix}} Y_f\big|_1 Z\,T_1$$



T_2=400K ***T_1=300K***

Definizione di T_{max}

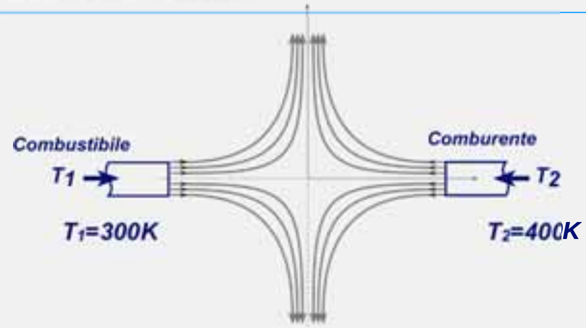
$Z \le Z_s$

$$T_{\max} = T_{frozen} + \frac{Y_f\big|_1}{\bar{c}_p\big|_{mix}} Z\,Q$$

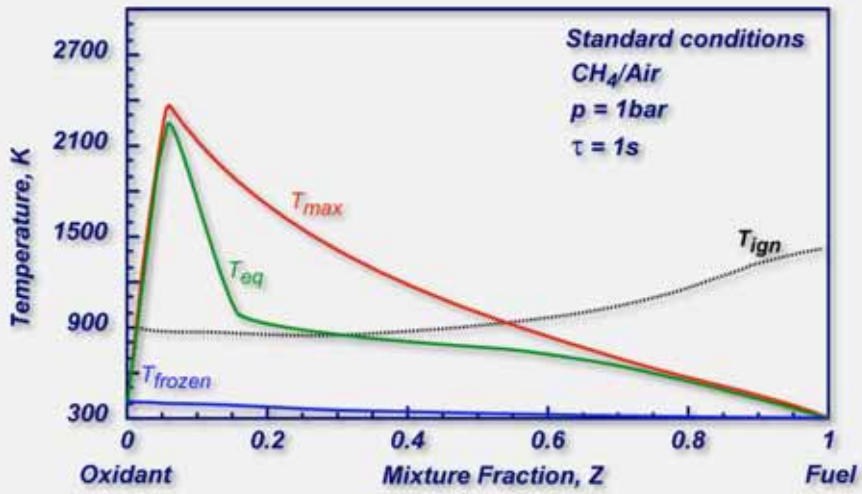
$Z > Z_s$

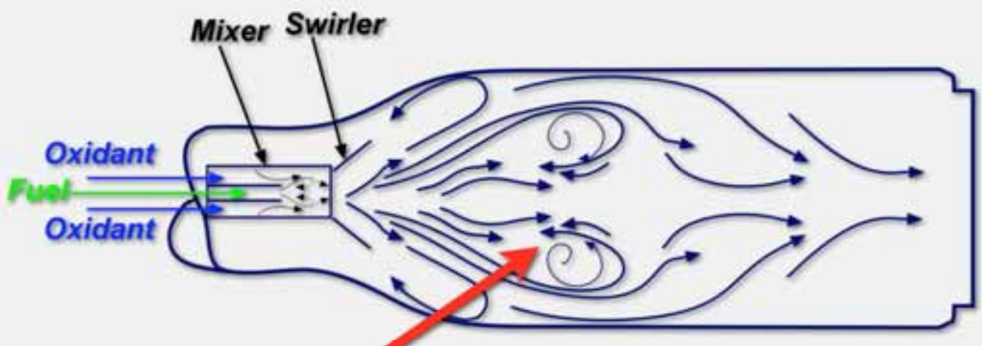
$$T_{\max} = T_{forzen} + \frac{Y_{ox}\big|_2}{\bar{c}_p\big|_{mix}\nu_{stec}}(1-Z)\,Q$$

dove Q è il calore di combustione

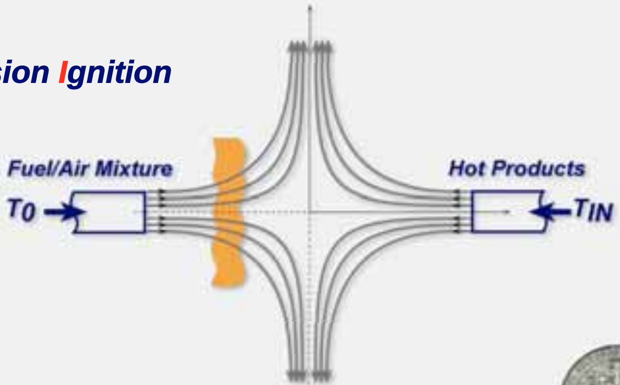


Per ogni valore di Z è la temperatura corrispondente al massimo livello di ossidazione (completa conversione del reagente limitante e formazione di CO_2 e H_2O)

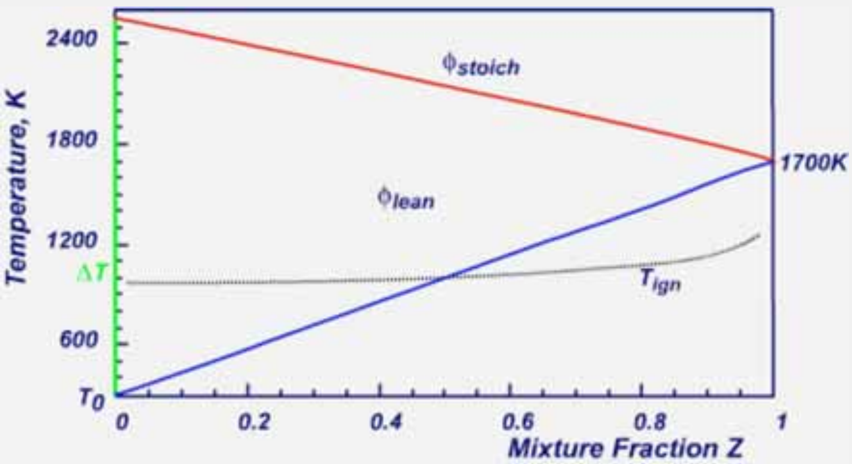




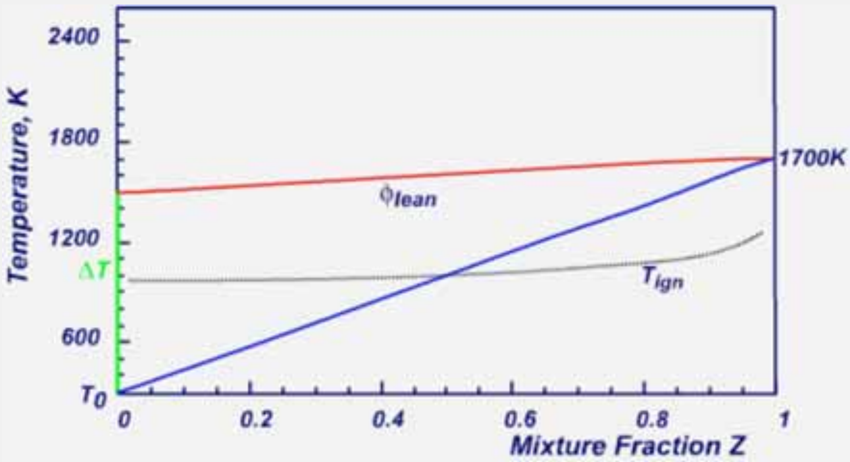
***H**omogeneous **C**harge **D**iffusion **I**gnition*
HCDI



HCDI



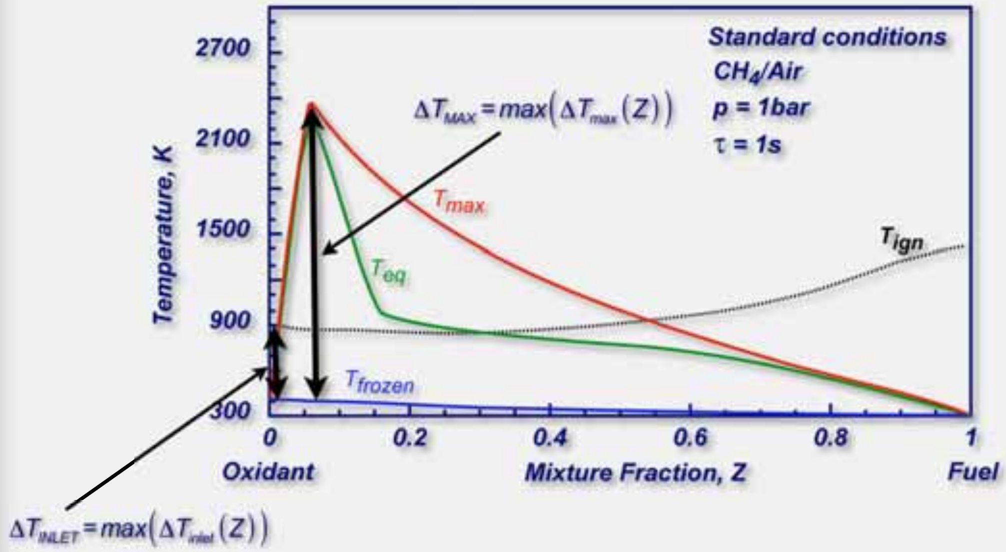
HCDI



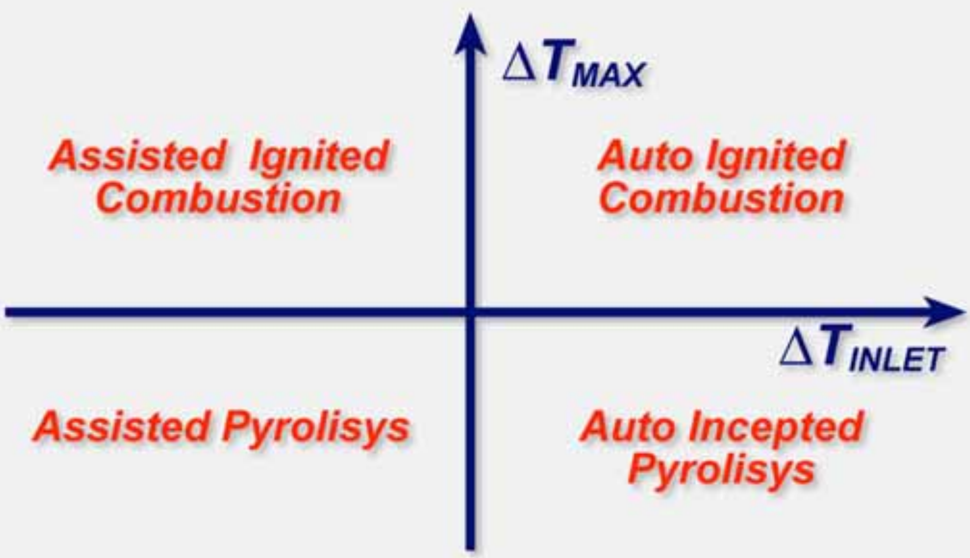
Definition of Temperature Differences

$$\Delta T_{max}(Z) = T_{max}(Z) - T_{froz}(Z)$$
$$\Delta T_{inlet}(Z) = T_{froz}(Z) - T_{ign}(Z)$$

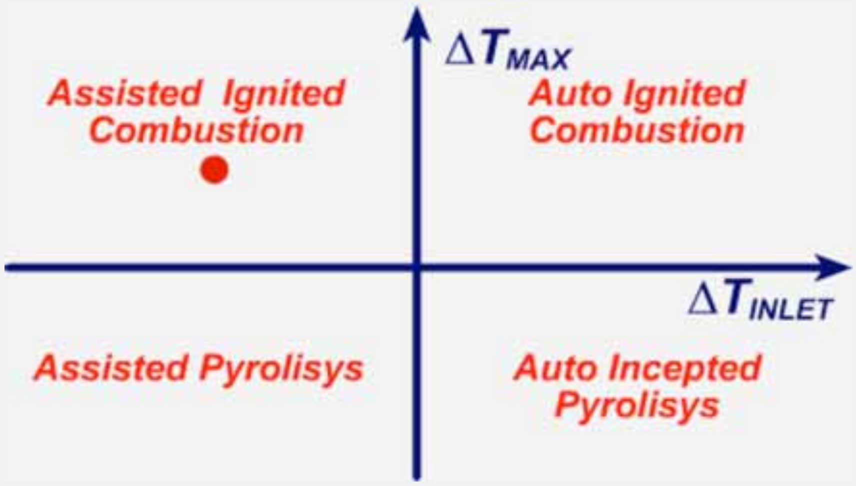
$$\Delta T_{MAX} = max\left(\Delta T_{max}(Z)\right)$$
$$\Delta T_{INLET} = max\left(\Delta T_{inlet}(Z)\right)$$

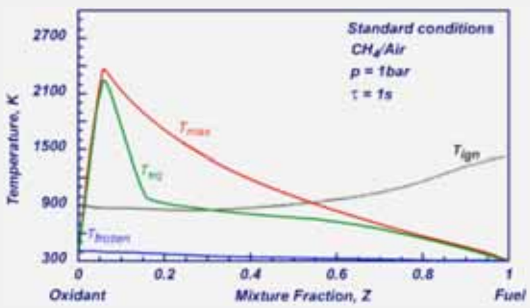


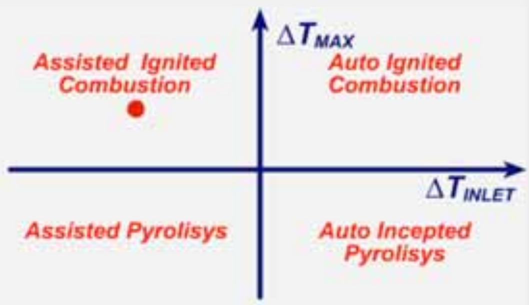
Regimes of Combustion

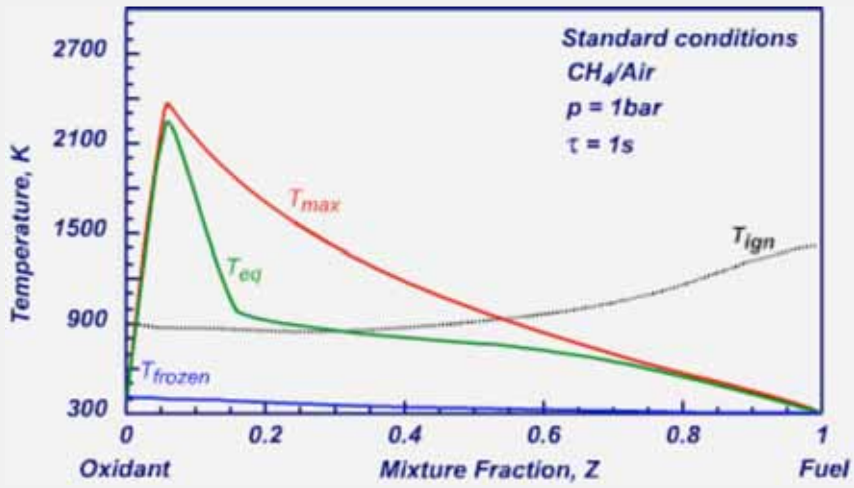


Regimes of Combustion

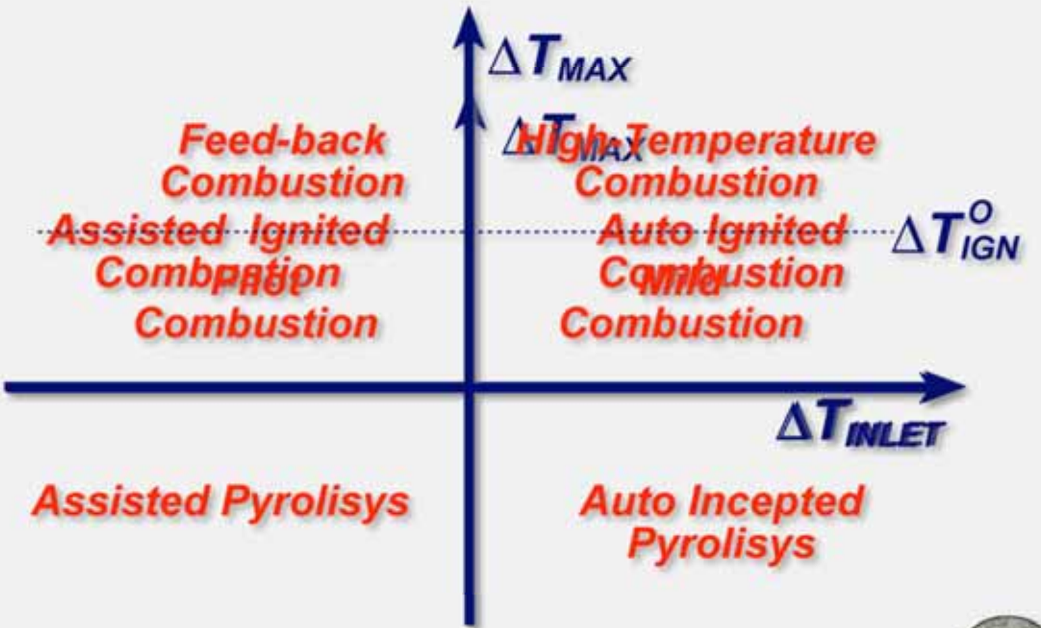








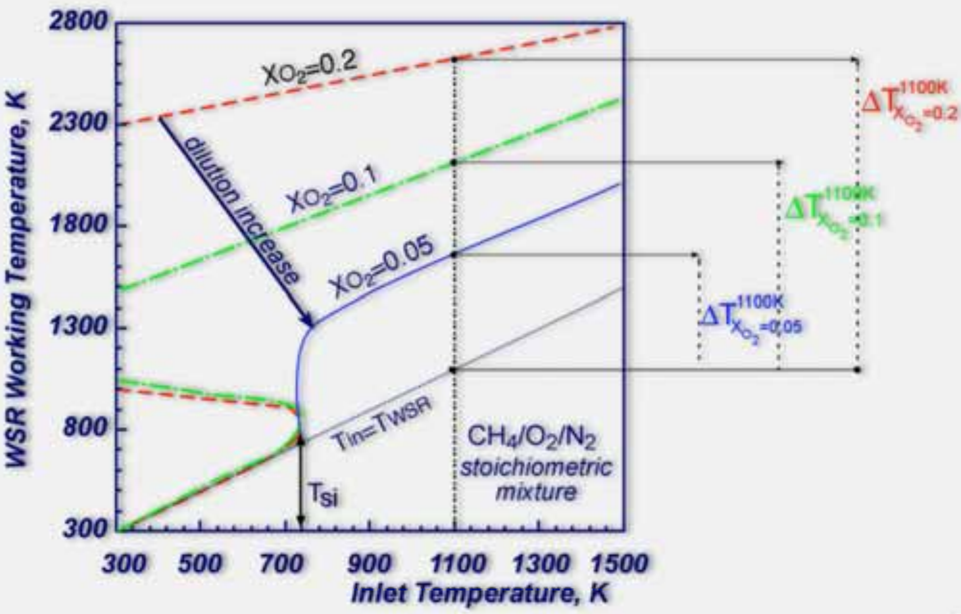
Regimes of Combustion



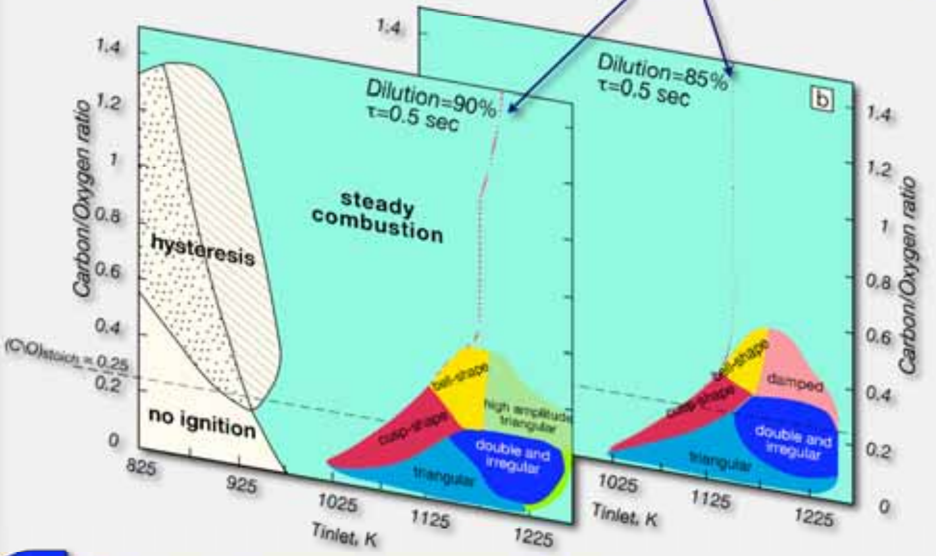
Combustion Taxonomy

	Assisted	MILD
a) well stirred	well stirred combustion	Homogeneous Burnt Backmixing Ignition HBBI
b) batch		Homogeneous Charge Compression Ignition HCCI
c) opposed flow	diffusion flame	Hot Diluted Diffusion Ignition HDDI
		Homogeneous Charge Diffusion Ignition HCDI
d) plug	deflagration/ detonation	Homogeneous Flow Flowing Ignition HFFI

Working Temperature in WSR



Methane Oxidation in JSFR



$CH_4/O_2/N_2$ **mixture**

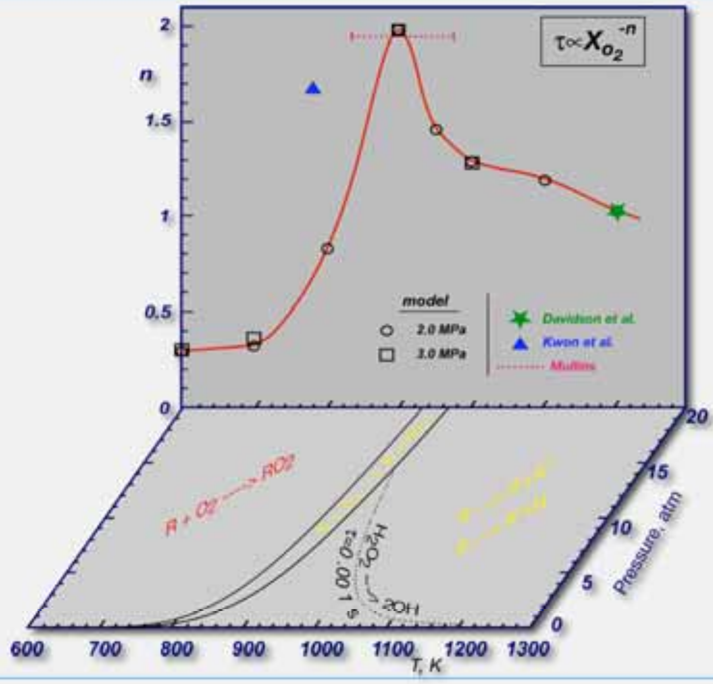
residence time
τ = 0.5 sec

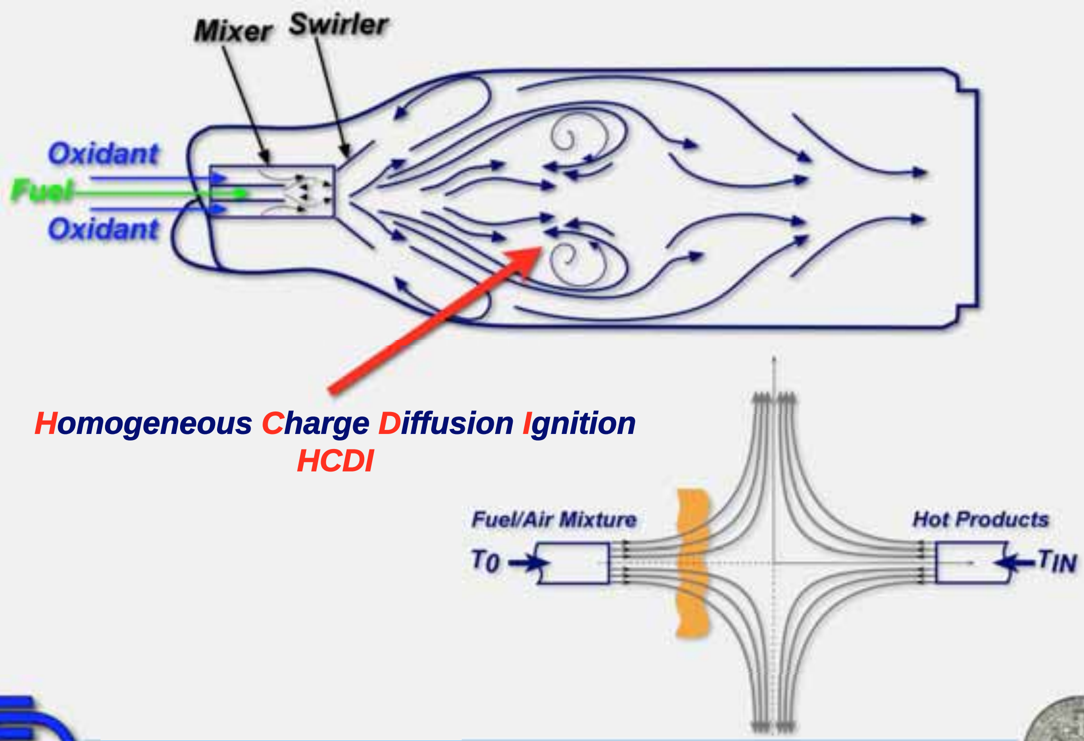
90% dilution

Jet Stirred
Flow Reactor

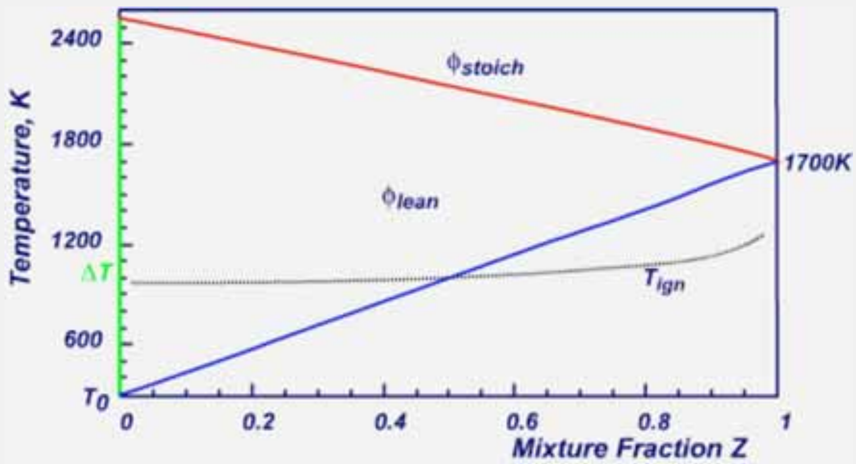
(de Joannon et al., Proceedings of ther Combustion Institute, vol. 30, in Press)

Ignition Reaction Order

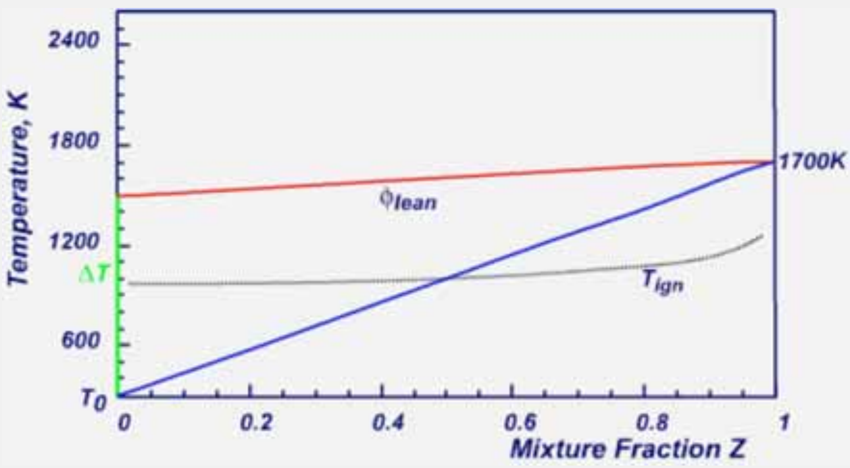



Mixer
Swirler
Oxidant
Fuel
Oxidant
Homogeneous Charge Diffusion Ignition
HCDI
Fuel/Air Mixture
T0
Hot Products
TIN

HCDI


2400
1800
1200
600
ΔT
T0
Temperature, K
φstoich
φlean
1700K
Tign
0
0.2
0.4
0.6
0.8
1
Mixture Fraction Z

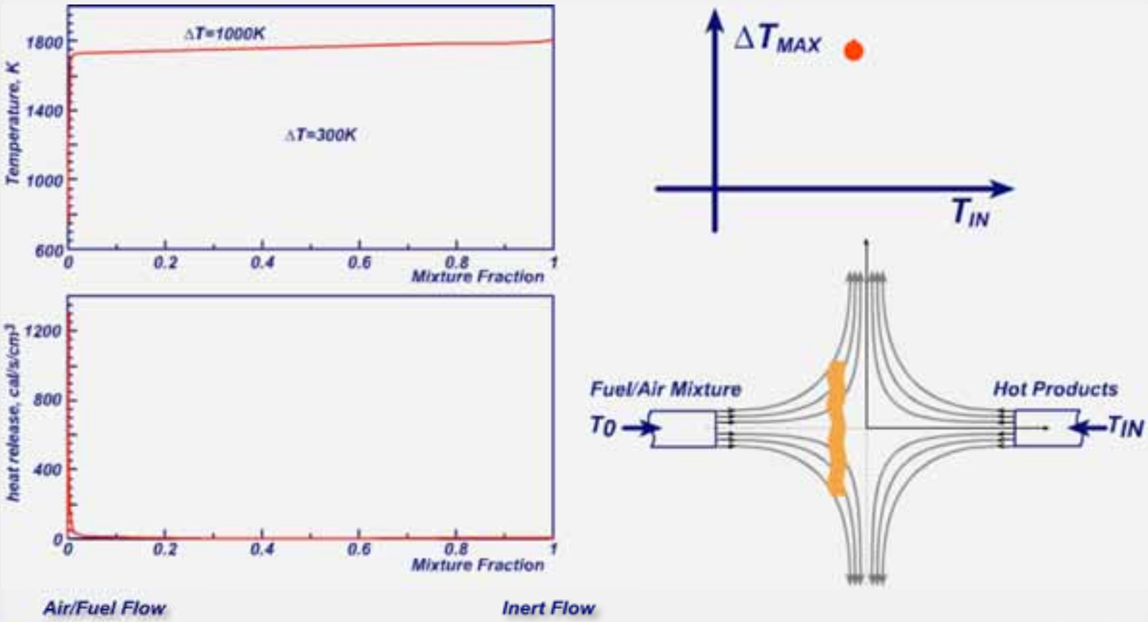
HCDI



HCDI

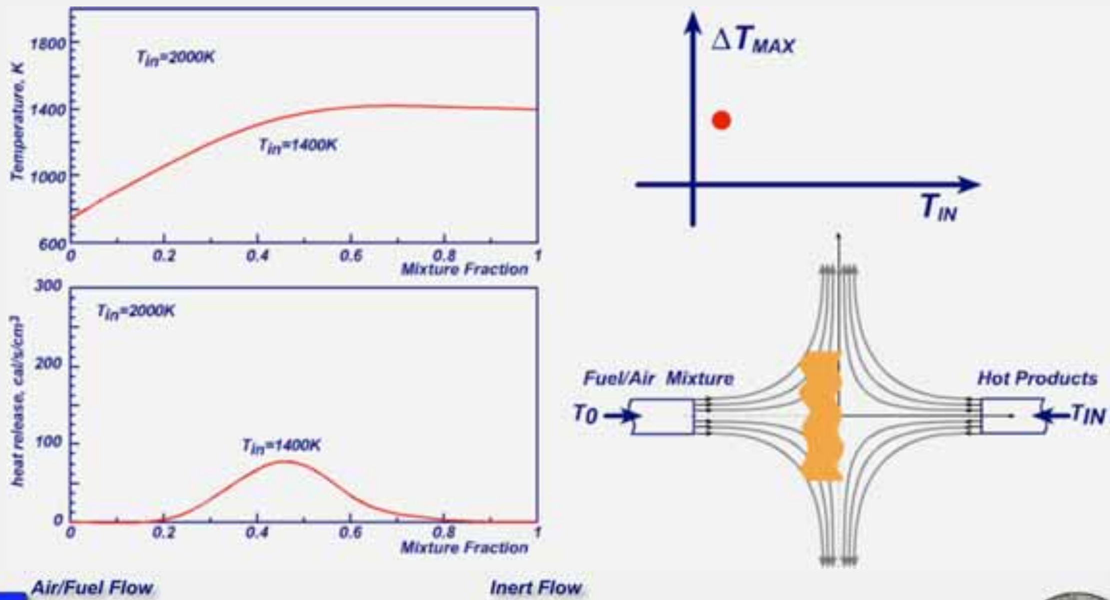
- $CH_4/O_2/N_2$
- GRI mechanism
- OPPDIF configuration of CHEMKIN package
- p = 5 atm
- k = 125 cm/s

HCDI



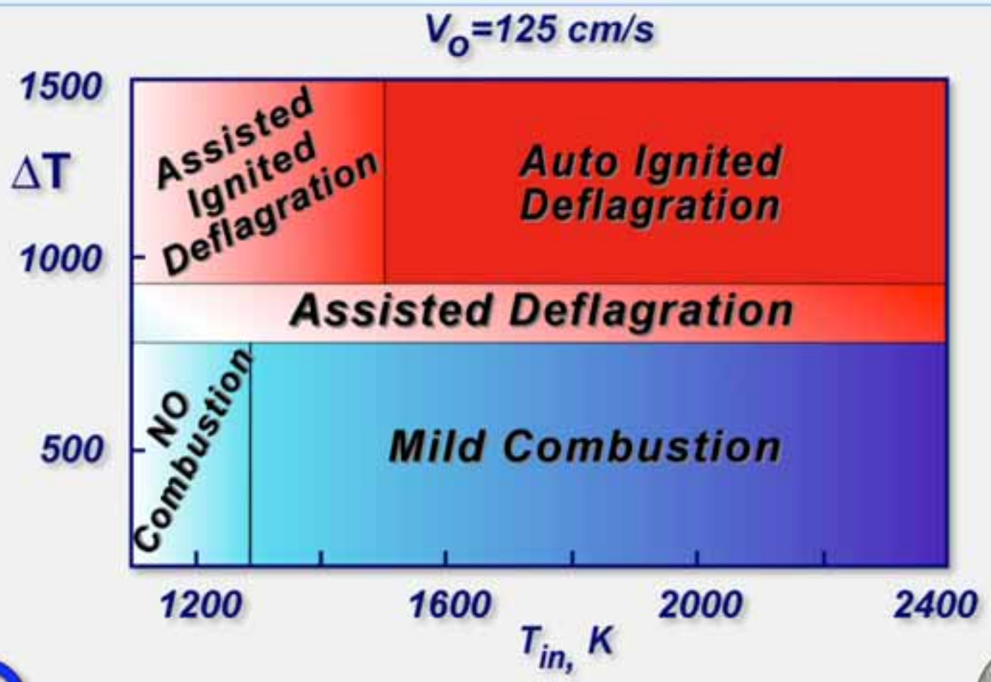
ΔT=1000K
ΔT=300K
Temperature, K
Mixture Fraction
heat release, cal/s/cm³
Mixture Fraction
ΔT_MAX
T_IN
Fuel/Air Mixture
Hot Products
T0
TIN
Air/Fuel Flow
Inert Flow

HCDI



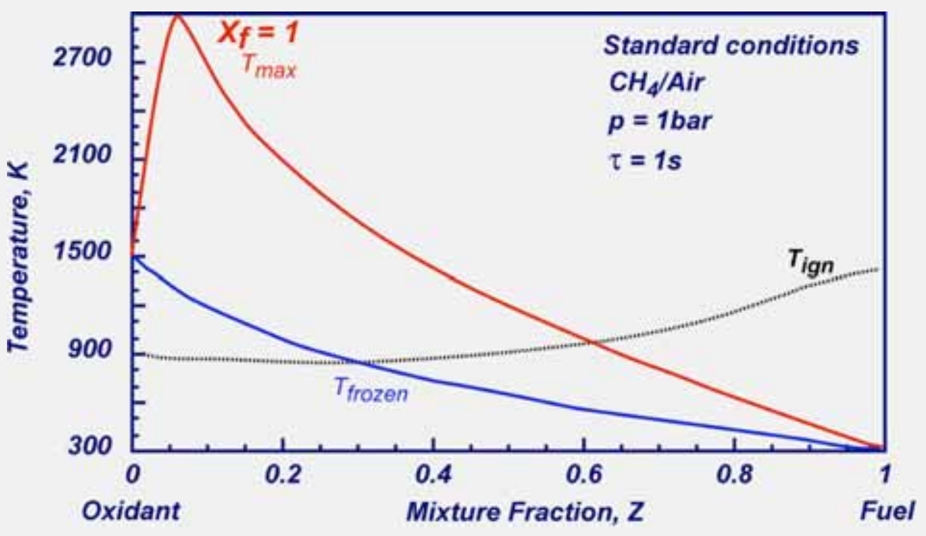
Tin=2000K
Tin=1400K
Temperature, K
Mixture Fraction
Tin=2000K
Tin=1400K
heat release, cal/s/cm³
Mixture Fraction
ΔT_MAX
T_IN
Fuel/Air Mixture
Hot Products
T0
TIN
Air/Fuel Flow
Inert Flow

HCDI



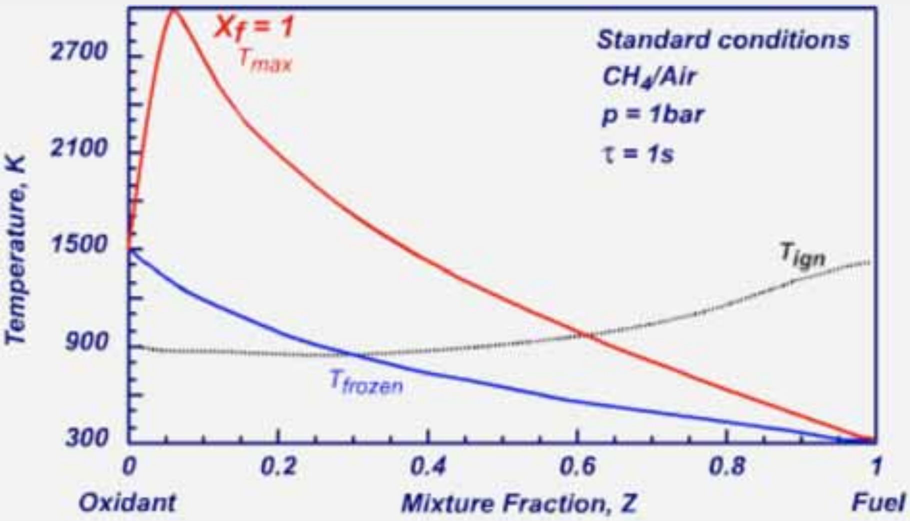
Vo=125 cm/s
1500
ΔT
1000
500
Assisted Ignited Deflagration
Auto Ignited Deflagration
Assisted Deflagration
NO Combustion
Mild Combustion
1200
1600
2000
2400
Tin, K

HDDI



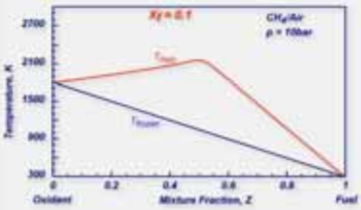
Xf = 1
Tmax
Standard conditions
CH4/Air
p = 1bar
τ = 1s
Tign
Tfrozen
Temperature, K
2700
2100
1500
900
300
0
0.2
0.4
0.6
0.8
1
Oxidant
Mixture Fraction, Z
Fuel

HDDI

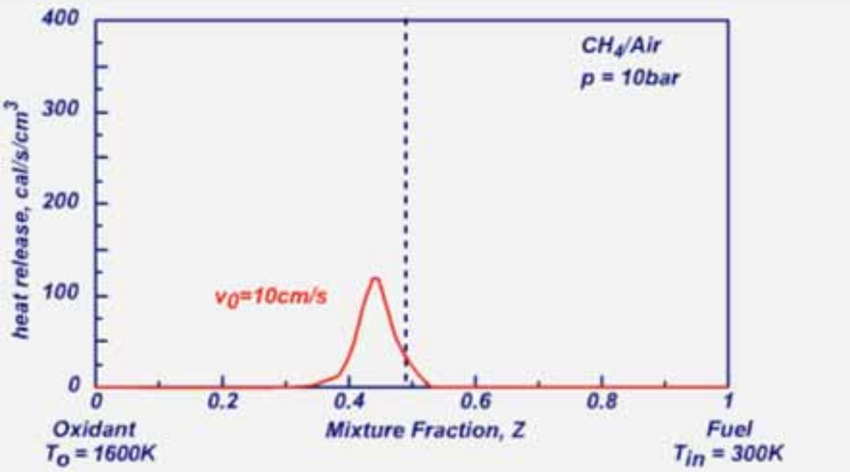


$X_f = 1$
T_{max}
Standard conditions
CH_4/Air
p = 1bar
τ = 1s
T_{ign}
T_{frozen}
Temperature, K
2700
2100
1500
900
300
0
0.2
0.4
0.6
0.8
1
Oxidant
Mixture Fraction, Z
Fuel

HDDI

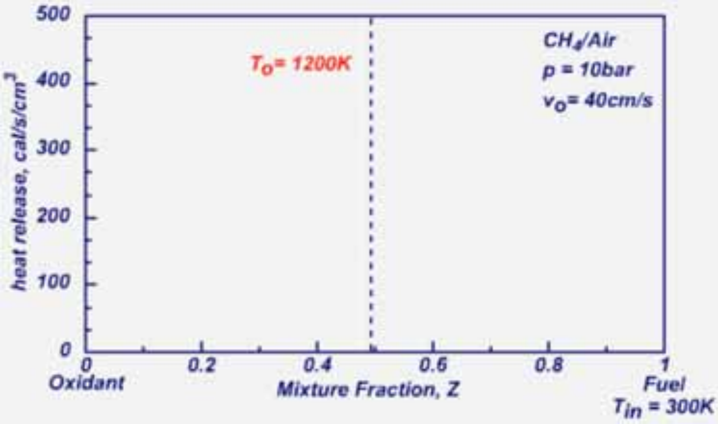


CH_4/Air
p = 10bar
Temperature, K
2700
2100
1500
900
300
Oxidant
Mixture Fraction, Z
Fuel

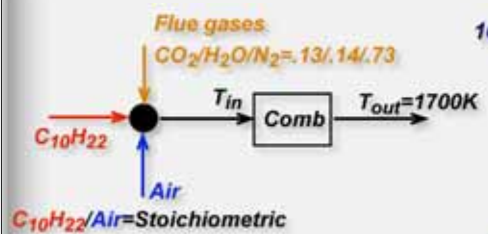


CH_4/Air
p = 10bar
v_0=10cm/s
heat release, cal/s/cm^3
400
300
200
100
0
0
0.2
0.4
0.6
0.8
1
Oxidant
T_o = 1600K
Mixture Fraction, Z
Fuel
T_{in} = 300K

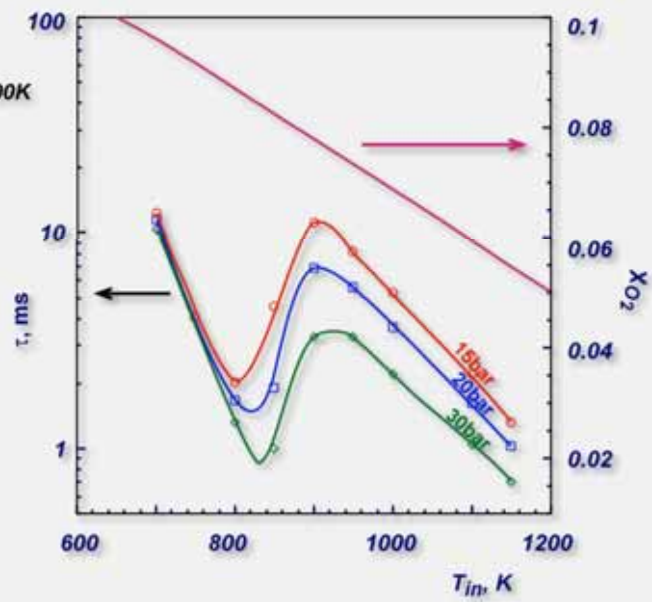
HDDI



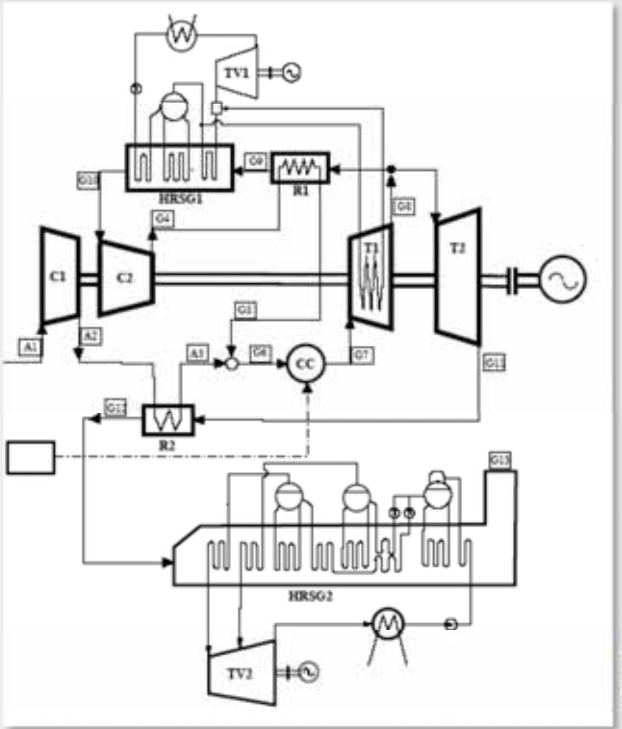
500
400
300
200
100
0
heat release, cal/s/cm^3
0
0.2
0.4
0.6
0.8
1
Oxidant
Mixture Fraction, Z
Fuel
T_{in} = 300K
T_O= 1200K
CH_4/Air
p = 10bar
v_O= 40cm/s



Flue gases
$CO_2/H_2O/N_2$=.13/.14/.73
$C_{10}H_{22}$
T_{in}
Comb
T_{out}=1700K
Air
$C_{10}H_{22}$/Air=Stoichiometric



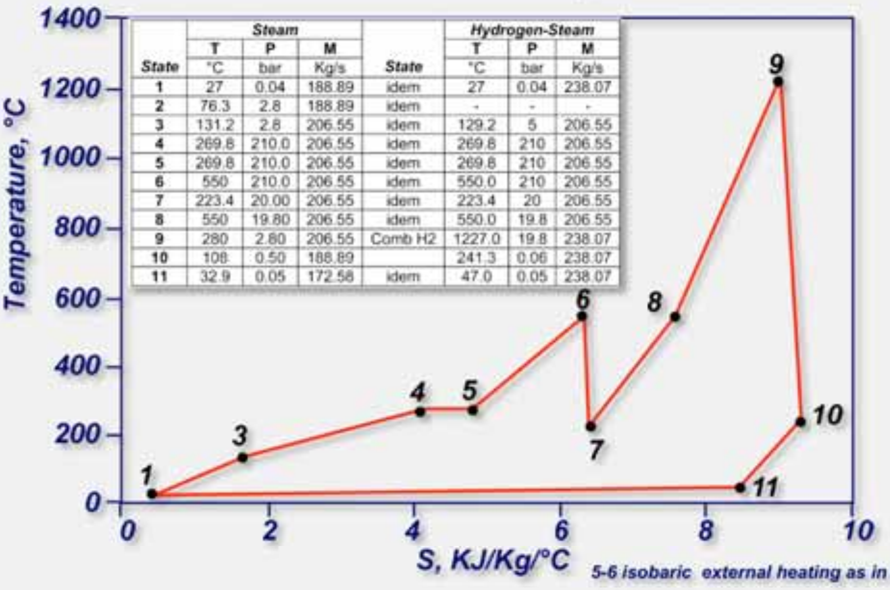
100
10
1
τ, ms
0.1
0.08
0.06
0.04
0.02
X_{O_2}
15bar
20bar
30bar
600
800
1000
1200
T_{in}, K



A1,A2,A3	regeneratively preheated compressed air
G4,G5	regeneratively preheated compressed exhausted flue gas
G6	diluted high temperature air
G7-G10	high pressure flue gas (turbine, recuperative heat exchanger R1, heat recovery steam generator HRSG1)
G11,G13	low pressure flue gas (turbine, recuperative heat exchanger R2, heat recovery steam generator HRSG2)

After Camporeale S. M., Casalini F., Saponaro A: "Semi-closed CCGT with High Temperature Reactants Combustion" Proceedings of 7th Biennial Conference on Engineering Systems Design and Analysis, ESDA2004-58472, 2004

Hirn Cycle



State	Steam T	Steam P	Steam M	State	Hydrogen-Steam T	Hydrogen-Steam P	Hydrogen-Steam M
	°C	bar	Kg/s		°C	bar	Kg/s
1	27	0.04	188.89	idem	27	0.04	238.07
2	76.3	2.8	188.89	idem	-	-	-
3	131.2	2.8	206.55	idem	129.2	5	206.55
4	269.8	210.0	206.55	idem	269.8	210	206.55
5	269.8	210.0	206.55	idem	269.8	210	206.55
6	550	210.0	206.55	idem	550.0	210	206.55
7	223.4	20.00	206.55	idem	223.4	20	206.55
8	550	19.80	206.55	idem	550.0	19.8	206.55
9	280	2.80	206.55	Comb H2	1227.0	19.8	238.07
10	108	0.50	188.89		241.3	0.06	238.07
11	32.9	0.05	172.58	idem	47.0	0.05	238.07

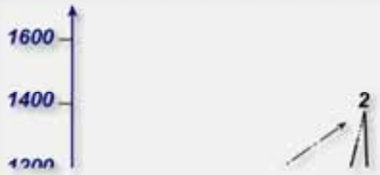
5-6 isobaric external heating as in Rankine cycle

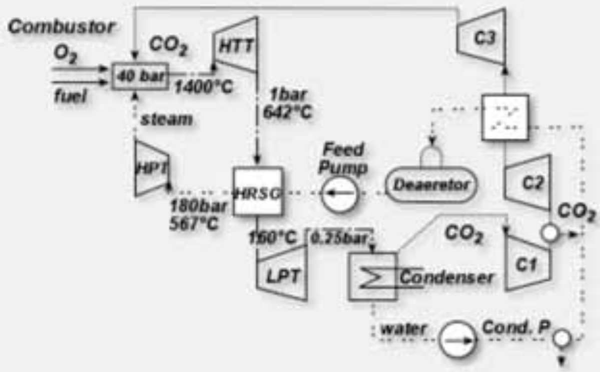
7-8 isobaric external heating as in Rankine cycle

8-9 isobaric internal heating with hydrogen combustion

Saponaro et al, Proceeding of ASME Turbo Expo, 2003

Graz Cycle

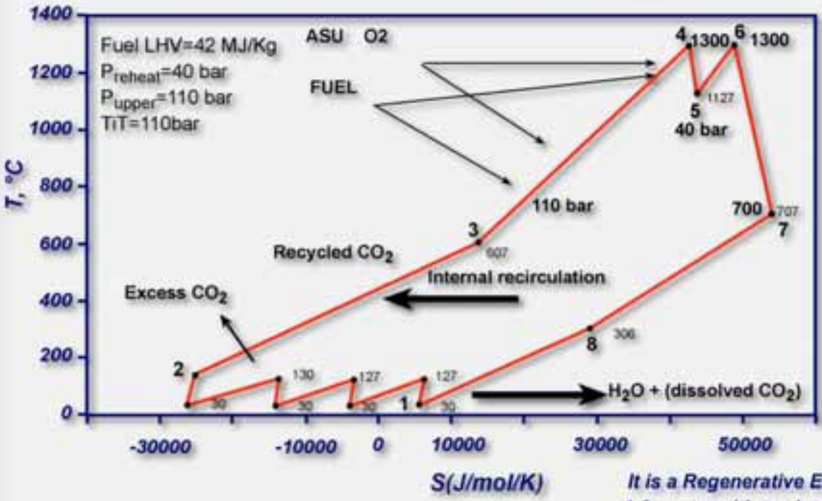




After Heitmeir F., Jerticha H.: Graz Cycle- An optimized Power plant concept for CO2 retention., First International Conference on Industrial Gas turbine Technologies Brussels 10-11 July 2003

1-2	Oxy-fuel combustion at 40 bar, inside a mixture of steam and carbon dioxide.
2-3, 3-4, 4-5	Expansion, cooling and expansion again of steam and carbon dioxide, takes
5-6	Condensation and Separation of water from Carbon dioxide
6-9-10	H_2O cycle,
7-8	Intercoled CO2 compression for partial recycling and sequestration.

MATIANT Cycles

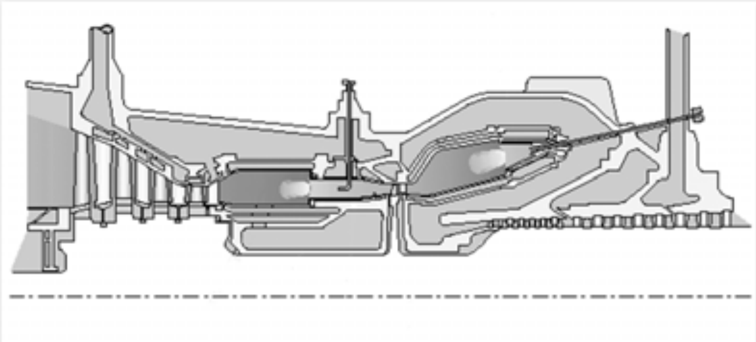


After Mathieu P., Nihart R.." Zero emission MAITIANT cycle", ASME Journal of Engineering for Gasturbine and Power, 116-120,1999.

It is a Regenerative Ericsson type CO_2 cycle

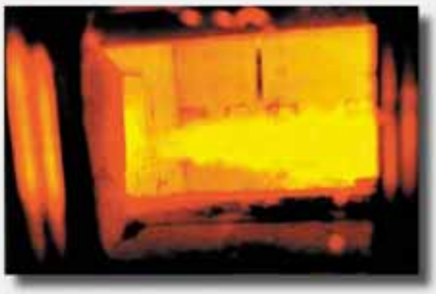
1-2	multistep intercooled compression in the branch
2-3	regenerative heating up to the temperature of 900 K
3-4,5-6	oxyfuel combustion at 110 bar and 40 bar
6-7	expansion in turbine
7-8	cooling in a regenerative heat exchanger
8-9	cooling and separation system

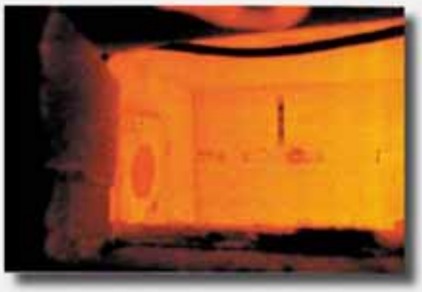
Sequential Combustion



Flameless

1.5MWth

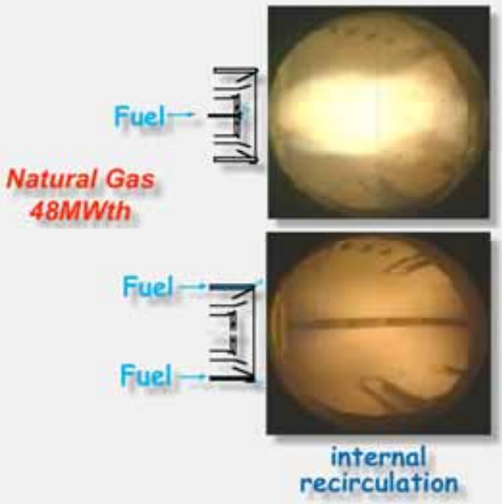




Stazione Sperimentale CSM

Noiseless

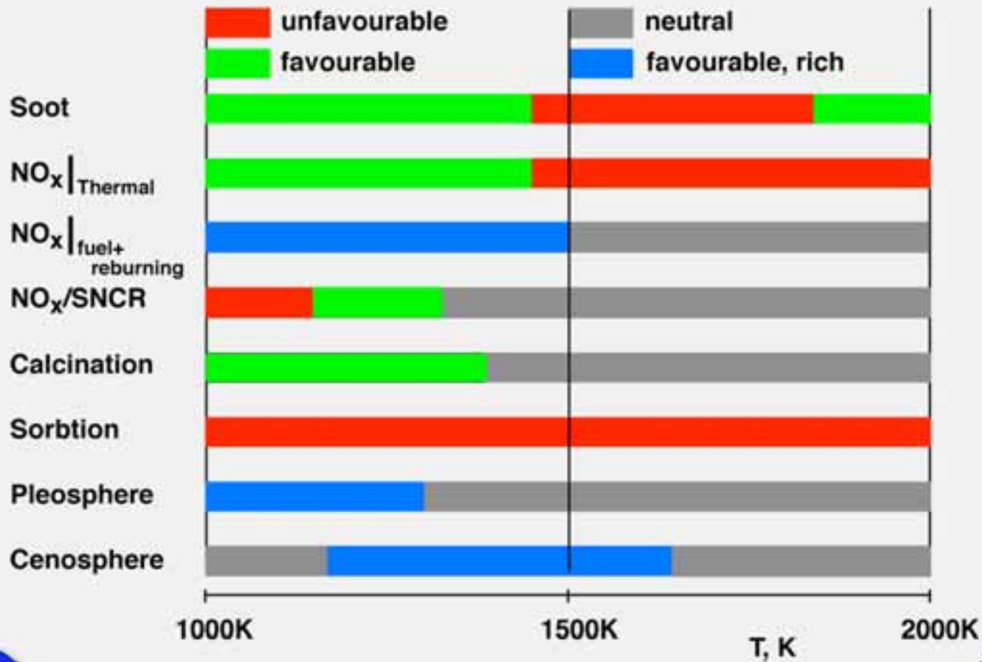
- *Furnaces and boilers*



➡ *Ideal for material treatment*

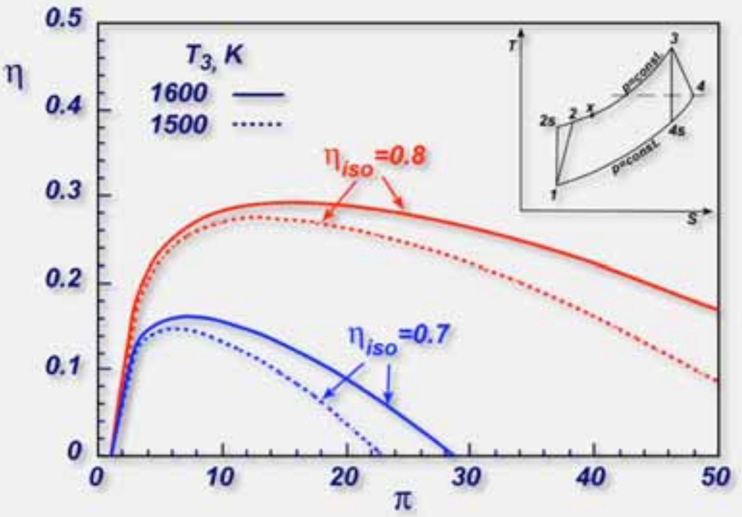
➡ *Suitable for flue gas treatment*

Emissionless



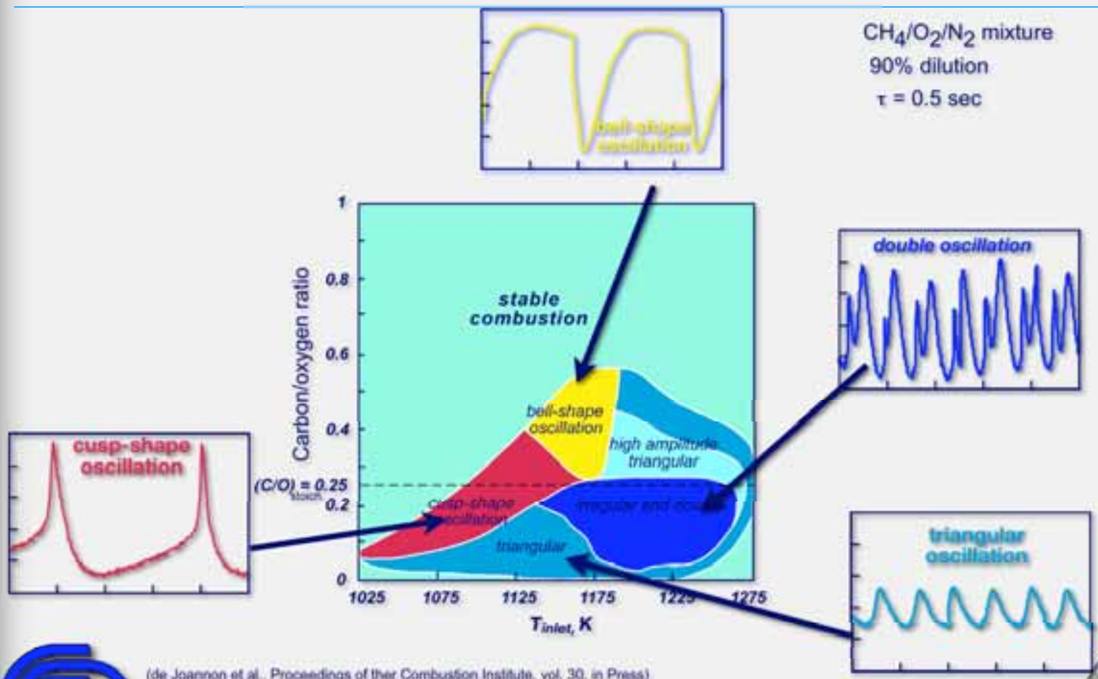
Conclusions

- *A combustion process different from explosion, deflagration, detonation exists*
- *It needs a name. Mild Combustion seems to be appropriate*
- *Homogeneous Charge Diffusion Ignition (HCDI) and Homogeneous Diluted Diffusion Ignition (HDDI) are the most interesting Mild Combustion Processes*
- *Rankine, Brayton, Hirn cycles can be combined in different ways so that Mild Combustion conditions are created in the combustion process*



Temperature Oscillation Typologies

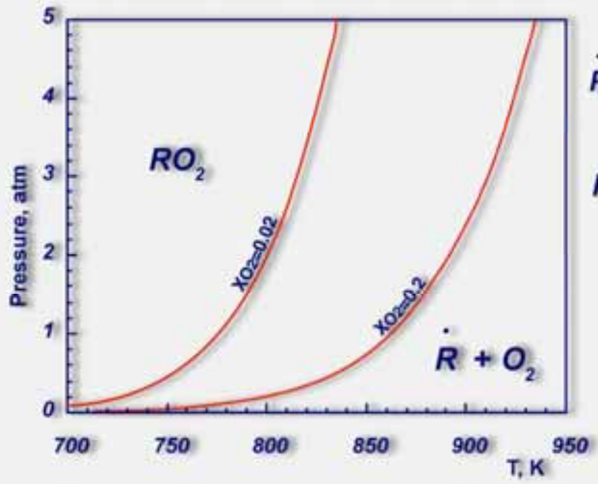
$CH_4/O_2/N_2$ mixture
90% dilution
τ = 0.5 sec



(de Joannon et al., Proceedings of ther Combustion Institute, vol. 30, in Press)

Chemistry

- ***Ceiling temperature***

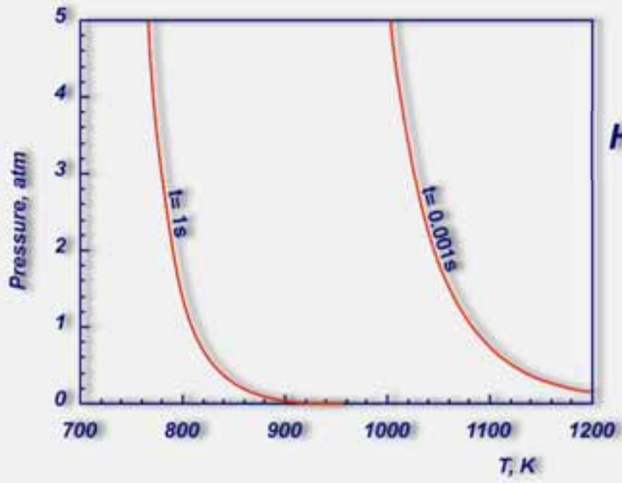


$$\dot{R} + O_2 \Leftrightarrow RO_2$$

$$K_c = \frac{[RO_2]}{[\dot{R}][O_2]}$$

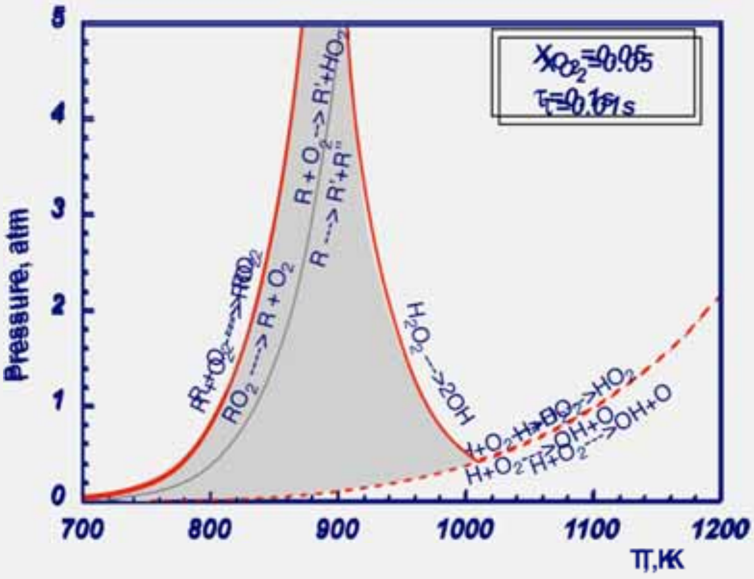
$$\frac{[RO_2]}{[\dot{R}]} = 1$$

Chemistry

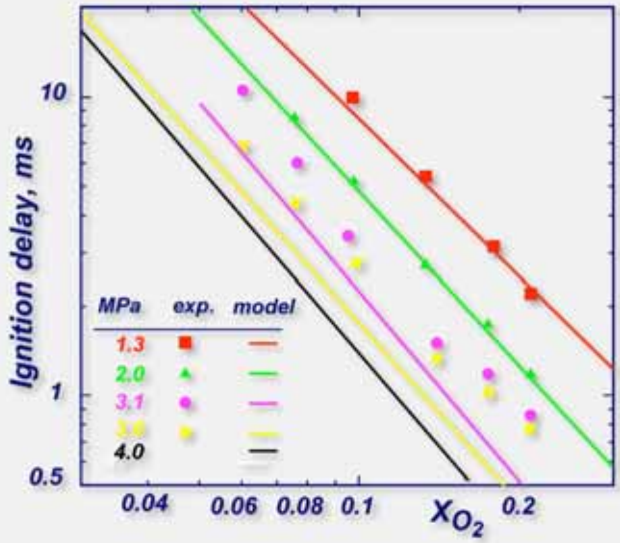


$H_2O_2 \Rightarrow 2\,OH$

Reactivity Plot

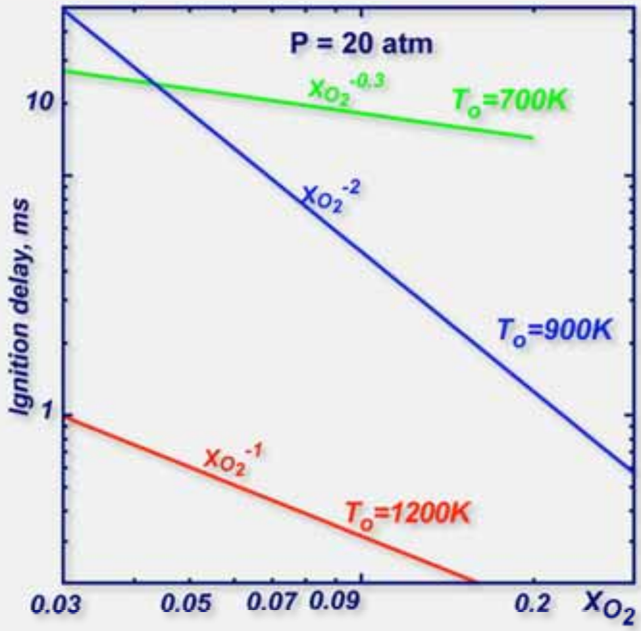


Autoignition Delay versus X_{O2}



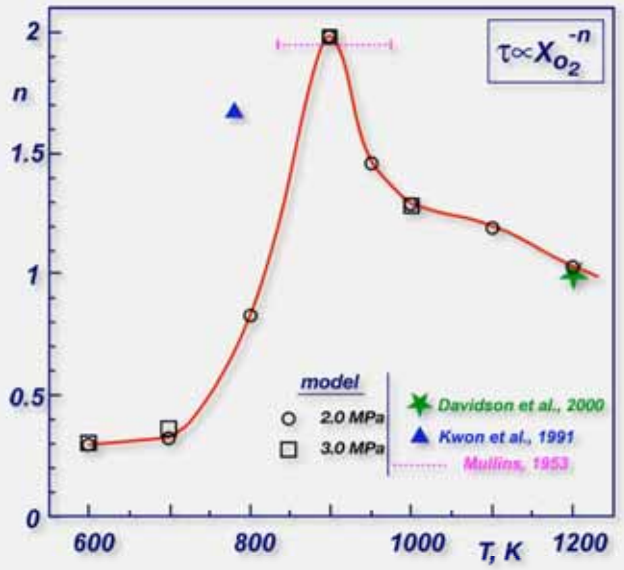
(de Joannon et al., Proceedings of ther Combustion Institute, vol. 29)

Ignition Reaction Order



(de Joannon et al., Proceedings of ther Combustion Institute, vol. 29)

Ignition Reaction Order



(de Joannon et al., Proceedings of ther Combustion Institute, vol. 29)