Modellierung der turbulenten Verbrennung für Wasserstoff-Antriebe

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1. Introduction – the turbulent combustion problem
2. Modeling of premixed turbulent flames
3. Validation of premixed combustion model (methane)
4. Modeling of non-premixed turbulent flames
5. Validation of non-premixed flame model (hydrogen)
6. Real gas effects – rocket motors
7. Conclusions

Overview

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Tab. 8.1. Mechanismus für die Beschreibung der Verbrennung von H_2, CO und Kohlenwasserstoffen bis herauf zum Propan (C_3H_8) bei nicht zu fetten Bedingungen (Warnatz 1983). Die Zahlen sind präexponentieller Faktor *A* (cm, mol, s), Temperaturexponent *b* (dimensionslos) und Aktivierungsenergie *E* (kJ/mol). Gleichheitszeichen kennzeichnen reversible Reaktionen, Pfeile nur Hinreaktionen.

Reaktion	A(cm,mol,s)	b	E(kJ/mol)	Nr.
1. H_2-O_2 Mechanismus				
1.1 Kettenreaktionen				
$O_2 + H = OH + O$	2.20E+14	0.00	70.3	(1, 2)
$H_2 + O = OH + H$	5.06E+04	2.67	26.3	(3, 4)
$H_2 + OH = H_2O + H$	1.00E+08	1.60	13.8	(5, 6)
$OH + OH = H_2O + O$	1.50E+09	1.14	0.4	(7, 8)
1.2 Rekombinationsreaktionen				
$H + H + M^* = H_2 + M^*$	1.80E+18	-1.00	0.0	(9, 10)
$H + OH + M^* = H_2O + M^*$	2.20E+22	-2.00	0.0	(11, 12)
$O + O + M^* = O_2 + M^*$	2.90E+17	-1.00	0.0	(13, 14)
1.3 HO_2-Bildung und -Verbrauch				
$H + O_2 + M^* = HO_2 + M^*$	2.30E+18	-0.80	0.0	(15, 16)
$HO_2 + H = OH + OH$	1.50E+14	0.00	4.2	(17, 18)
$HO_2 + H = H_2 + O_2$	2.50E+13	0.00	2.9	(19, 20)
$HO_2 + H = H_2O + O$	3.00E+13	0.00	7.2	(21, 22)
$HO_2 + O = OH + O_2$	1.80E+13	0.00	-1.7	(23, 24)
$HO_2 + OH = H_2O + O_2$	6.00E+13	0.00	0.0	(25, 26)
1.4 H_2O_2-Bildung und -Verbrauch				
$HO_2 + HO_2 \rightarrow H_2O_2 + O_2$	2.50E+11	0.00	-5.2	(27)
$OH + OH + M^* = H_2O_2 + M^*$	3.25E+22	-2.00	0.0	(28, 29)
$H_2O_2 + H = H_2 + HO_2$	1.70E+12	0.00	15.7	(30, 31)
$H_2O_2 + H = H_2O + OH$	1.00E+13	0.00	15.0	(32, 33)
$H_2O_2 + O = OH + HO_2$	2.80E+13	0.00	26.8	(34, 35)
$H_2O_2 + OH = H_2O + HO_2$	5.40E+12	0.00	4.2	(36, 37)
2. CO-CO_2-Mechanismus				
2.1 CO-CO_2-Reaktionen				
$CO + OH = CO_2 + H$	4.40E+06	1.50	-3.1	(38, 39)
$CO + HO_2 = CO_2 + OH$	1.50E+14	0.00	98.7	(40, 41)
$CO + O + M^* = CO_2 + M^*$	7.10E+13	0.00	-19.0	(42, 43)
$CO + O_2 = CO_2 + O$	2.50E+12	0.00	200.0	(44, 45)
3. C_1-Mechanismus				
3.1 Verbrauch von CH				
$CH + O = CO + H$	4.00E+13	0.00	0.0	(46, 47)
$CH + O_2 = CHO + O$	3.00E+13	0.00	0.0	(48, 49)
$CH + CO_2 \rightarrow CHO + CO$	3.40E+12	0.00	2.9	(50)
3.2 Verbrauch von CHO				
$CHO + H = CO + H_2$	2.00E+14	0.00	0.0	(51, 52)
$CHO + O = CO + OH$	3.00E+13	0.00	0.0	(53, 54)
$CHO + O = CO_2 + H$	3.00E+13	0.00	0.0	(55, 56)
$CHO + OH = CO + H_2O$	1.00E+14	0.00	0.0	(57, 58)
$CHO + O_2 = CO + HO_2$	3.00E+12	0.00	0.0	(59, 60)
$CHO + M^* = CO + H + M^*$	7.10E+14	0.00	70.3	(61, 62)
3.3 Verbrauch von CH_2				
$CH_2 + H = CH + H_2$	8.40E+09	1.50	1.4	(63, 64)
$CH_2 + O \rightarrow CO + H + H$	8.00E+13	0.00	0.0	(65)
$CH_2 + O_2 \rightarrow CO + OH + H$	6.50E+12	0.00	6.3	(66)
$CH_2 + O_2 \rightarrow CO_2 + H + H$	6.50E+12	0.00	6.3	(67)
3.4 Verbrauch von CH_2O				
$CH_2O + H = CHO + H_2$	2.50E+13	0.00	16.7	(68, 69)
$CH_2O + O = CHO + OH$	3.50E+13	0.00	14.6	(70, 71)
$CH_2O + OH = CHO + H_2O$	3.00E+13	0.00	5.0	(72, 73)
$CH_2O + HO_2 = CHO + H_2O_2$	1.00E+12	0.00	33.5	(74, 75)
$CH_2O + CH_3 = CHO + CH_4$	1.00E+11	0.00	25.5	(76, 77)
$CH_2O + M^* = CHO + H + M^*$	1.40E+17	0.00	320.0	(78, 79)
3.5 Verbrauch von CH_3				
$CH_3 + H = CH_2 + H_2$	1.80E+14	0.00	63.0	(80, 81)
$CH_3 + O = CH_2O + H$	7.00E+13	0.00	0.0	(82, 83)
$CH_3 + OH \rightarrow CH_2O + H + H$	9.00E+14	0.00	64.8	(84)
$CH_3 + OH \rightarrow CH_2O + H_2$	8.00E+12	0.00	0.0	(85)
$CH_3 + O_2 \rightarrow CH_2O + H + O$	1.50E+13	0.00	120.0	(86)
$CH_3 + CH_3 = C_2H_6$	7.47E+52	-11.9	80.2	(87, 88)
$CH_3 + M = CH_2 + H + M$	1.00E+16	0.00	380.0	(89, 90)
$CH_3 + CH_3 \rightarrow C_2H_4 + H_2$	1.00E+16	0.00	134.0	(91)
$CH_3 + CH_2 \rightarrow C_2H_4 + H$	1.00E+13	0.00	0.0	(92)
3.6 Verbrauch von CH_4				
$CH_4 + H = H_2 + CH_3$	2.20E+04	3.00	36.6	(93, 94)
$CH_4 + O = OH + CH_3$	1.20E+07	2.10	31.9	(95, 96)
$CH_4 + OH = H_2O + CH_3$	1.60E+06	2.10	10.3	(97, 98)
$CH_4 + HO_2 = H_2O_2 + CH_3$	4.00E+12	0.00	81.2	(99,100)
$CH_4 = CH_3 + H$	3.20E+34	-6.00	457.5	(101,102)
$CH_4 + CH_2 = CH_3 + CH_3$	1.30E+13	0.00	39.9	(103,104)
$CH_4 + CH = C_2H_4 + H$	3.00E+13	0.00	-1.7	(105,106)
4. C_2-Mechanismus				
4.1 Verbrauch von C_2H				
$C_2H + O = CO + CH$	1.00E+13	0.00	0.0	(107,108)
$C_2H + H_2 = C_2H_2 + H$	1.10E+13	0.00	12.0	(109,110)
$C_2H + O_2 = C_2HO + O$	5.00E+13	0.00	6.3	(111,112)
4.2 Verbrauch von CH-CO				
$C_2HO + H = CH_2 + CO$	3.00E+13	0.00	0.0	(113,114)
$C_2HO + O \rightarrow CO + CO + H$	1.00E+14	0.00	0.0	(115)
4.3 Verbrauch von C_2H_2				
$C_2H_2 + O = CH_2 + CO$	4.10E+08	1.50	7.1	(116,117)
$C_2H_2 + O = C_2HO + H$	4.30E+14	0.00	50.7	(118,119)
$C_2H_2 + OH = H_2O + C_2H$	1.00E+13	0.00	29.3	(120,121)
$C_2H_2 + M = C_2H + H + M$	3.60E+16	0.00	446.0	(122,123)
4.4 Verbrauch von CH_2-CO				
$CH_2CO + H = CH_3 + CO$	7.00E+12	0.00	12.6	(124,125)
$CH_2CO + O = CHO + CHO$	1.80E+12	0.00	5.6	(126,127)
$CH_2CO + OH = CH_2O + CHO$	1.00E+13	0.00	0.0	(128,129)
$CH_2CO + M^* = CH_2 + CO + M^*$	1.00E+16	0.00	248.0	(130,131)
4.5 Verbrauch von C_2H_3				
$C_2H_3 + H = H_2 + C_2H_2$	2.00E+13	0.00	0.0	(132,133)
$C_2H_3 + O = CH_2CO + H$	3.00E+13	0.00	0.0	(134,135)
$C_2H_3 + O_2 \rightarrow CH_2O + CHO$	1.50E+12	0.00	0.0	(136)
$C_2H_3 = C_2H_2 + H$	1.60E+32	-5.50	193.5	(137,138)
4.6 Verbrauch von CH_3-CO				
$CH_3CO + H = CH_2CO + H_2$	2.00E+13	0.00	0.0	(139,140)
$CH_3CO + O = CH_3 + CO_2$	2.00E+13	0.00	0.0	(141,142)
$CH_3CO + CH_3 = C_2H_6 + CO$	5.00E+13	0.00	0.0	(143,144)
$CH_3CO = CH_3 + CO$	2.30E+26	-5.00	75.2	(145,146)
4.7 Verbrauch von C_2H_4				
$C_2H_4 + H = C_2H_3 + H_2$	1.50E+14	0.00	42.7	(147,148)
$C_2H_4 + O \rightarrow CH_3CO + H$	1.60E+09	1.20	3.1	(149)
$C_2H_4 + OH = C_2H_3 + H_2O$	3.00E+13	0.00	12.6	(150,151)
$C_2H_4 + CH_3 = C_2H_3 + CH_4$	4.20E+11	0.00	46.5	(152,153)
$C_2H_4 + M^* = C_2H_3 + H_2 + M^*$	2.50E+17	0.00	319.8	(154,155)
4.8 Verbrauch von CH_3-CHO				
$CH_3CHO + H = CH_3CO + H_2$	4.00E+13	0.00	17.6	(156,157)
$CH_3CHO + O = CH_3CO + OH$	5.00E+12	0.00	7.5	(158,159)
$CH_3CHO + OH = CH_3CO + H_2O$	8.00E+12	0.00	0.0	(160,161)
$CH_3CHO + HO_2 = CH_3CO + H_2O_2$	1.70E+12	0.00	44.8	(162,163)
$CH_3CHO + CH_2 = CH_3CO + CH_3$	2.50E+12	0.00	15.9	(164,165)
$CH_3CHO + CH_3 = CH_3CO + CH_4$	8.50E+10	0.00	25.1	(166,167)
$CH_3CHO = CH_3 + CHO$	2.00E+15	0.00	331.0	(168,169)
4.9 Verbrauch von C_2H_5				
$C_2H_5 + H = CH_3 + CH_3$	3.00E+13	0.00	0.0	(170,171)
$C_2H_5 + O = H + CH_3CHO$	5.00E+13	0.00	0.0	(172,173)
$C_2H_5 + O_2 = C_2H_4 + HO_2$	2.00E+12	0.00	20.9	(174,175)
$C_2H_5 + CH_3 = C_3H_8$	7.00E+12	0.00	0.0	(176,177)
$C_2H_5 + C_2H_5 = C_2H_4 + C_2H_6$	1.40E+12	0.00	0.0	(178,179)
$C_2H_5 = C_2H_4 + H$	1.00E+43	-9.1	224.1	(180,181)
4.10 Verbrauch von C_2H_6				
$C_2H_6 + H = H_2 + C_2H_5$	5.40E+02	3.50	21.8	(182,183)
$C_2H_6 + O = OH + C_2H_5$	3.00E+07	2.00	21.4	(184,185)
$C_2H_6 + OH = H_2O + C_2H_5$	6.30E+06	2.00	2.7	(186,187)
$C_2H_6 + HO_2 = H_2O_2 + C_2H_5$	6.00E+12	0.00	81.2	(188,189)
$C_2H_6 + CH_3 = C_2H_5 + CH_4$	5.50E-01	4.00	34.7	(190,191)
$C_2H_6 + CH_2 = CH_3 + C_2H_5$	2.20E+13	0.00	36.3	(192,193)
$C_2H_6 + CH = H + C_3H_6$	1.10E+14	0.00	-1.1	(194,195)
5. C_3 Mechanismus				
5.1 Verbrauch von C_3H_8				
$C_3H_8 + H = p\text{-}C_3H_7 + H_2$	1.30E+14	0.00	40.6	(196,197)
$C_3H_8 + H = s\text{-}C_3H_7 + H_2$	1.00E+14	0.00	34.9	(198,199)
$C_3H_8 + O = p\text{-}C_3H_7 + OH$	3.00E+13	0.00	24.1	(200,201)
$C_3H_8 + O = s\text{-}C_3H_7 + OH$	2.60E+13	0.00	18.7	(202,203)
$C_3H_8 + OH = p\text{-}C_3H_7 + H_2O$	6.30E+06	2.00	2.7	(204,205)
$C_3H_8 + OH = s\text{-}C_3H_7 + H_2O$	1.20E+08	1.46	-0.8	(206,207)
$C_3H_8 + HO_2 = p\text{-}C_3H_7 + H_2O_2$	6.00E+12	0.00	81.2	(208,209)
$C_3H_8 + HO_2 = s\text{-}C_3H_7 + H_2O_2$	2.00E+12	0.00	71.1	(210,211)
$C_3H_8 + CH_3 = p\text{-}C_3H_7 + CH_4$	7.50E+12	0.00	62.5	(212,213)
$C_3H_8 + CH_3 = s\text{-}C_3H_7 + CH_4$	4.30E+12	0.00	55.5	(214,215)
5.2 Verbrauch von C_3H_7				
$p\text{-}C_3H_7 + H = C_3H_8$	2.00E+13	0.00	0.0	(216,217)
$s\text{-}C_3H_7 + H = C_3H_8$	2.00E+13	0.00	0.0	(218,219)
$p\text{-}C_3H_7 + O_2 = C_3H_6 + HO_2$	1.00E+12	0.00	20.9	(220,221)
$s\text{-}C_3H_7 + O_2 = C_3H_6 + HO_2$	1.00E+12	0.00	12.5	(222,223)
$s\text{-}C_3H_7 = C_3H_6 + H$	2.00E+14	0.00	161.9	(224,225)
$p\text{-}C_3H_7 = C_2H_4 + CH_3$	3.00E+14	0.00	139.0	(226,227)
$p\text{-}C_3H_7 = C_3H_6 + H$	1.00E+14	0.00	156.1	(228,229)
5.5 Verbrauch von C_3H_6				
$C_3H_6 + O \rightarrow CH_3CO + CH_3$	5.00E+12	0.00	1.9	(230)
$C_3H_6 + OH \rightarrow CH_3CHO + CH_3$	2.00E+13	0.00	12.8	(231)

$k = A \cdot T^b \exp(-E/RT)$

[M] = Gesamtkonzentration

$[M^*] = [H_2] + 6.5 \cdot [H_2O] + 0.4 \cdot [O_2] + 0.4 \cdot [N_2] + 0.75 \cdot [CO] + 1.5 \cdot [CO_2] + 3.0 \cdot [CH_4]$

Hydrocarbon elementary reaction mechanism:

- 231 Elementary reactions !
- 29 Species!

Methan detailed chemistry

Favre-averaged Conservation Equations

Mass:

$$\frac{\partial\bar{\rho}}{\partial t}+\frac{\partial(\bar{\rho}\tilde{u}_i)}{\partial x_i}=0$$

Momentum:

$$\frac{\partial}{\partial t}(\bar{\rho}\tilde{u}_i)+\frac{\partial}{\partial x_j}(\bar{\rho}\tilde{u}_i\tilde{u}_j)=\bar{\rho}g_i-\frac{\partial\bar{p}}{\partial x_i}+\frac{\partial\bar{\tau}_{ij}}{\partial x_j}-\frac{\partial}{\partial x_j}(\bar{\rho}\widetilde{u_i''u_j''})$$

Species:

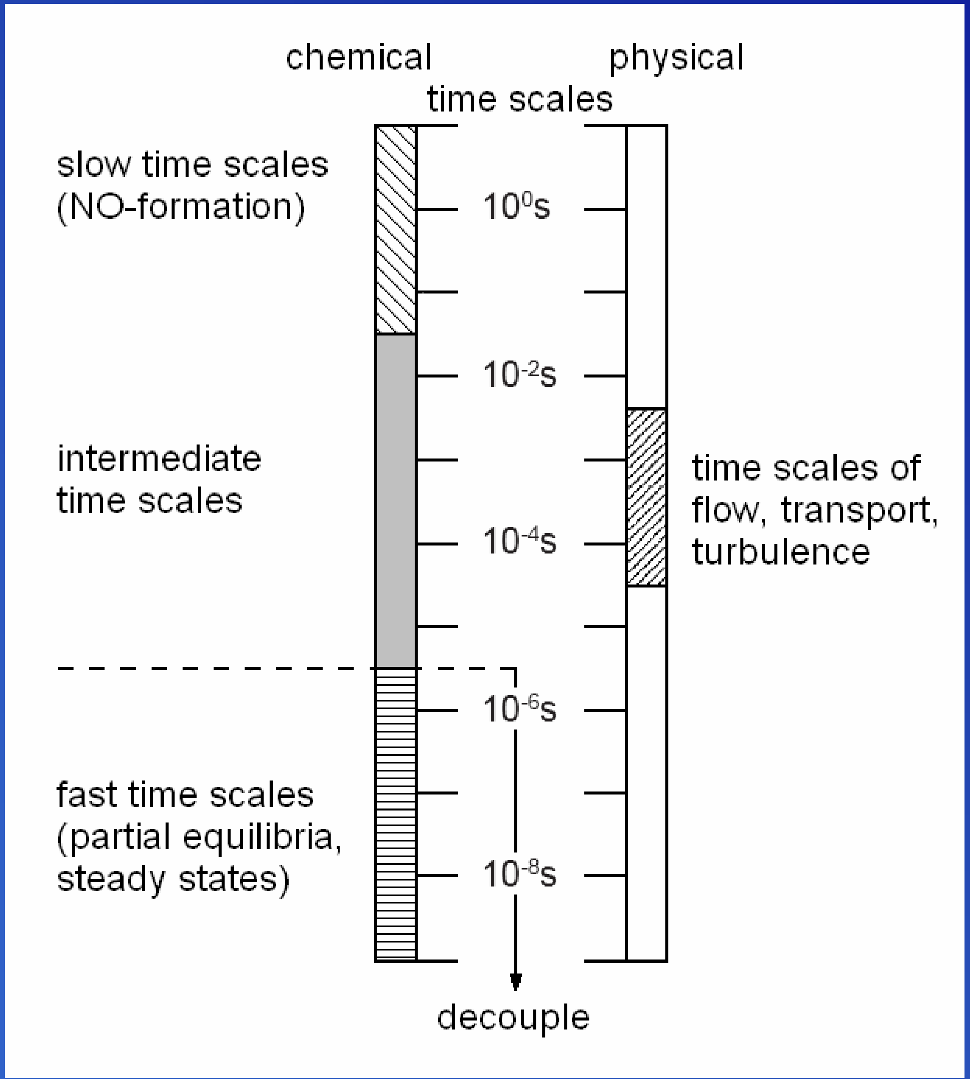
$$\frac{\partial}{\partial t}(\bar{\rho}\tilde{Y}_\alpha)+\frac{\partial}{\partial x_i}(\bar{\rho}\tilde{u}_i\tilde{Y}_\alpha)=\frac{\partial}{\partial x_i}\left(\bar{\rho}D_\alpha\frac{\partial\tilde{Y}_\alpha}{\partial x_i}\right)-\frac{\partial}{\partial x_i}\bar{\rho}\widetilde{u_i''Y_\alpha''}+\tilde{\rho}\overline{R}_\alpha$$

Enthalpy:

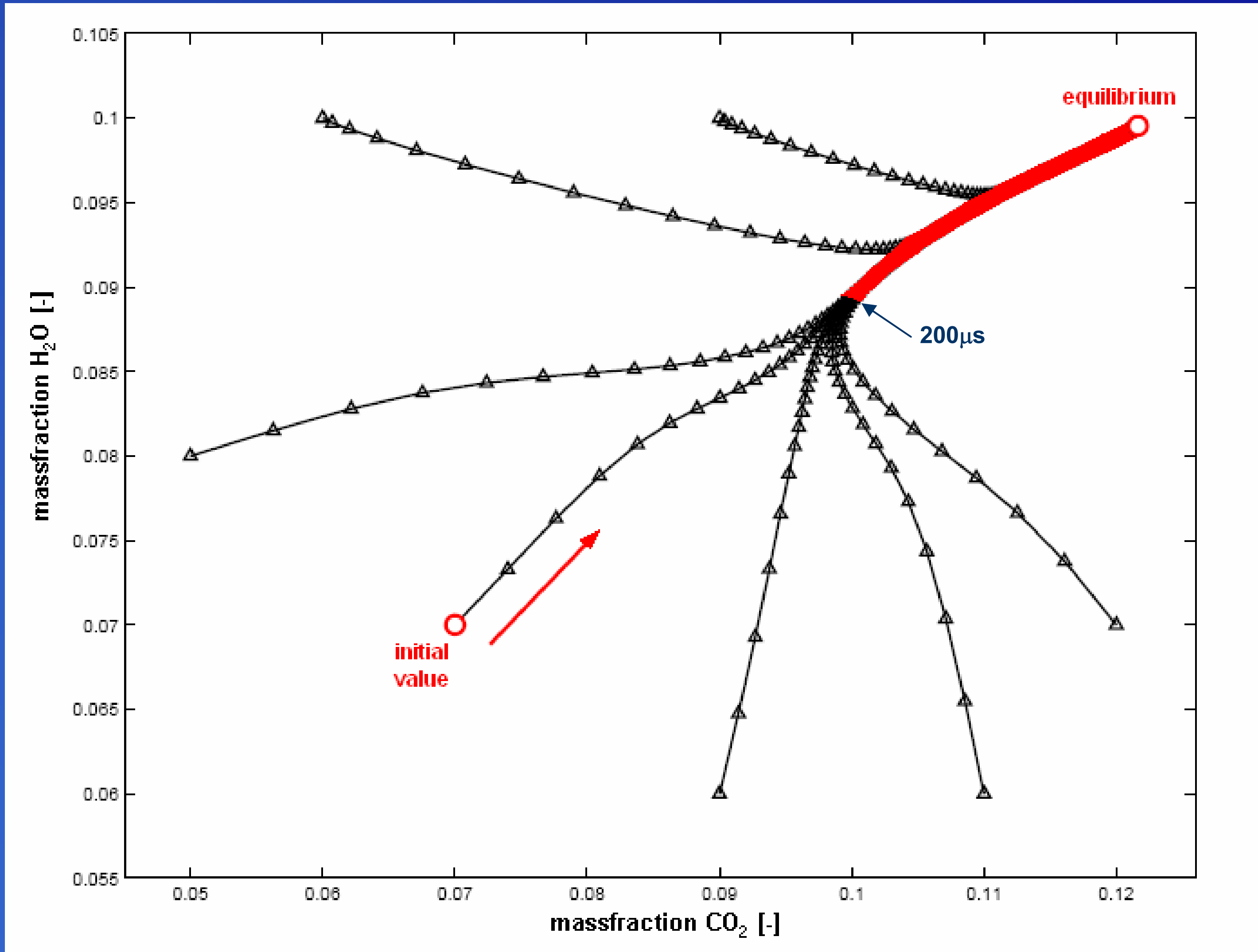
$$\frac{\partial}{\partial t}(\bar{\rho}\tilde{h})+\frac{\partial}{\partial x_i}(\bar{\rho}\tilde{u}_i\tilde{h})=\frac{\partial}{\partial x_i}\left(\bar{\rho}D_h\frac{\partial\tilde{h}}{\partial x_i}\right)-\frac{\partial}{\partial x_i}\bar{\rho}\widetilde{u_i''h''}+\dot{q}_{str}$$

→ unclosed Terms need modelling, reaction source term very nonlinear:

$$\widetilde{R}_\alpha\neq f(\widetilde{c}_i,\widetilde{T})$$



Timescales of Chemical and Physical Processes



Trajectories of a Methane-Air Reaction → use tables

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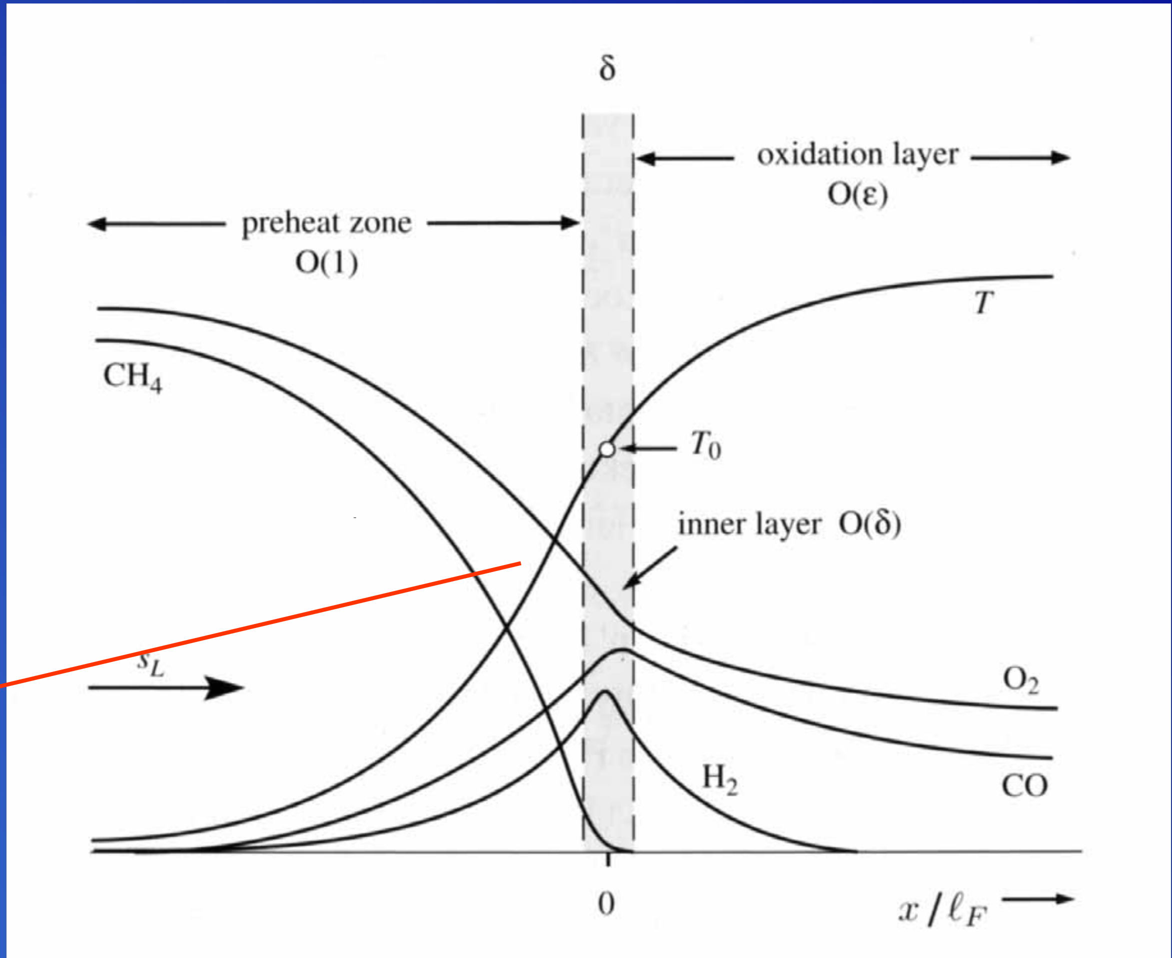
thin reaction zone

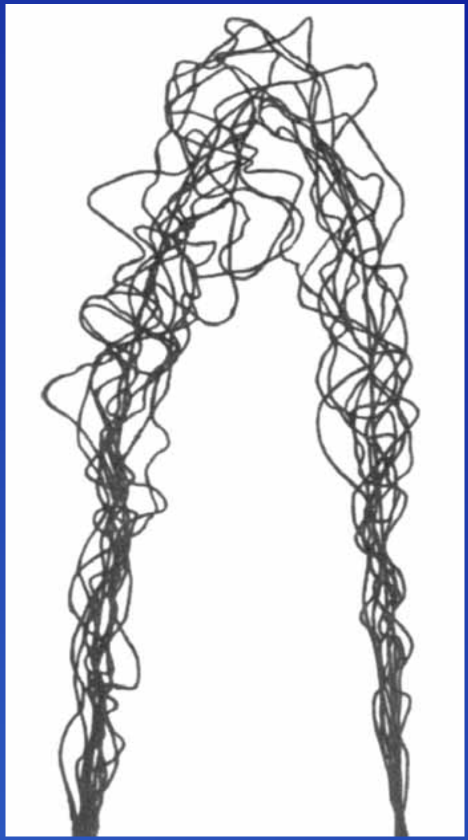


progress variable

Structure of a premixed laminar methan-air flame

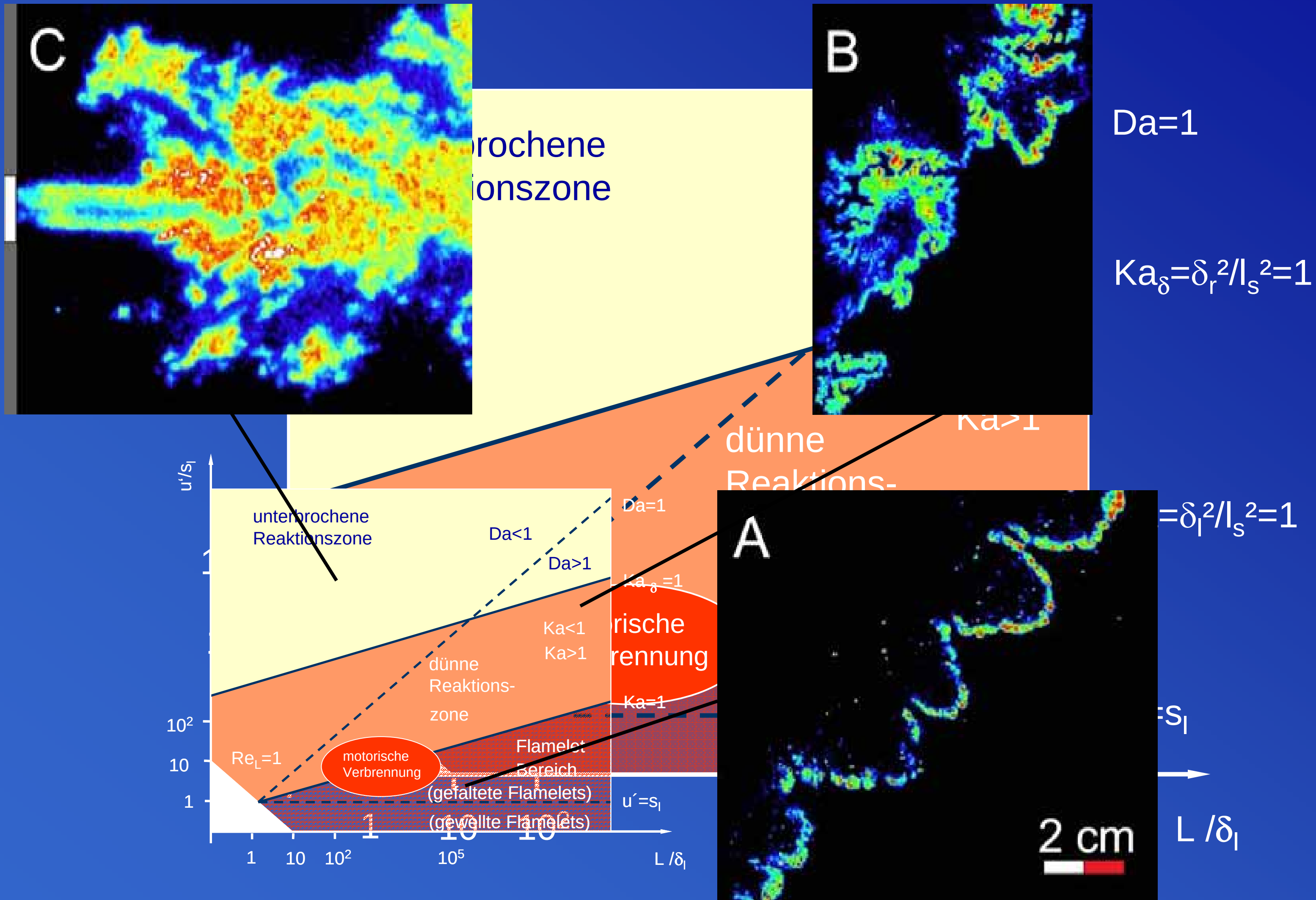
Increase of burning rate through folding of flame

Schlieren picture



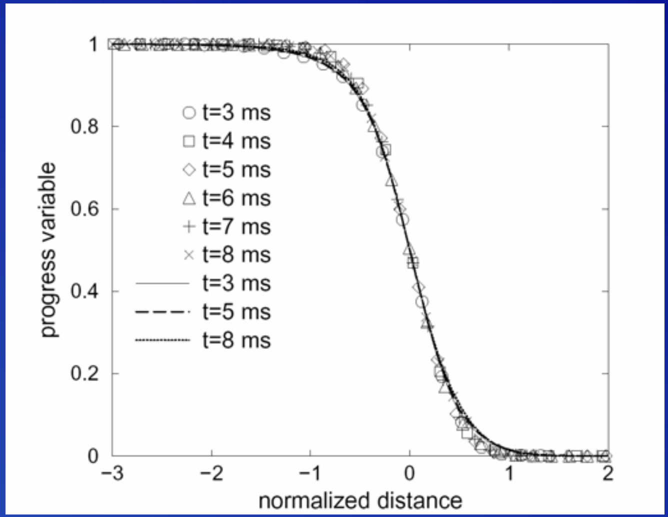
Instantaneous flame front

Visualisations of a turbulent premixed Bunsen flame



Regime-Diagram turbulent premixed combustion

OH visualisation flame front



Reaction progress turbulent premixed flame

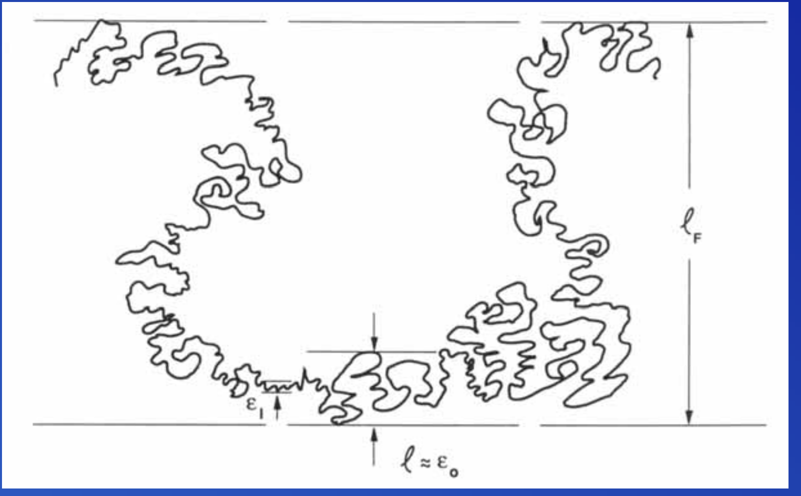
Transport equation for Favre-averaged progress variable:

$$\frac{\partial}{\partial t}(\bar{\rho}\tilde{c}) + \frac{\partial}{\partial x_i}(\bar{\rho}\tilde{u}_i\tilde{c}) = -\frac{\partial}{\partial x_i}\left(\bar{\rho}\widetilde{u_i''c''}\right) + \bar{S}_c$$

Constant pressure:

$$\tilde{c} = \frac{\tilde{T} - T_u}{T_b - T_u}$$

Reaction progress variable transport equation



fractal flame front

Turbulent burning rate:

$$\overline{S_c} = \rho_u \cdot s_{l,0} \cdot \Sigma$$

- ρ_u density of unburnt gases
- $s_{l,0}$ laminar flame speed
- Σ flame surface density Σ (fractal theory, Gouldin):

$$\overline{S_c} = C_R \cdot \rho_u \cdot \frac{s_l}{\nu_u^{1/4}} \cdot \frac{\tilde{\varepsilon}^{3/4}}{\tilde{k}} \cdot \tilde{c} \cdot (1 - \tilde{c})$$

Lindstedt-Vaos model

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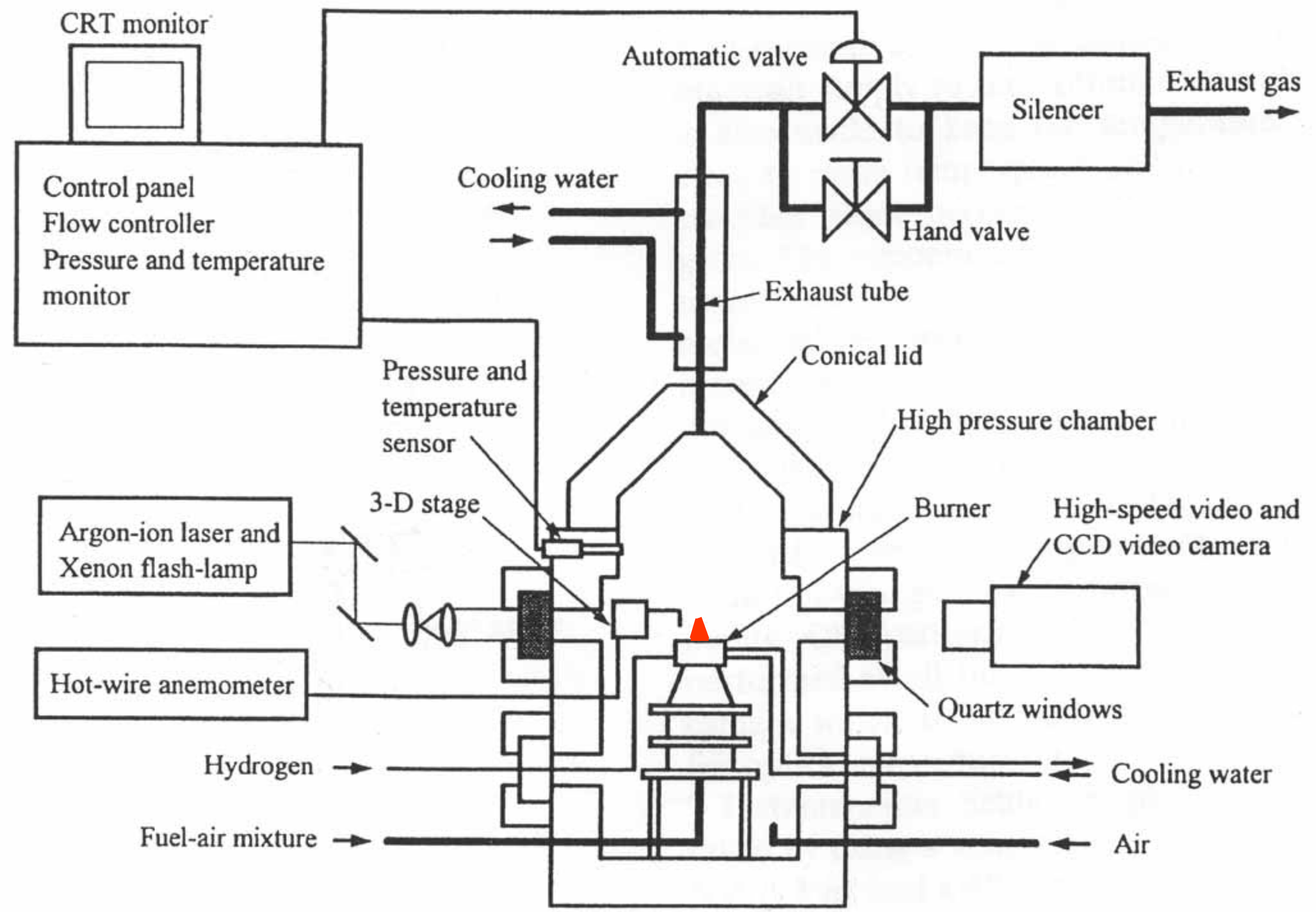
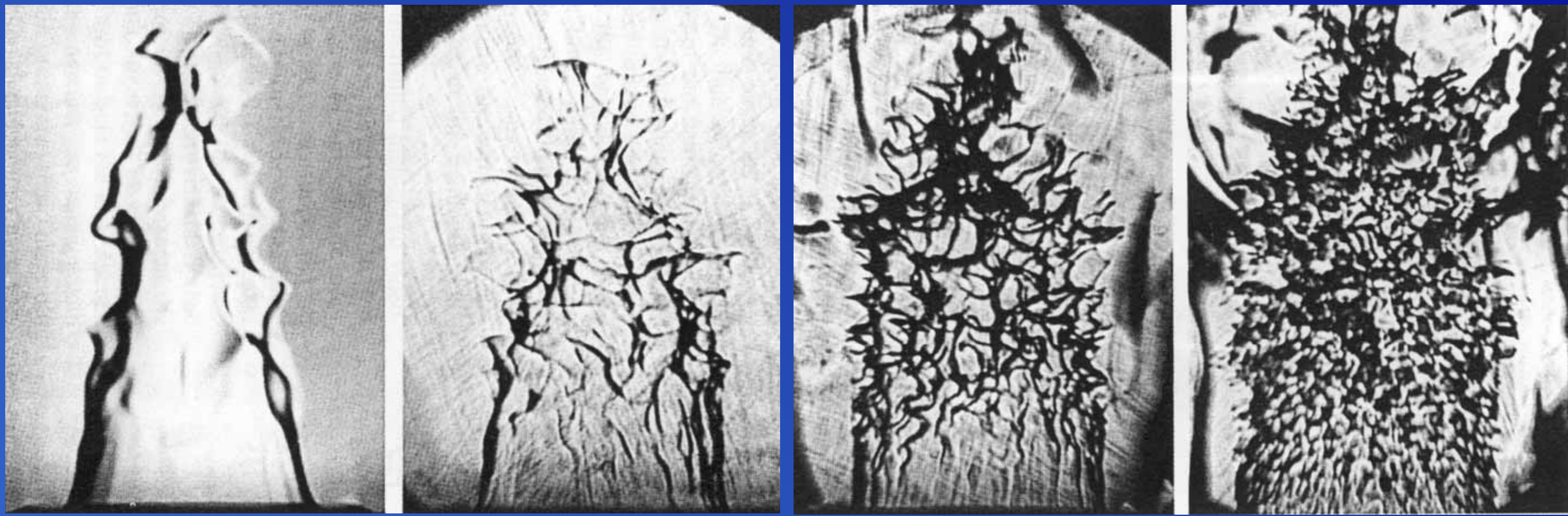


Fig. 1. Schematic of the high-pressure combustion test facility.

Validation configuration (Kobayashi)

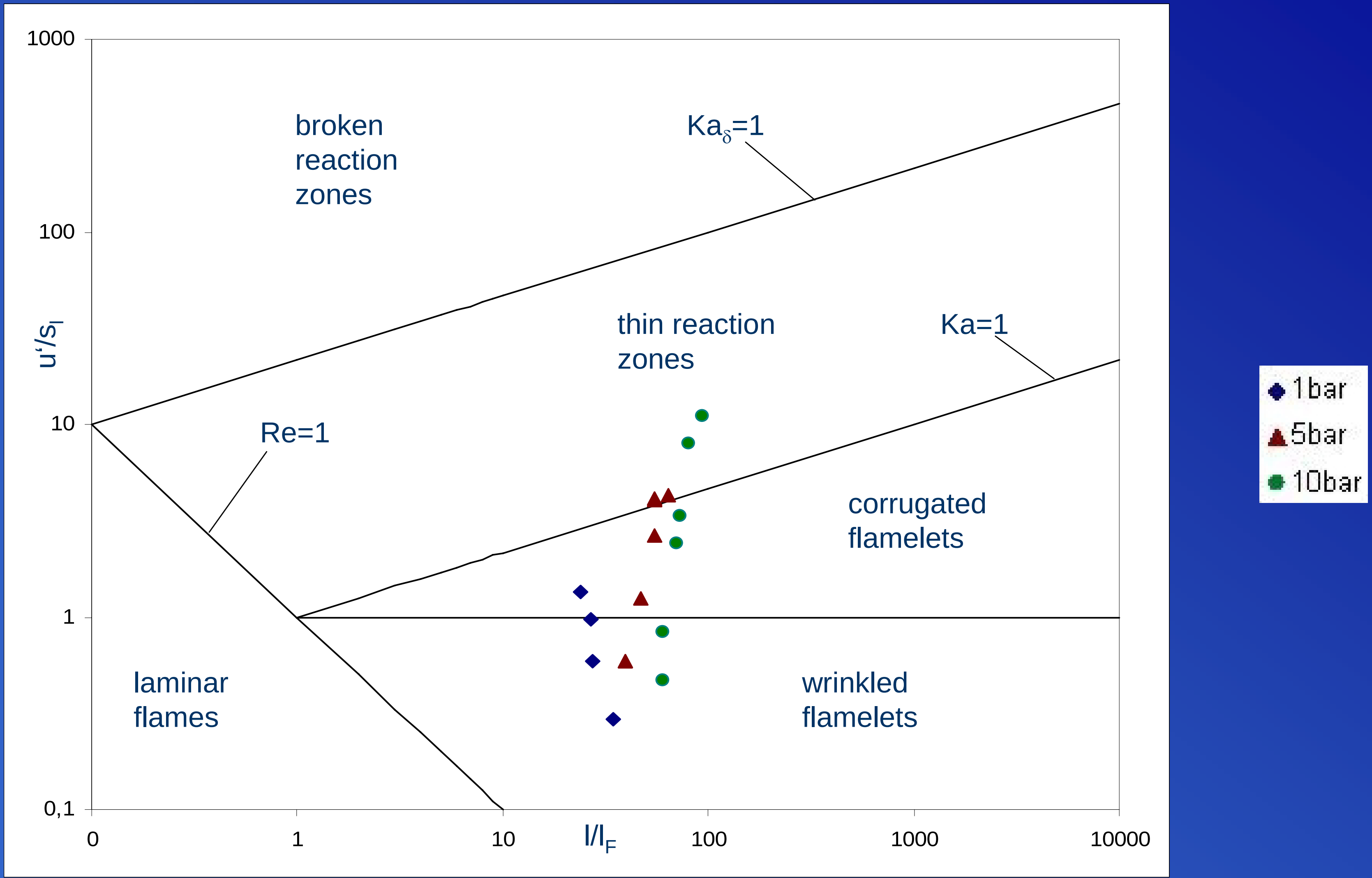


0.1 MPa | 0.25 MPa | 0.5 MPa | 1 MPa

Φ=0.9, u=2.0m/s, d=20mm

Re ↑ : fractal flame structure more pronounced

Schlieren pictures of methane Bunsen flame (variation of pressure)

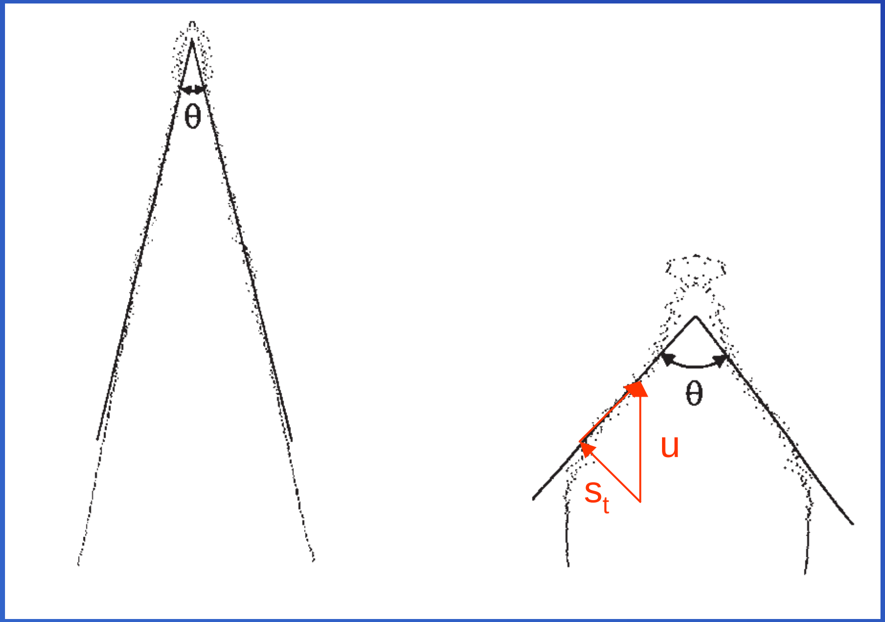


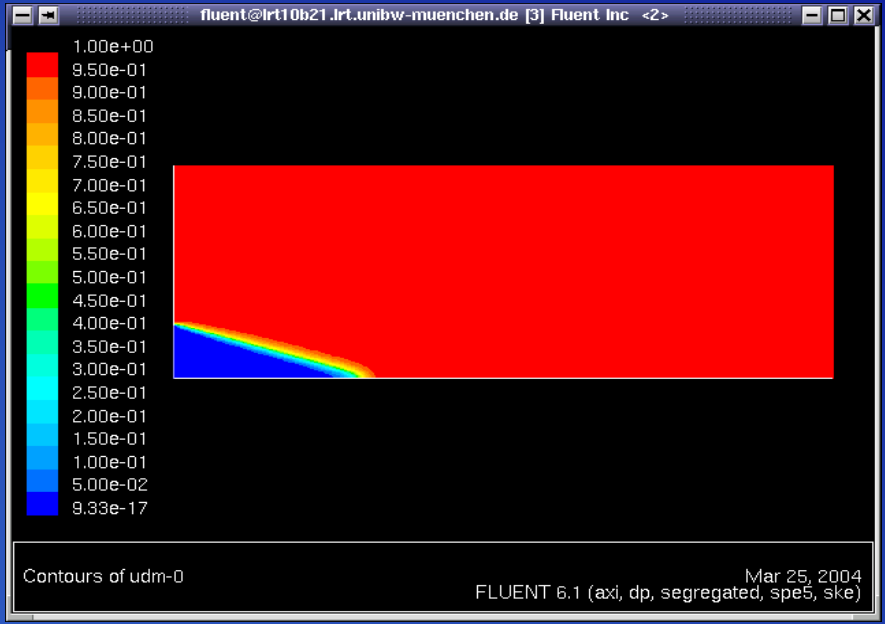
Experimental conditions in Borghi-Peters-regime-diagram

Flame angle from flame conus: $s_t = u \cdot \sin\left(\frac{\theta}{2}\right)$

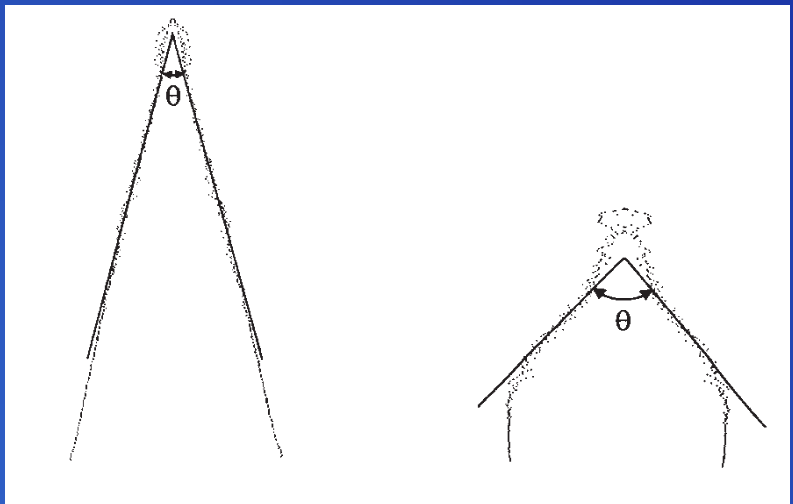
Experiment

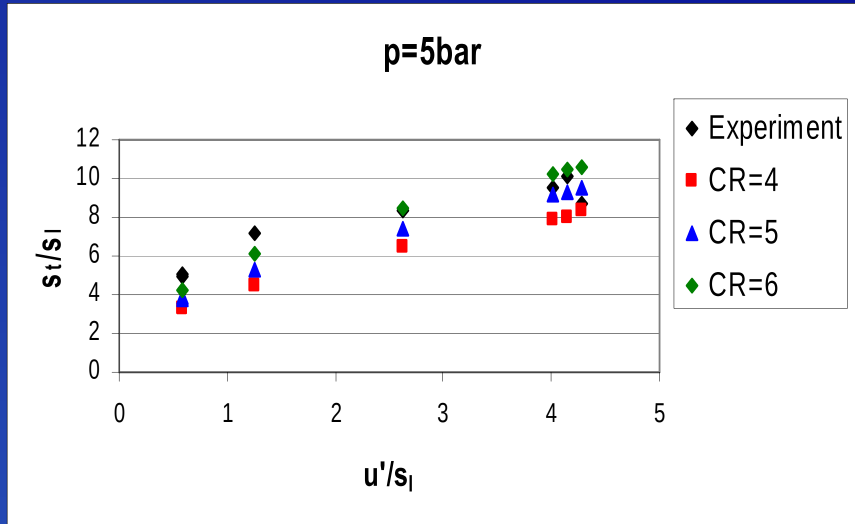
Simulation: $\bar{c} = \frac{(1+\tau)\tilde{c}}{1+\tau\tilde{c}}$

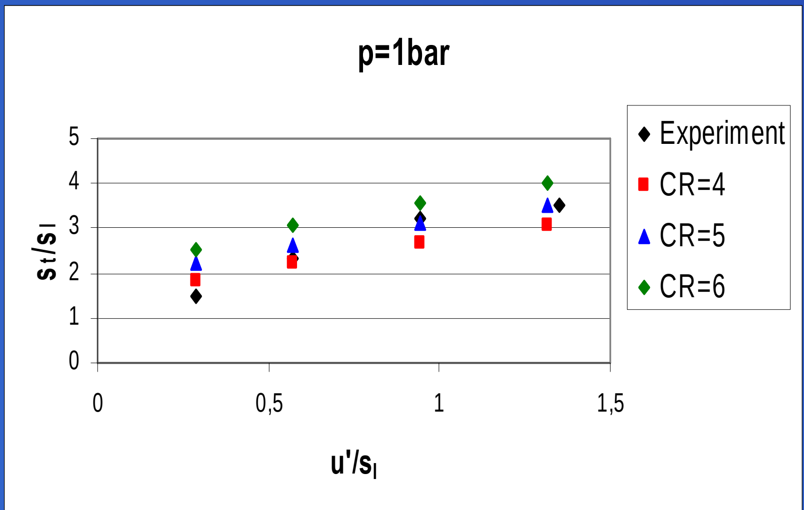


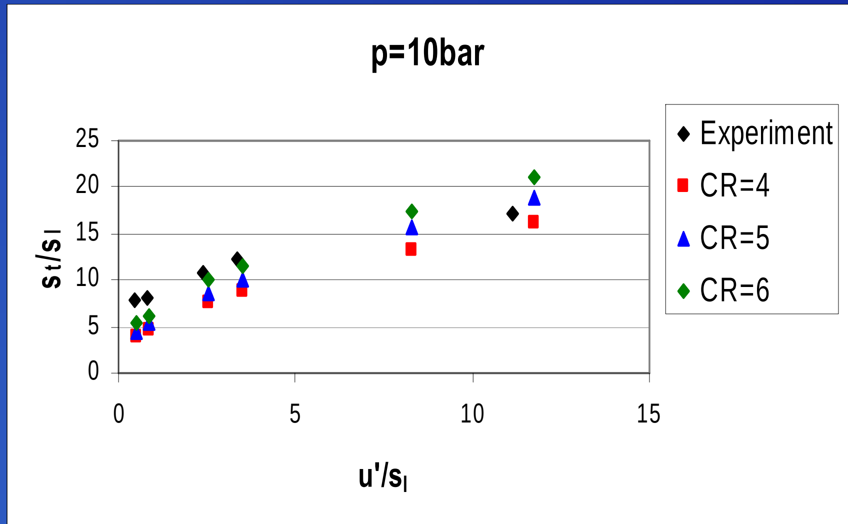


Validation of combustion model using flame cone angle



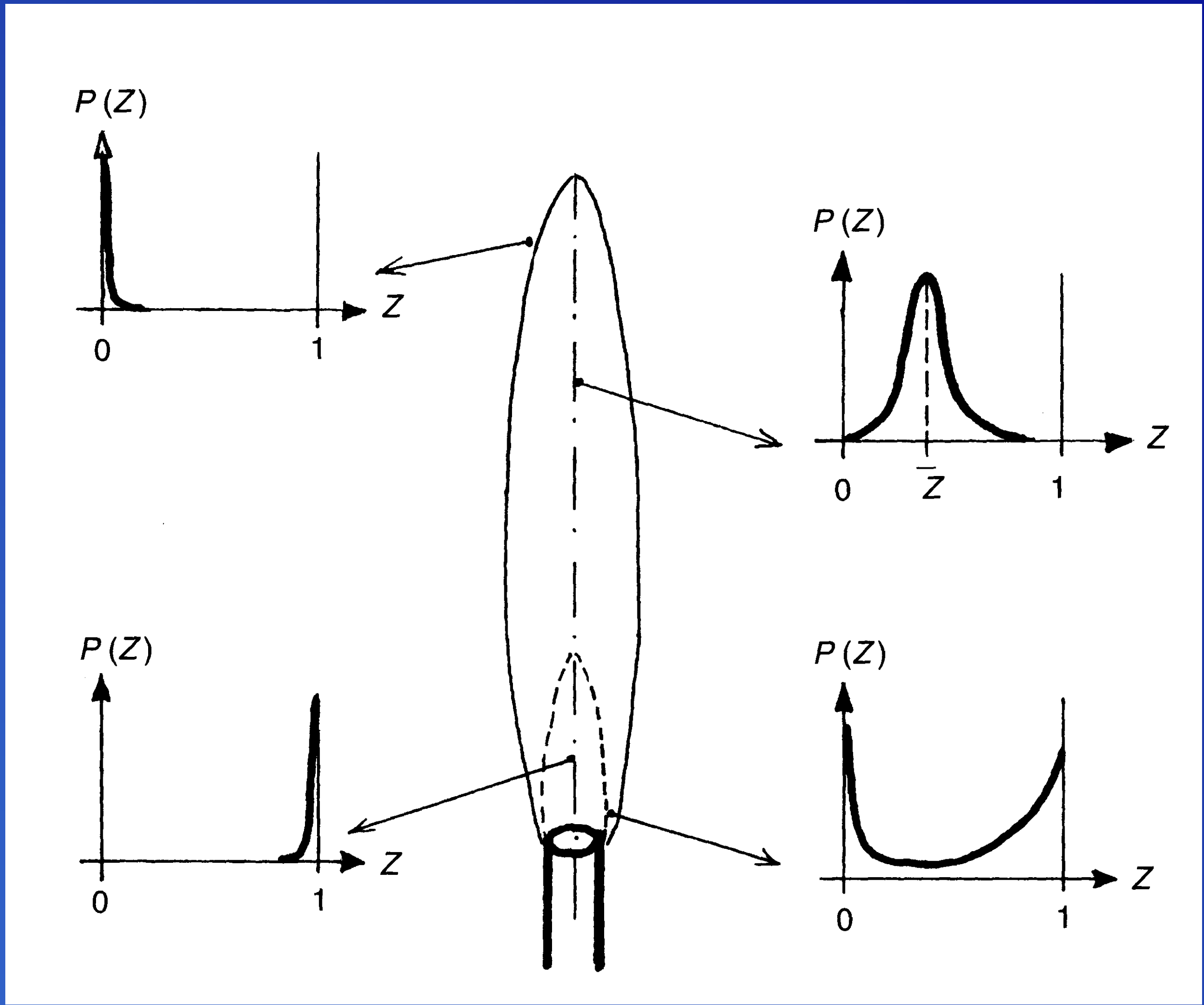






Results with Lindstedt-Vaos-Model (Methane/Air Φ=0.9)

1. Introduction – the turbulent combustion problem
2. Modeling of premixed turbulent flames
3. Validation of premixed combustion model (methane)
4. Modeling of non- / partially premixed turbulent flames
5. Validation of non-premixed flame model (hydrogen)
6. Real gas effects – rocket motors
7. Conclusions



PDF's of mixture fraction in non-premixed flame

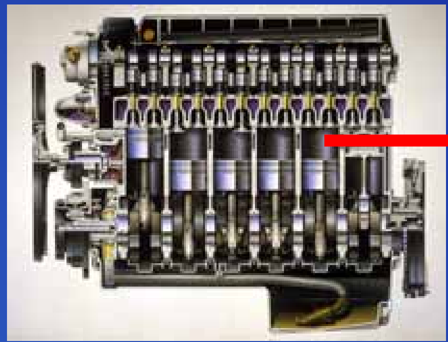
Balance equation for the mixture fraction and its variance

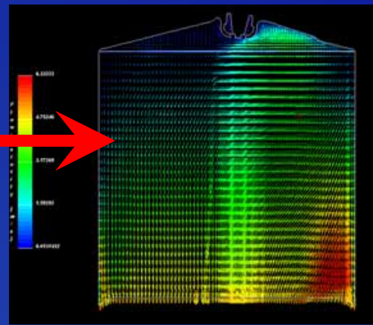
$$\frac{\partial\left(\bar{\rho}\tilde{Z}\right)}{\partial t}+\frac{\partial\left(\bar{\rho}\tilde{u}\tilde{Z}\right)}{\partial x_j}=\frac{\partial}{\partial x_j}\left\{\left(\bar{\mu}+\frac{\mu_t}{\sigma_Z}\right)\frac{\partial\tilde{Z}}{\partial x_j}\right\}$$

and its variance

$$\frac{\partial\left(\bar{\rho}\widetilde{Z''^2}\right)}{\partial t}+\frac{\partial\left(\bar{\rho}\tilde{u}_j\widetilde{Z''^2}\right)}{\partial x_j}=\frac{\partial}{\partial x_j}\left\{\left(\bar{\mu}+\frac{\mu_t}{\sigma_{\widetilde{Z''^2}}}\right)\frac{\partial\widetilde{Z''^2}}{\partial x_j}\right\}+2\frac{\mu_t}{\sigma_Z}\left(\frac{\partial Z}{\partial x_j}\right)^2-\bar{\rho}\tilde{\chi}$$

Transport equation for mixture fraction





Mass fraction transport equation for partial premixing:

$$\frac{\partial}{\partial t}(\bar{\rho}\tilde{Y}_i) + \frac{\partial}{\partial x_i}(\bar{\rho}\tilde{u}_i\tilde{Y}_i) = -\frac{\partial}{\partial x_i}\bar{\rho}\widetilde{u_i'' Y_i''} + \overline{R}_i$$

$$\tilde{c} = \frac{\tilde{Y}_P - Y_u}{Y_b - Y_u}$$

$$\overline{R}_i = \overline{S}_c \cdot (Y_b - Y_u)$$

1-step global reaction:

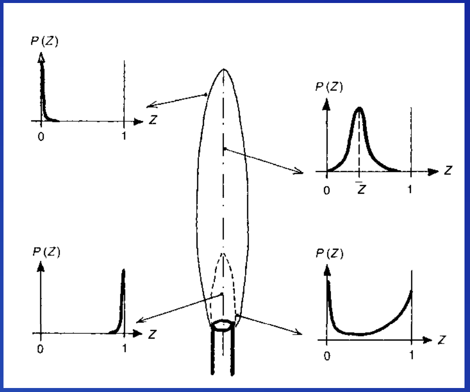
$$C_nH_m + \frac{4n+m}{4\Phi}O_2 + \frac{79}{21}\frac{4n+m}{4\Phi}N_2 \rightarrow nCO_2 + \frac{m}{2}H_2O + \left(\frac{1}{\Phi} - 1\right)\frac{4n+m}{4}O_2 + \frac{79}{21}\frac{4n+m}{4\Phi}N_2$$

Changes through partial premixing

Lindstedt-Vaos model:

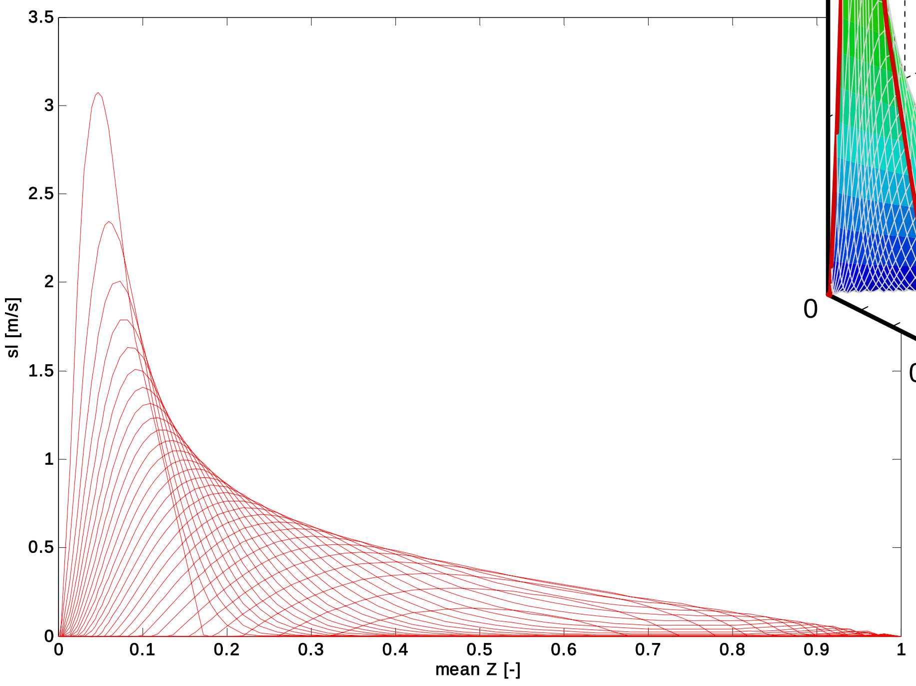
$$\overline{S_c} = C_R \cdot \rho_u \cdot \frac{s_l}{\nu^{1/4}} \cdot \frac{\tilde{\varepsilon}^{3/4}}{\tilde{k}} \cdot \tilde{c} \cdot (1 - \tilde{c})$$

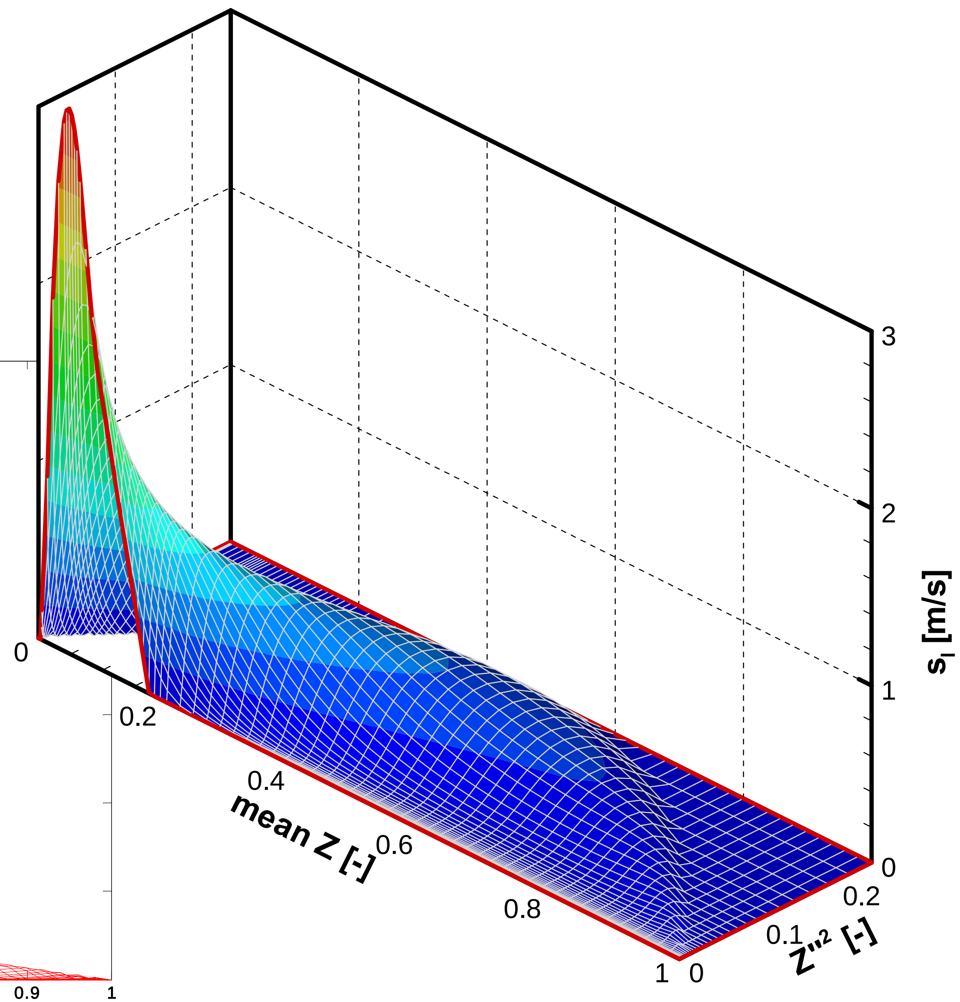
local flame speed: $s_l = s_l\left(\tilde{Z}(x,t)\right)$



turbulence effect: $$\widetilde{s_l}\left(\vec{x},t\right) = \int s_{l_{\tilde{Z},\widetilde{Z''^2}}}\left(Z\right) \tilde{P}_{\tilde{Z},\widetilde{Z''^2}}\left(Z;\vec{x},t\right) dZ$$

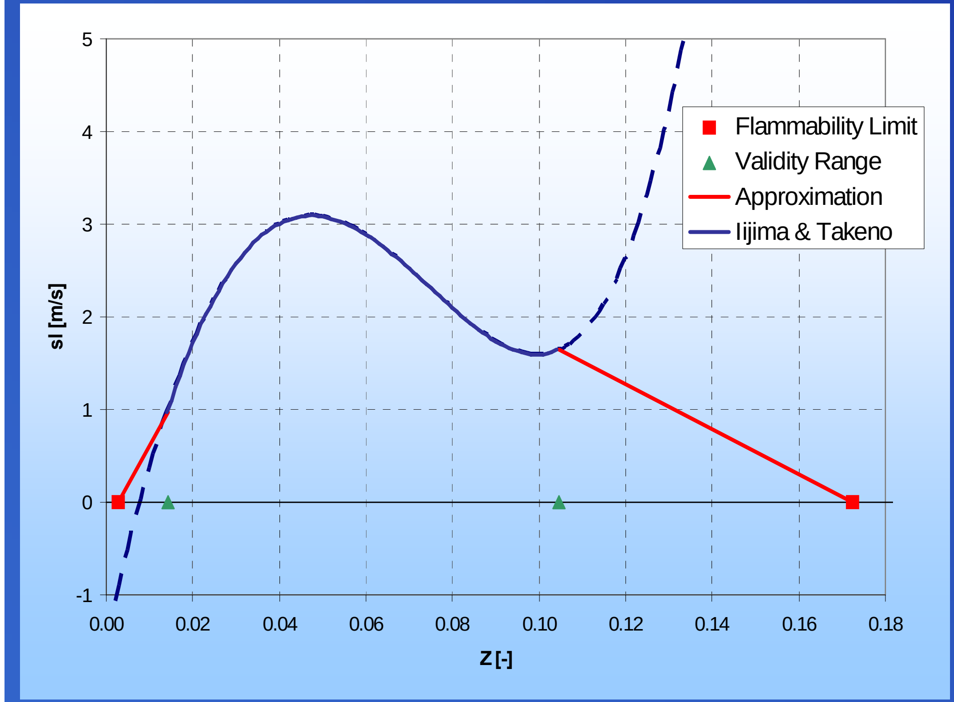
Turbulent burning rate in partially premixed flame



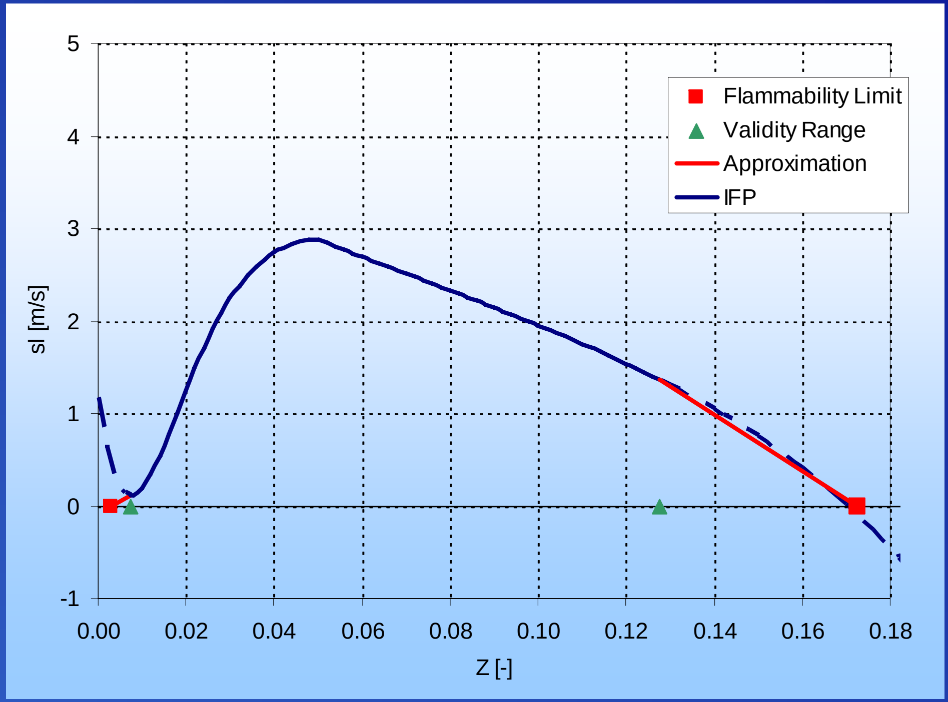


Laminar Flame Speed Table (Hydrogen, p = 1 Bar)

Correlation of Iijima & Takeno

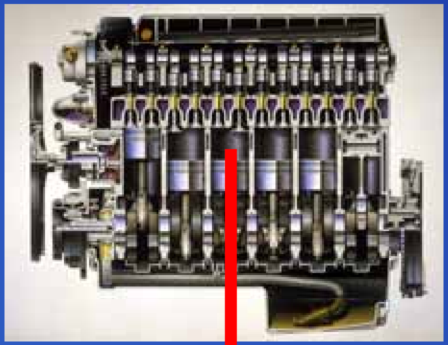


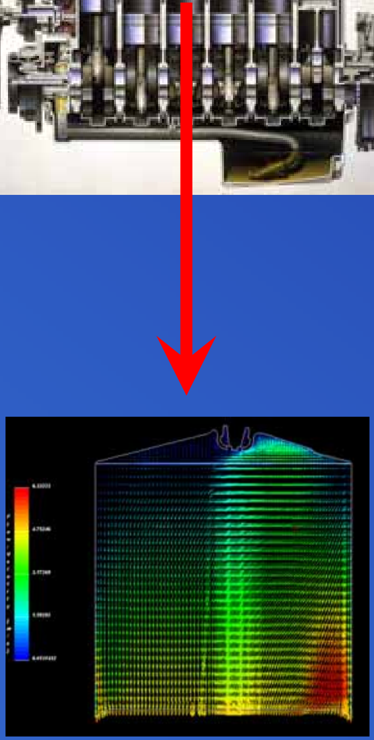
Correlation of IFP

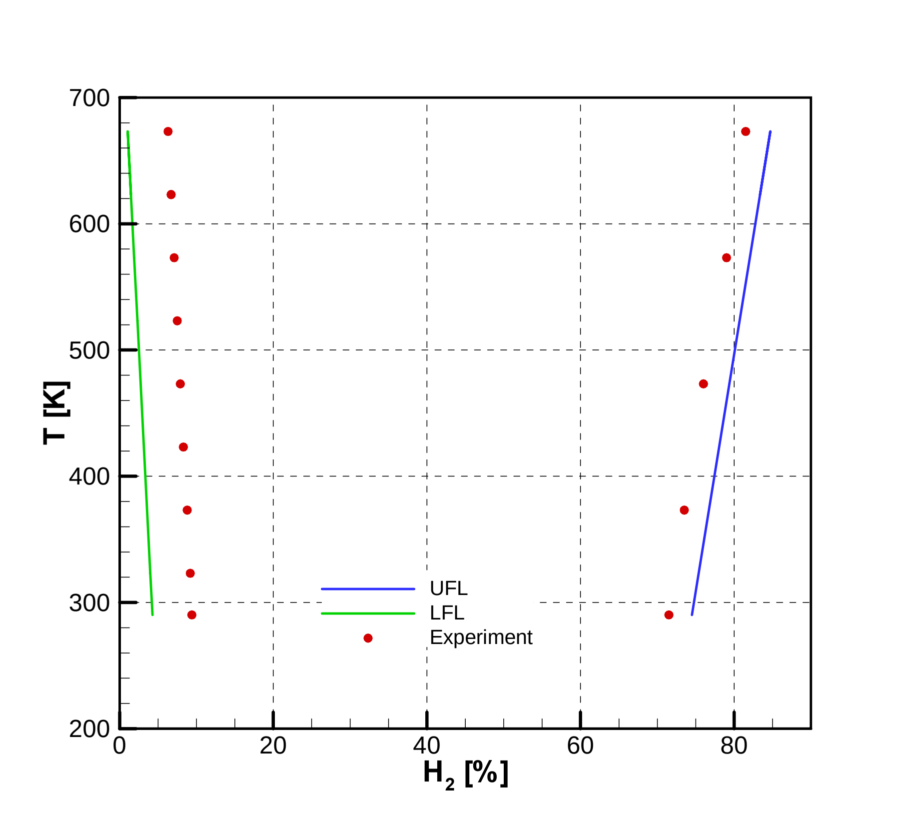


Extension of laminar flame speed correlations

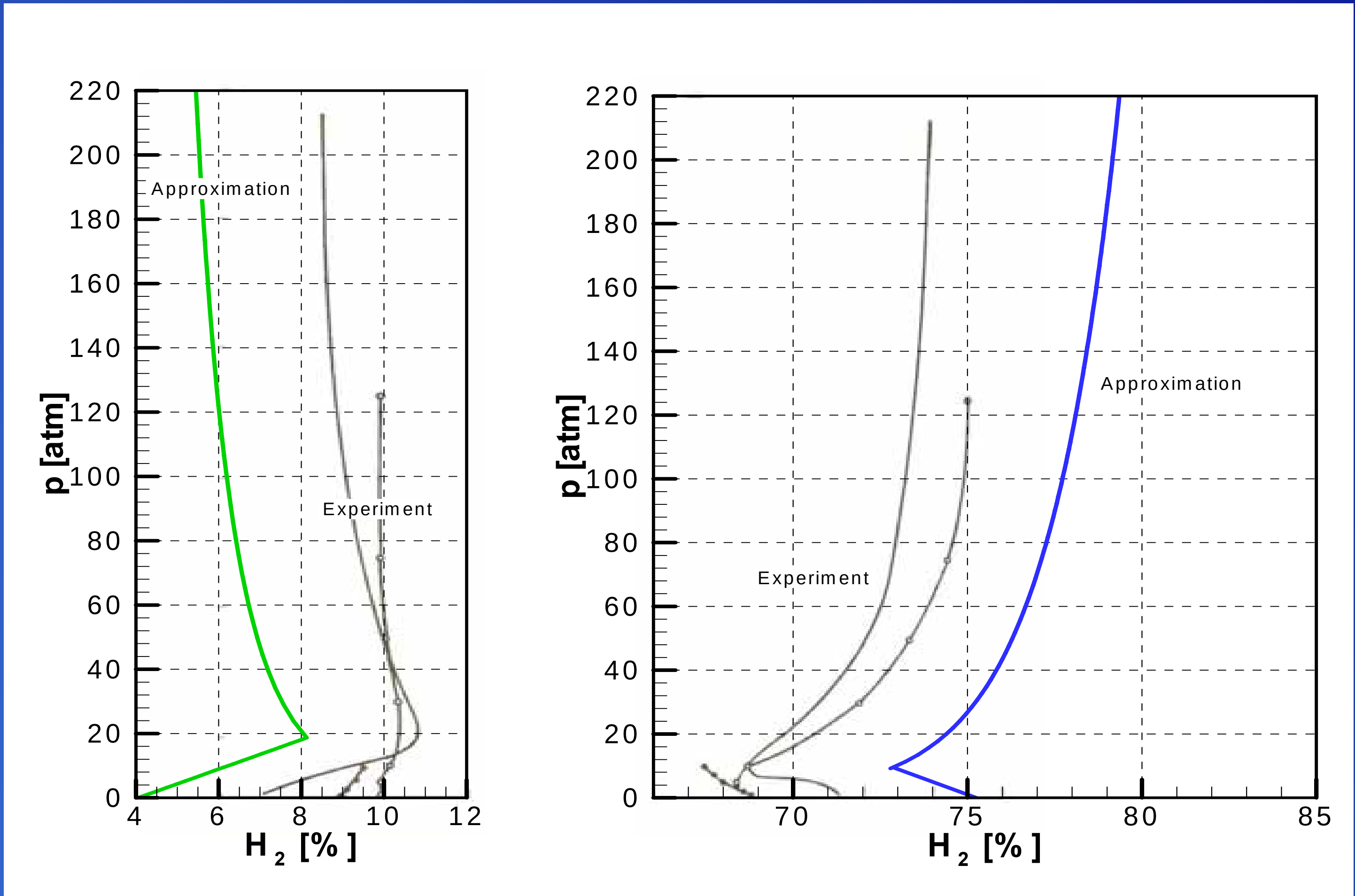
ICE application: p, $T_{u,f}$, $T_{u,ox}$ changes during simulation, partial premixing







Flammability Limits – Temperature Dependence



Experiment

Bureau of Mines
Bulletin 503

Flammability Limits – Pressure Dependence

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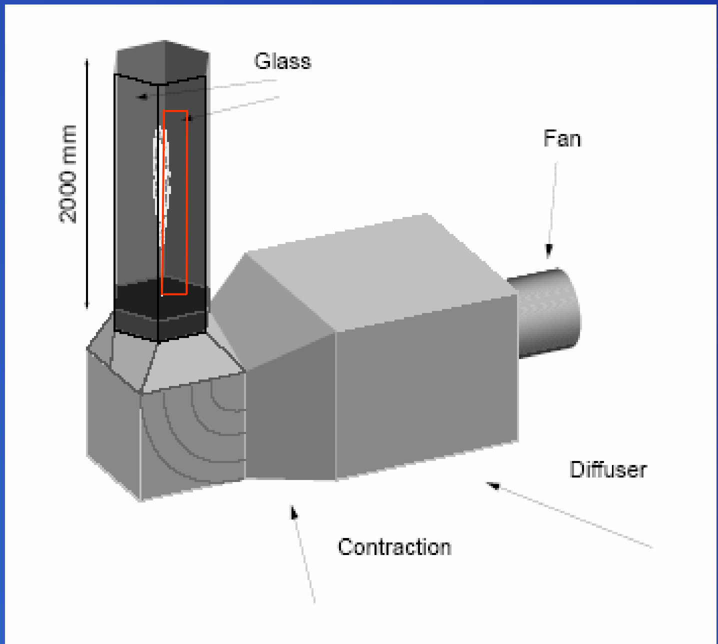
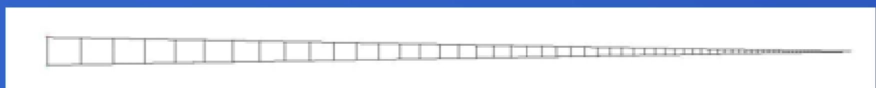


Elements: 131518

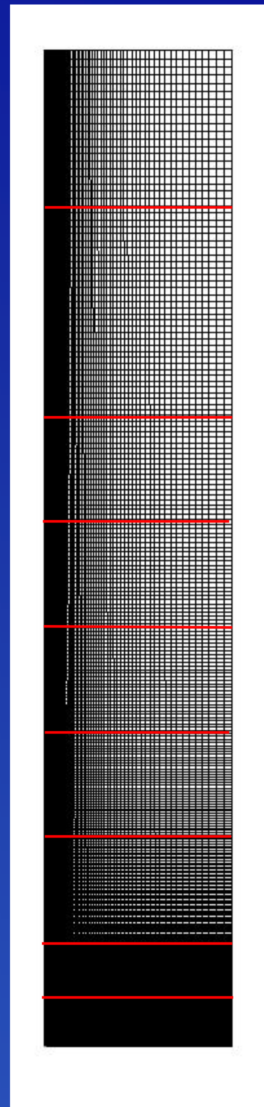
Nodes: 87200

Grid dimension:

150 mm x 800 mm

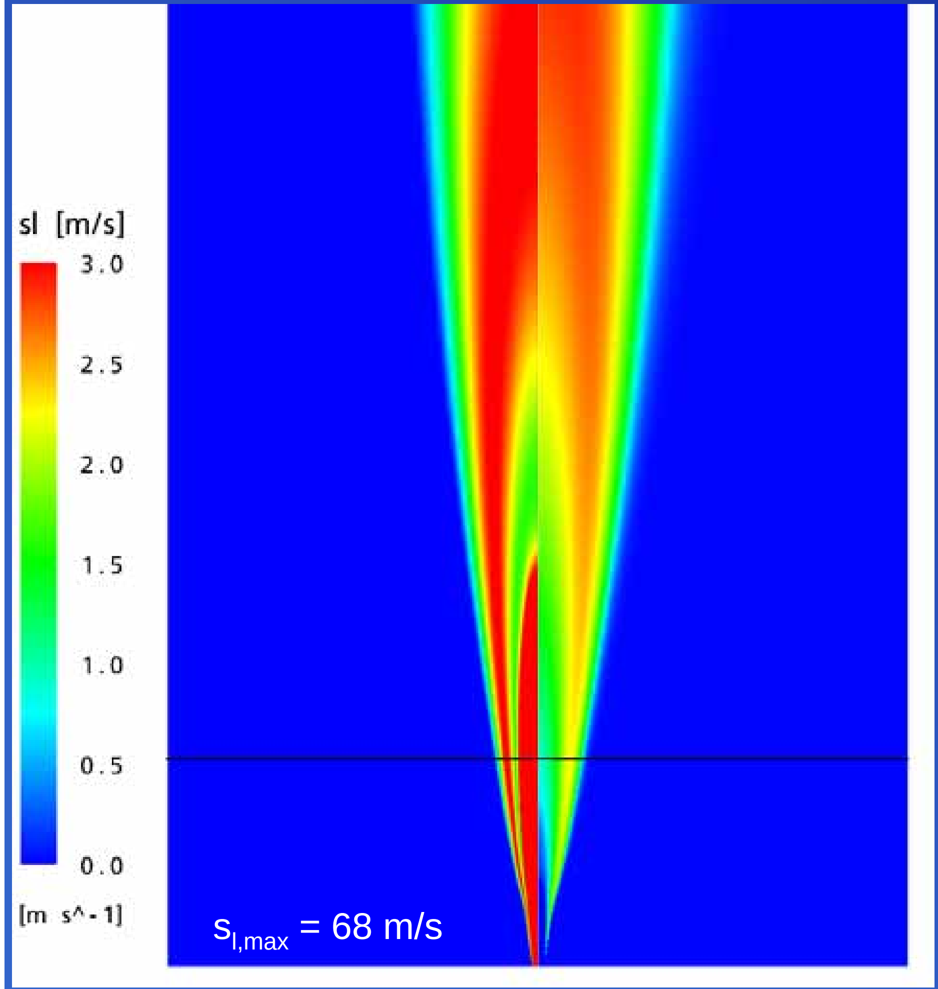


y [mm]	y/L	y/D
675	1/1	180
506	3/4	135
422	5/8	113
338	1/2	90
253	3/8	68
169	1/4	45
84	1/8	23
42	1/16	11

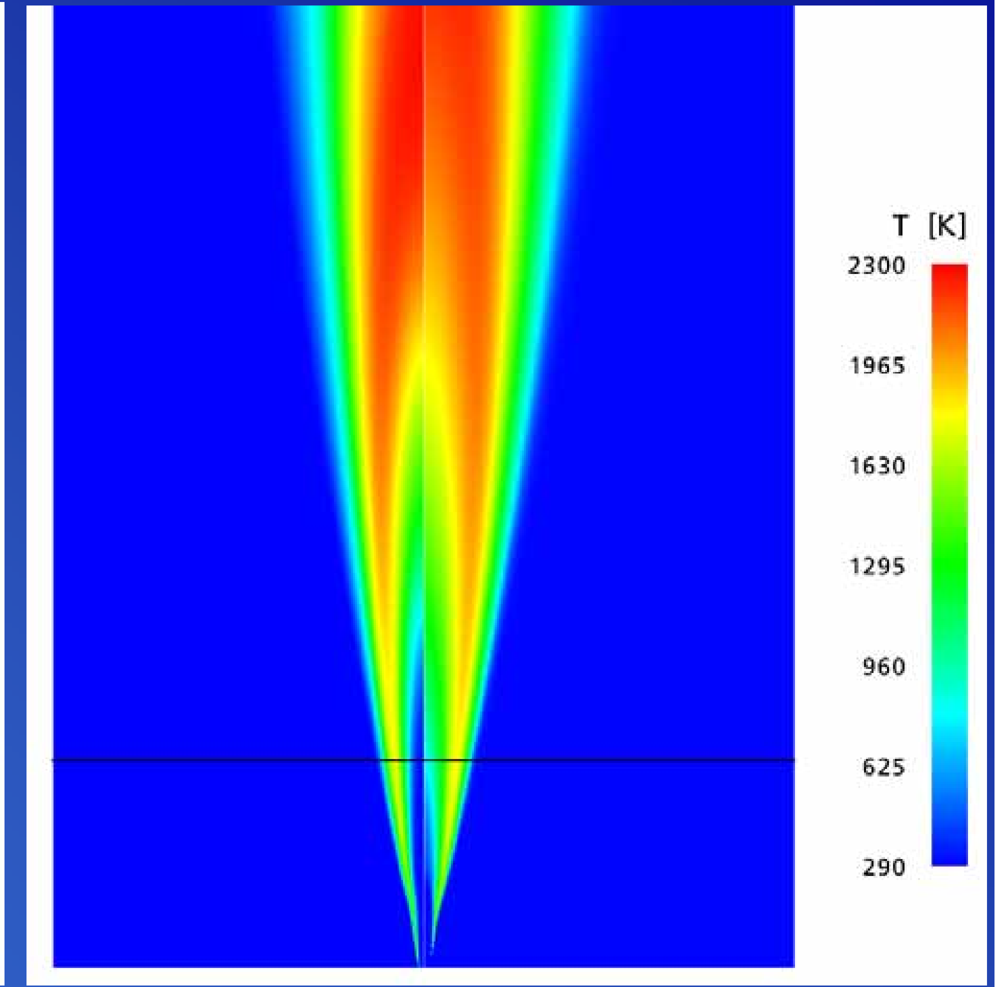


Hydrogen Jet Flame

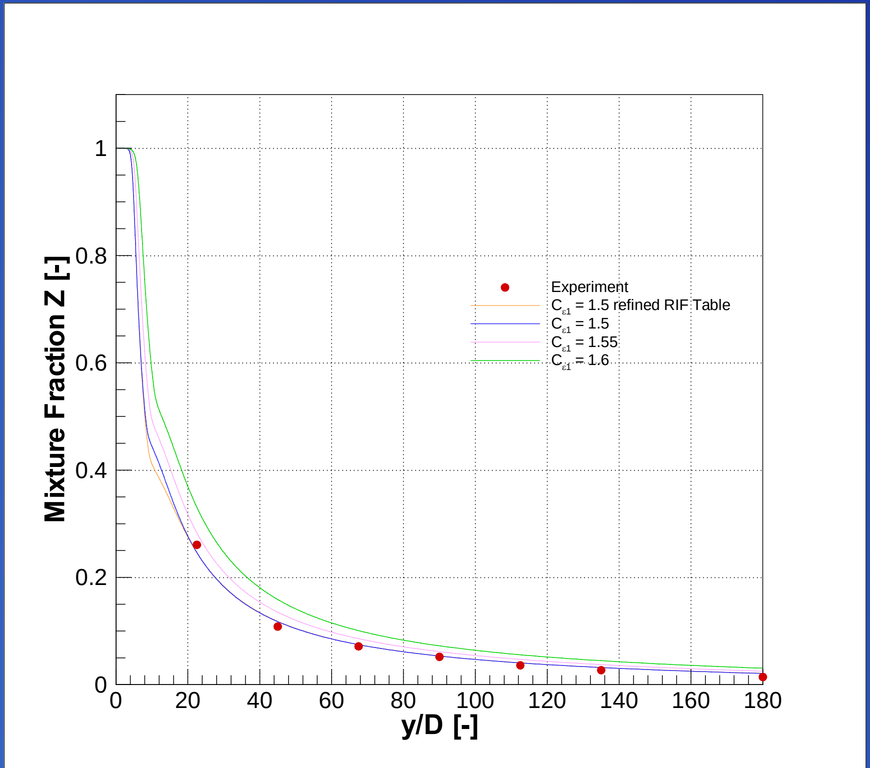
Iijima & Takeno Correlation



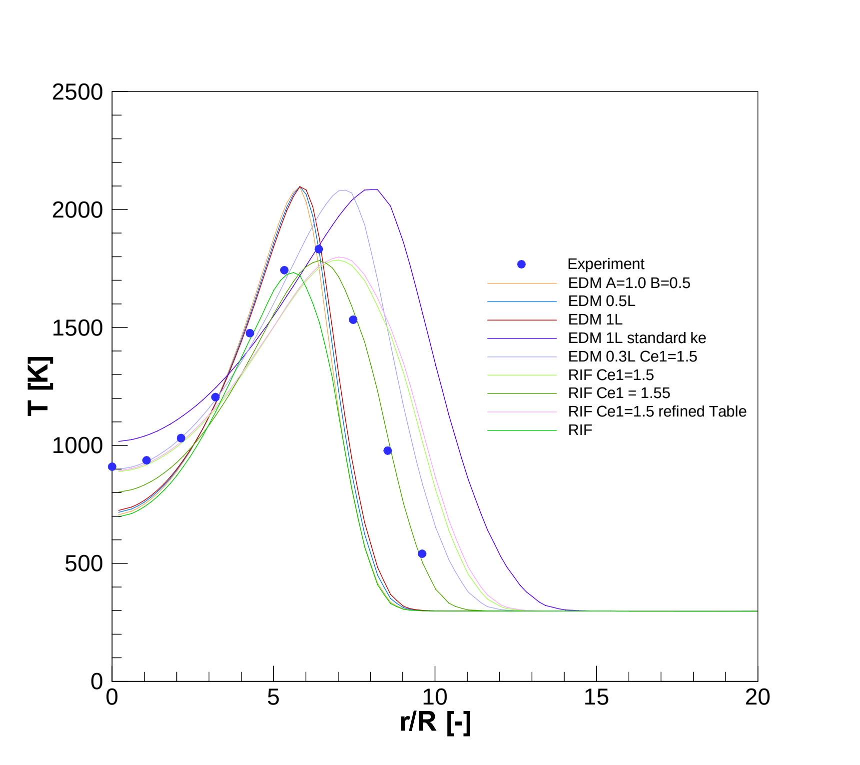
Iijima & Takeno Table



Results

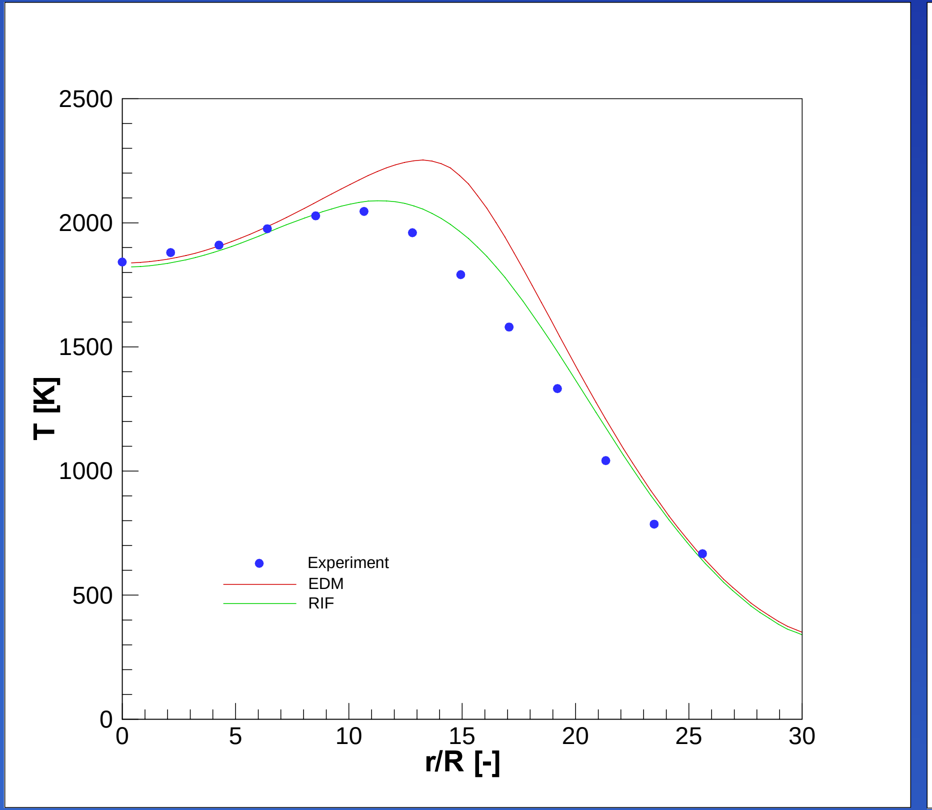


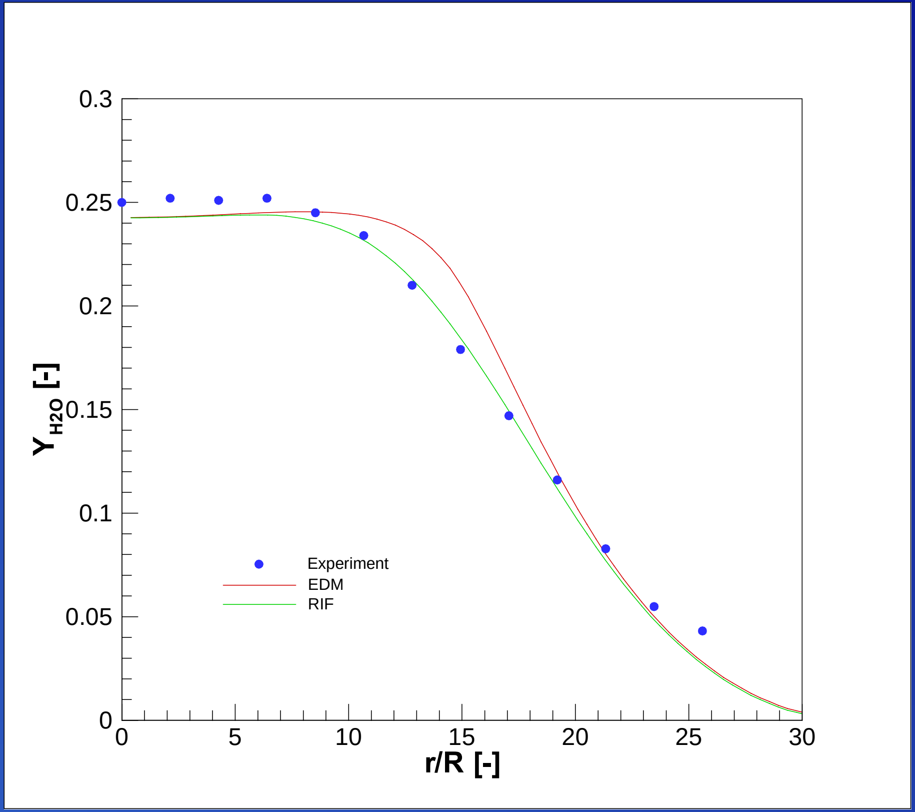
Mixture fraction on axis



Radial temperature profile
(y/D = 23)

H_2 Jet Flame – Influence from turbulence model

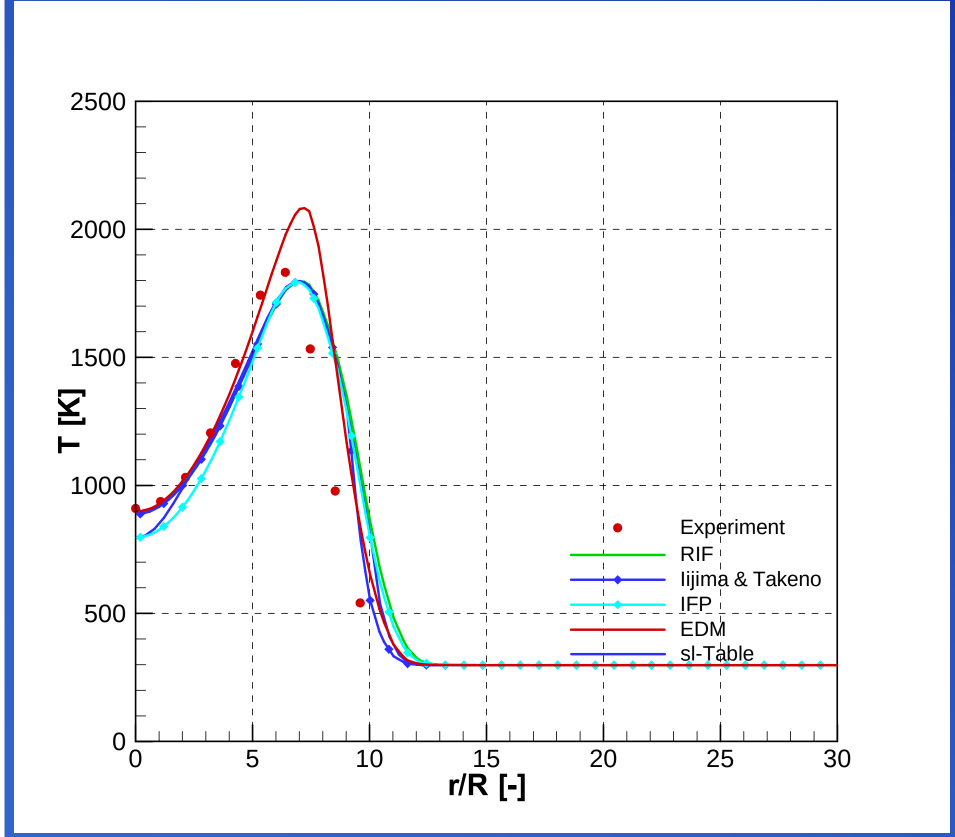


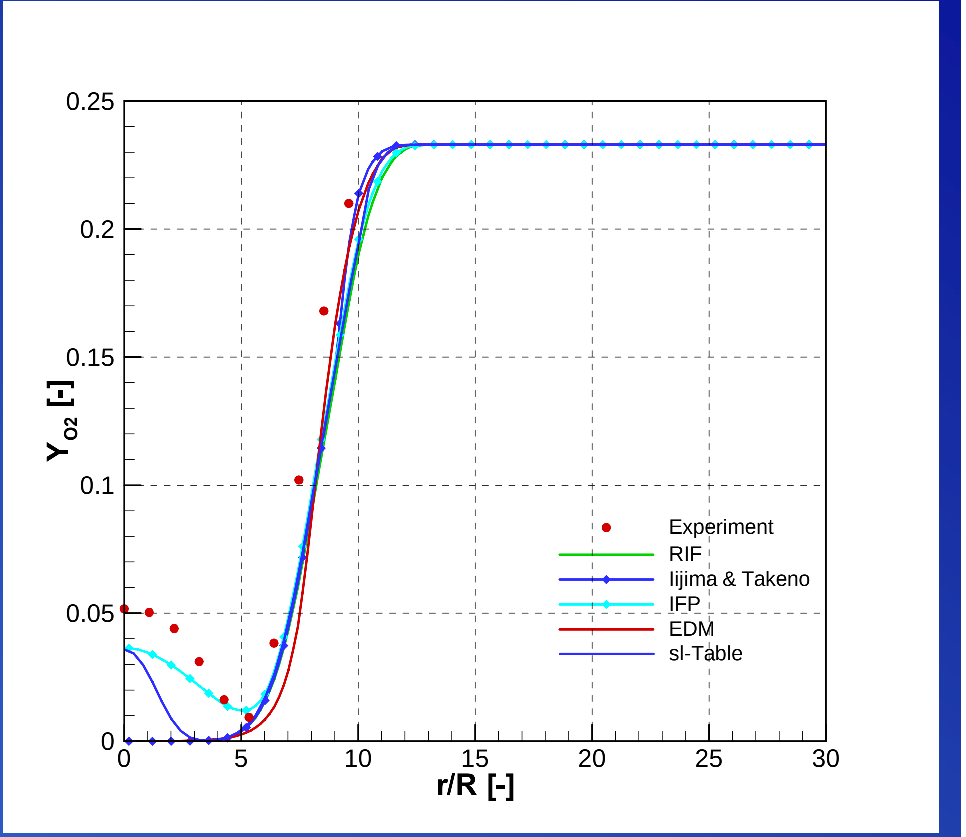


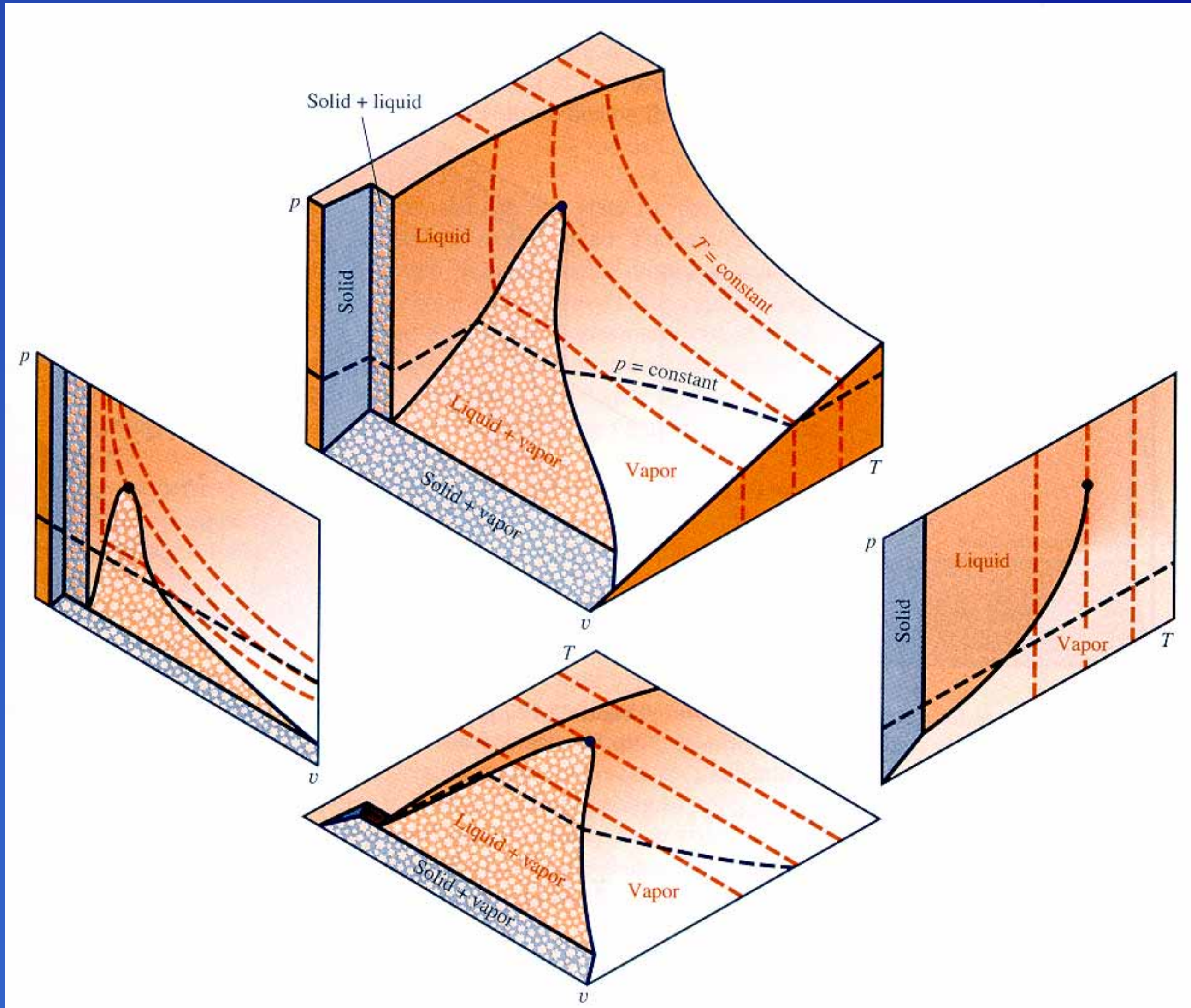
$C_{\varepsilon 1} = 1.5$

Axial Position 253 mm (y/D = 68)

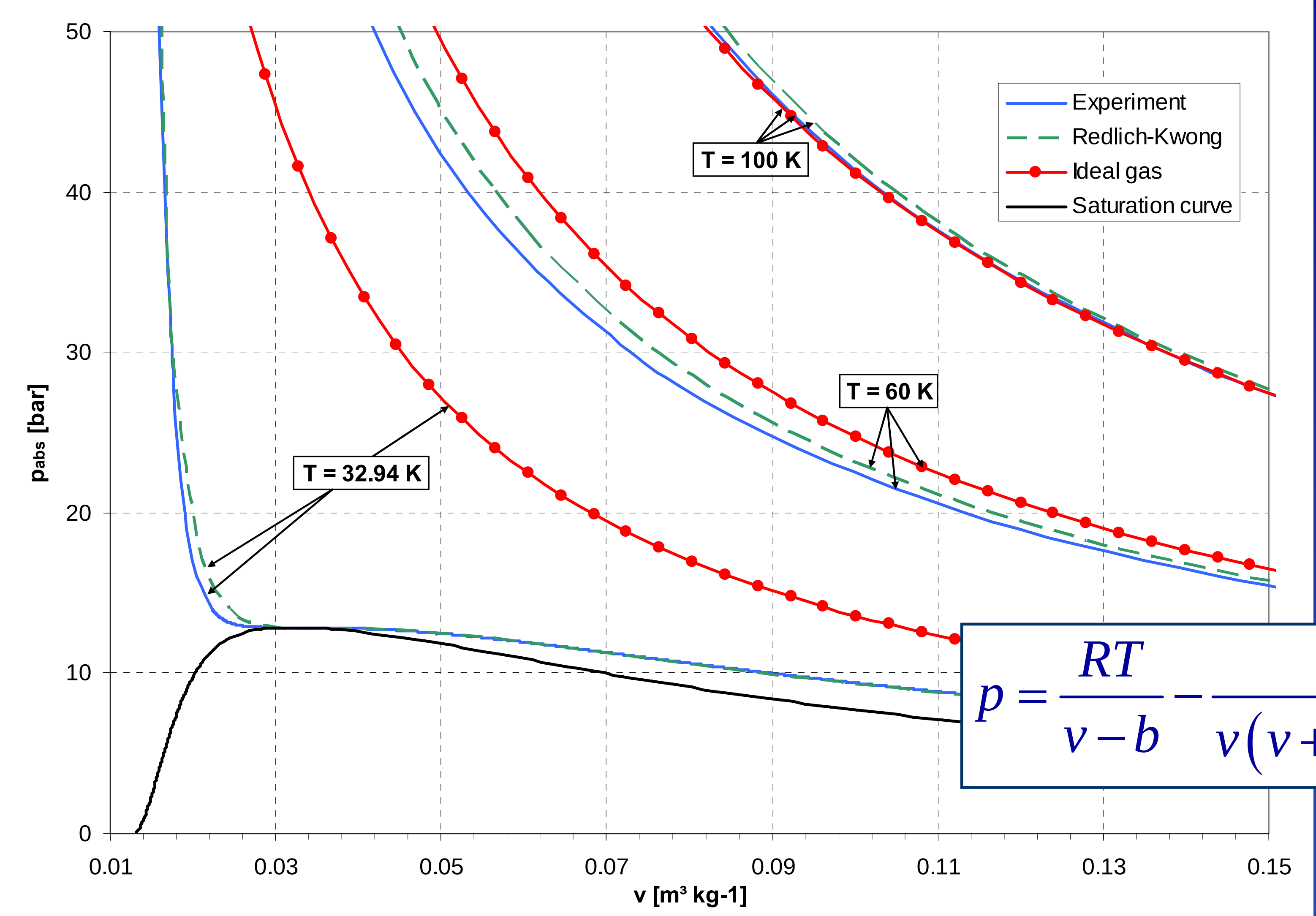
y/L = 1/8


2500
2000
1500
1000
500
0
T [K]
0
5
10
15
20
25
30
r/R [-]
Experiment
RIF
Iijima & Takeno
IFP
EDM
sl-Table


0.25
0.2
0.15
0.1
0.05
0
Y O2 [-]
0
5
10
15
20
25
30
r/R [-]
Experiment
RIF
Iijima & Takeno
IFP
EDM
sl-Table

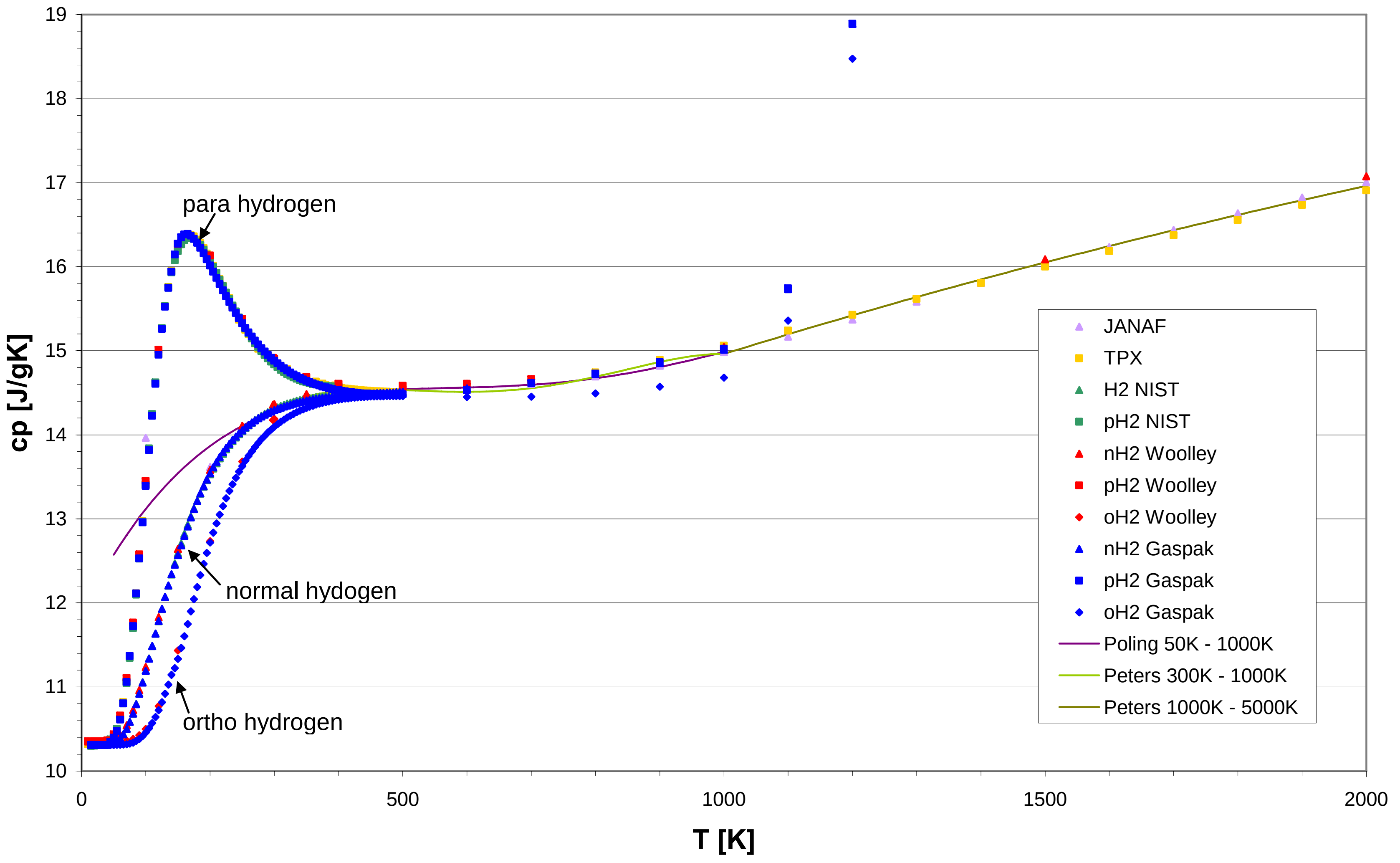


Real gas effects: pvT-surface of pure normal substances

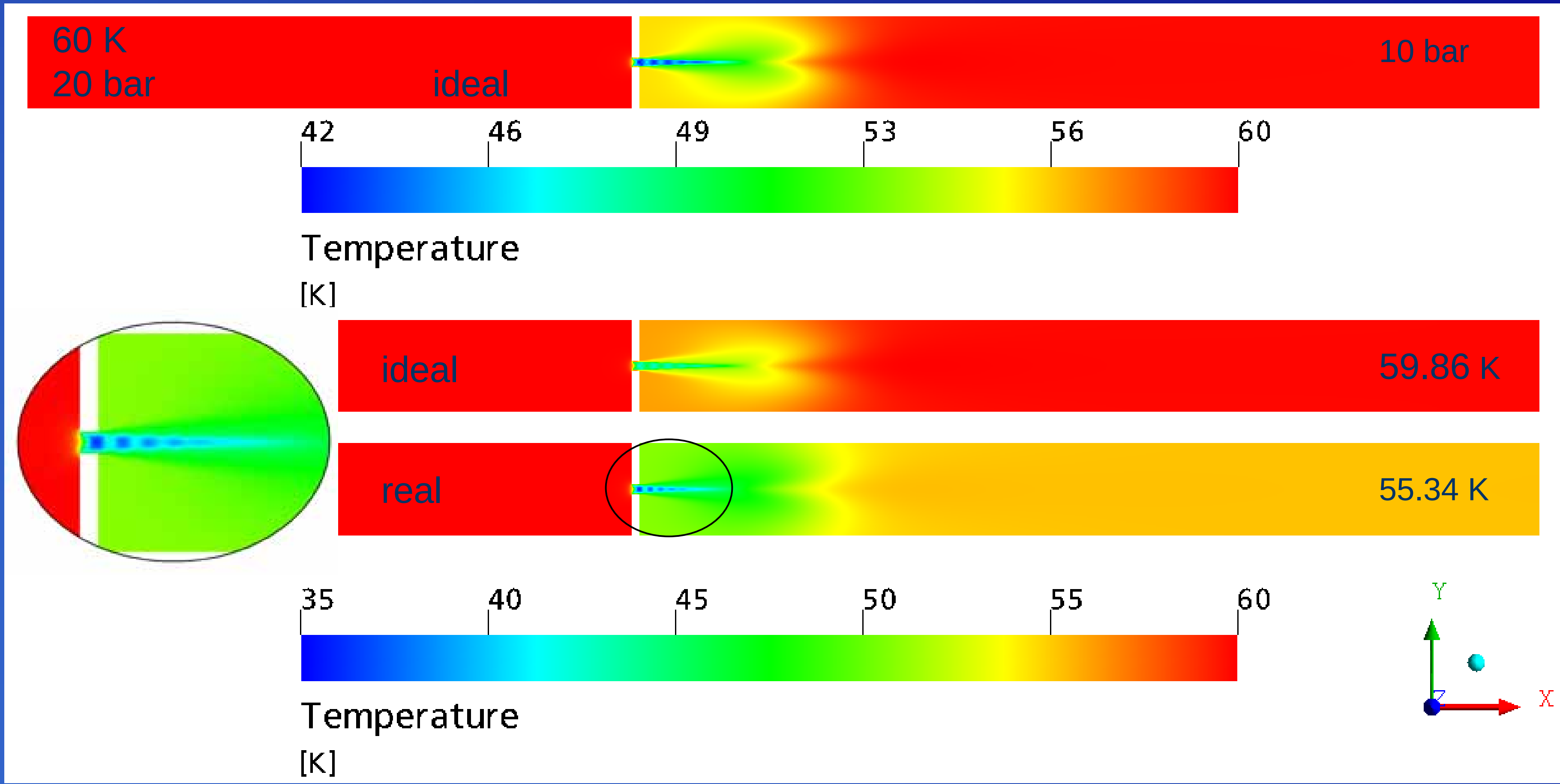


$$p = \frac{RT}{v-b} - \frac{a}{v(v+b)\sqrt{T}}$$

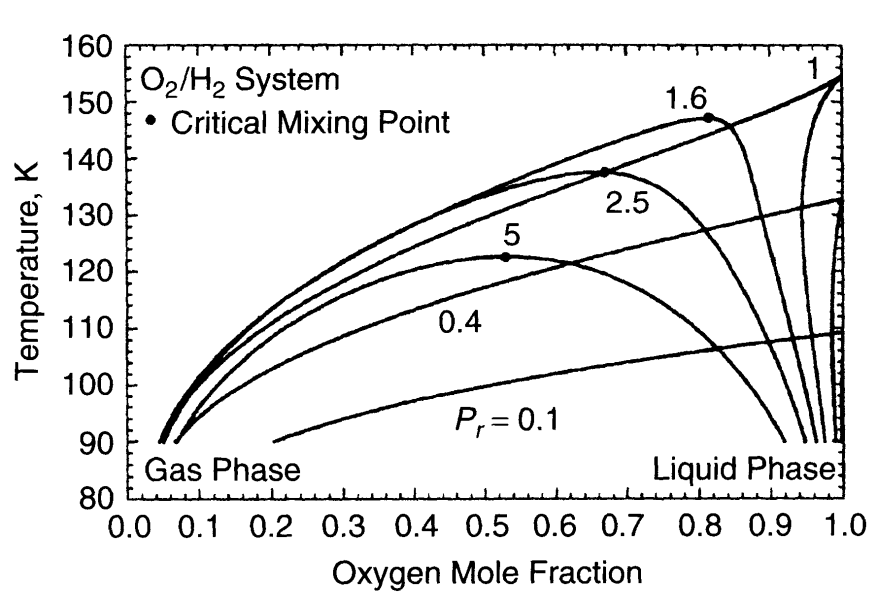
pvT-data for hydrogen

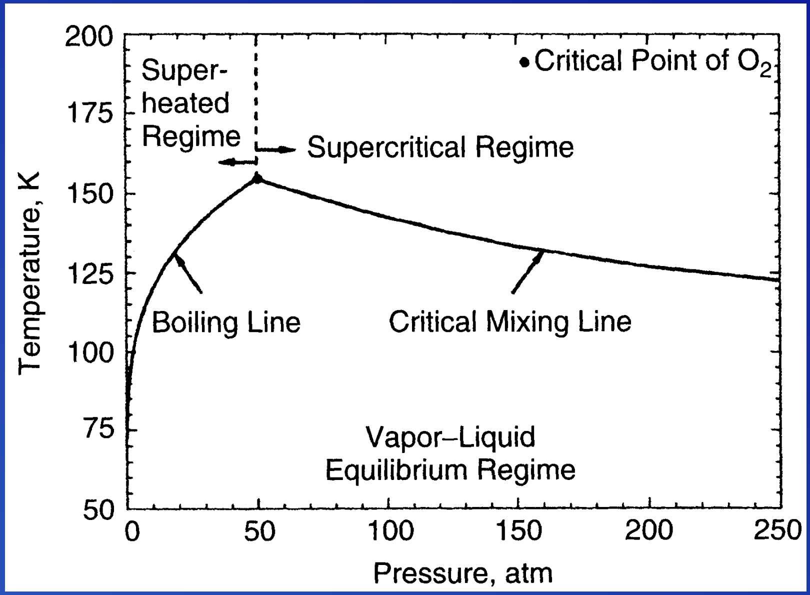


H2 specific heat at low temperatures



Hydrogen Joule-Thomson effect

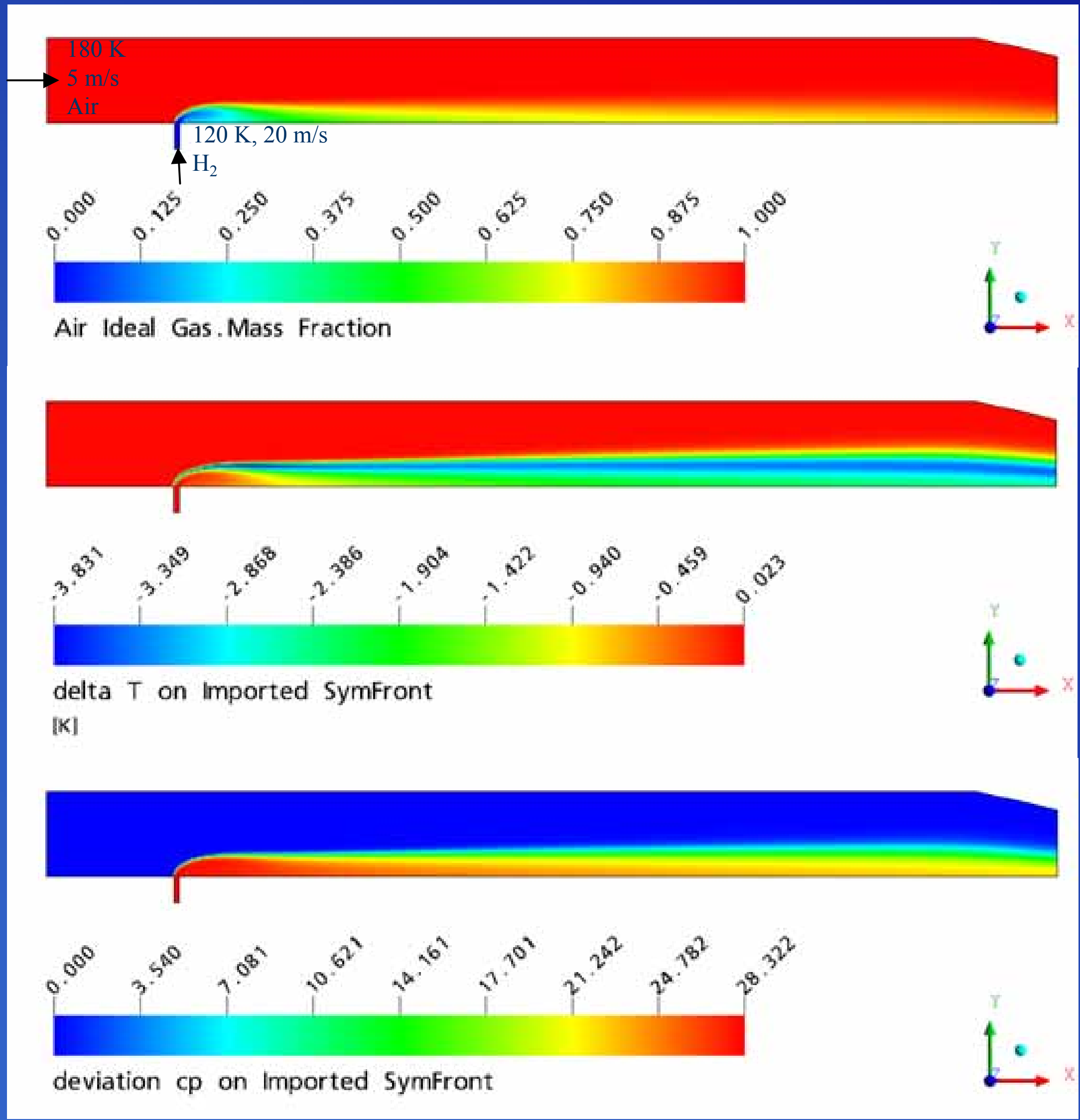




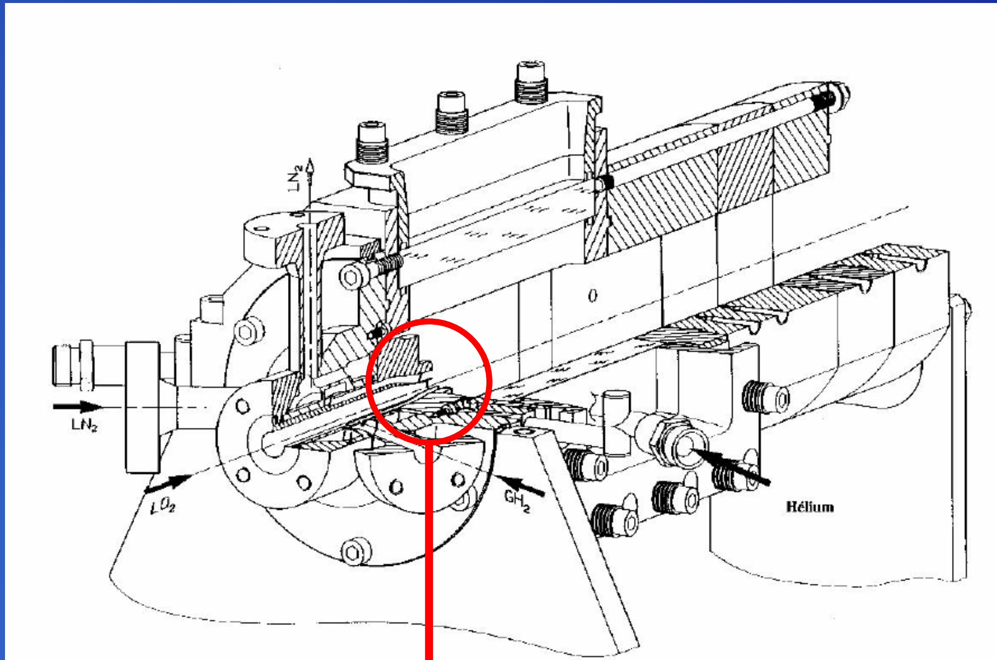
Critical mixture temperature

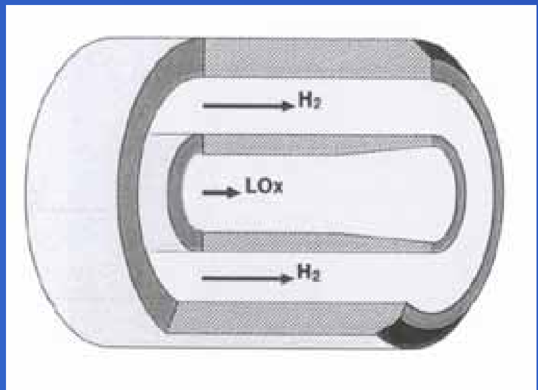
Critical mixture regime

H_2-O_2 Supercritical mixing regine



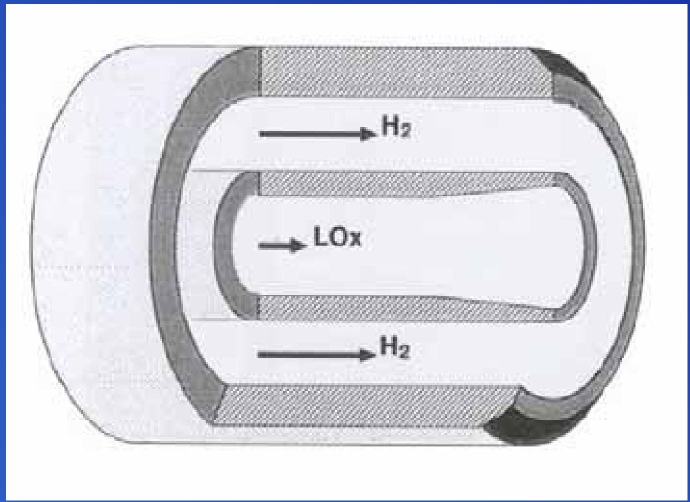
Injection of para and ortho hydrogen in air

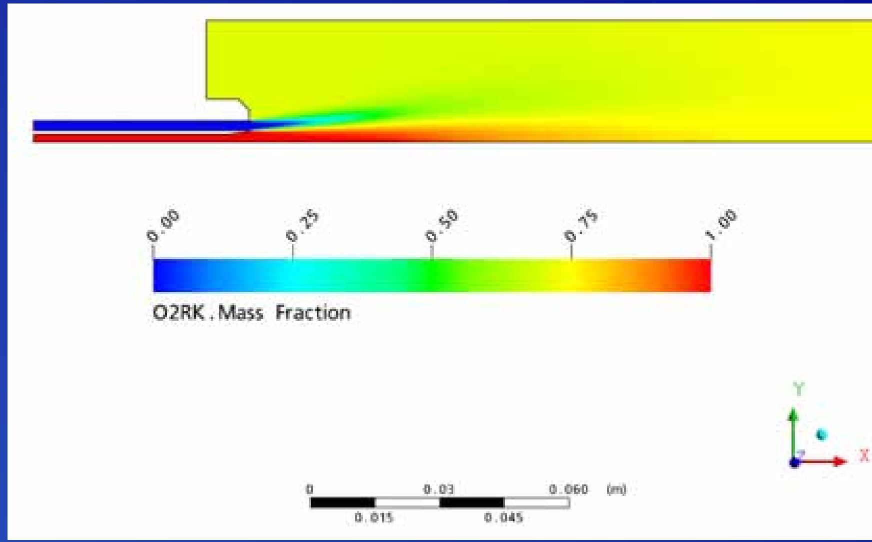


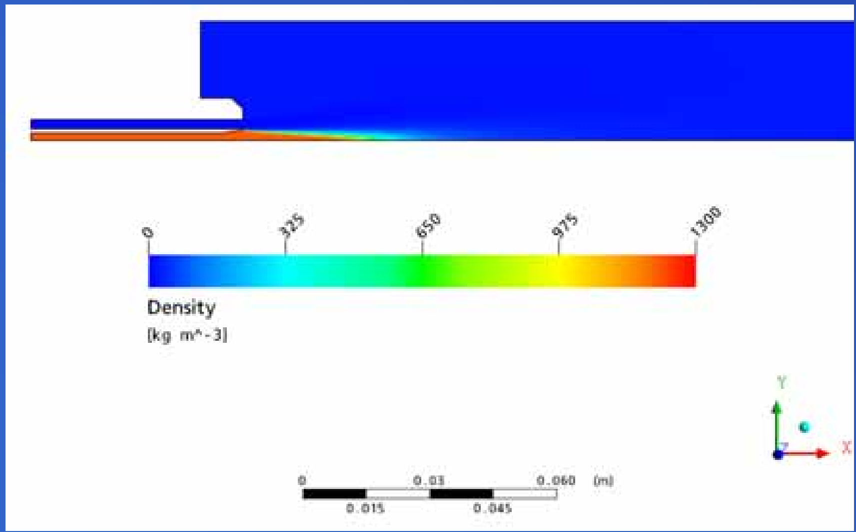


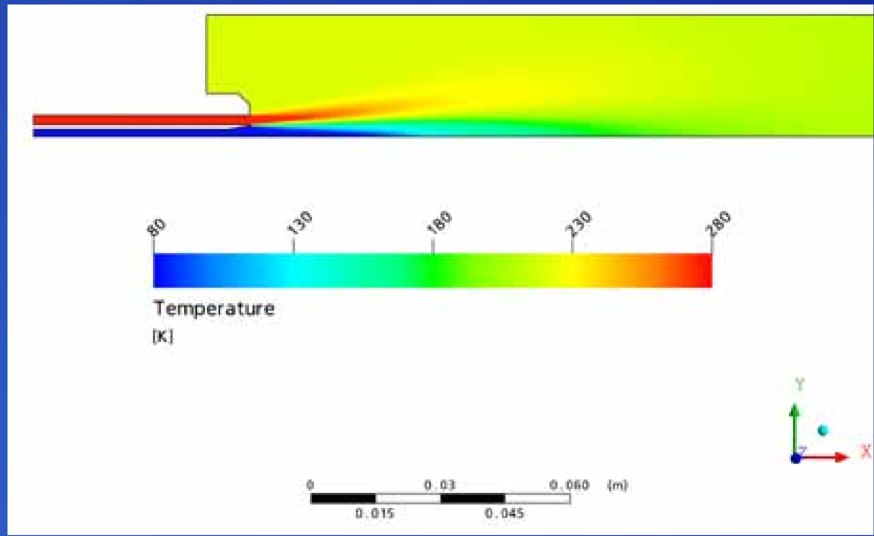
Conditions	H2	O2
Pressure [MPa]	6	6
Massflow [g/s]	42	105
Temperature [K]	275	83
Density [kg/m³]	5.66	1188.3
Cp [J/kg/K]	14412	1663
Velocity [m/s]	138	4.5
Viscosity [kg/m/s]	8.61e-4	2.57e-4

Mascotte single injector validation case









Mascotte real gas cold mixing results

- Modelling of partially premixed turbulent flames by combination of premixed and non-premixed concepts
- Reduced chemistry if only temperature / main species required
- Models validated at atmospheric / medium pressure
- Application to gas turbine / ICE / rocket motor combustion
- Real gas effects: important in rocket motors
- additional equations → new effects → extended models

Conclusions