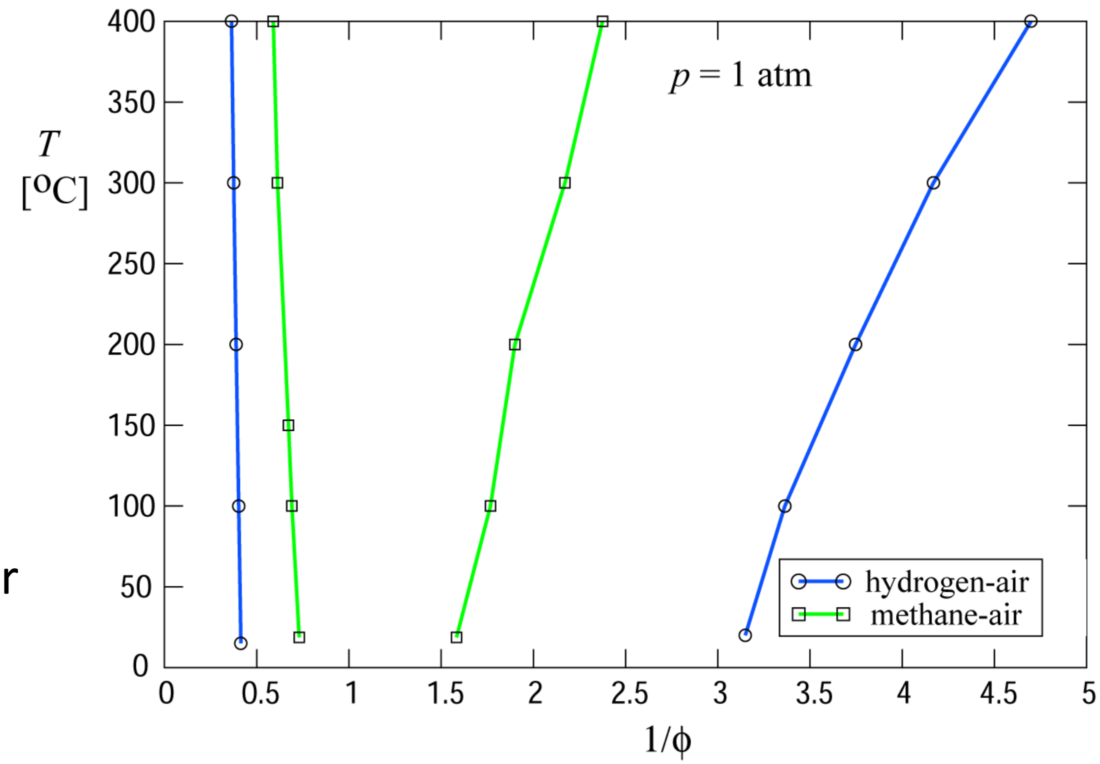
Lecture 7

Flame Extinction and Flamability Limits

- Lean and rich flammability limits are a function of temperature and pressure of the original mixture

- Flammability limits of methane and hydrogen for increasing temperatures as function of air-fuel equivalence ratio

- For lean mixtures (RHS of the diagram), flammability limits of hydrogen extend to much larger values than for methane

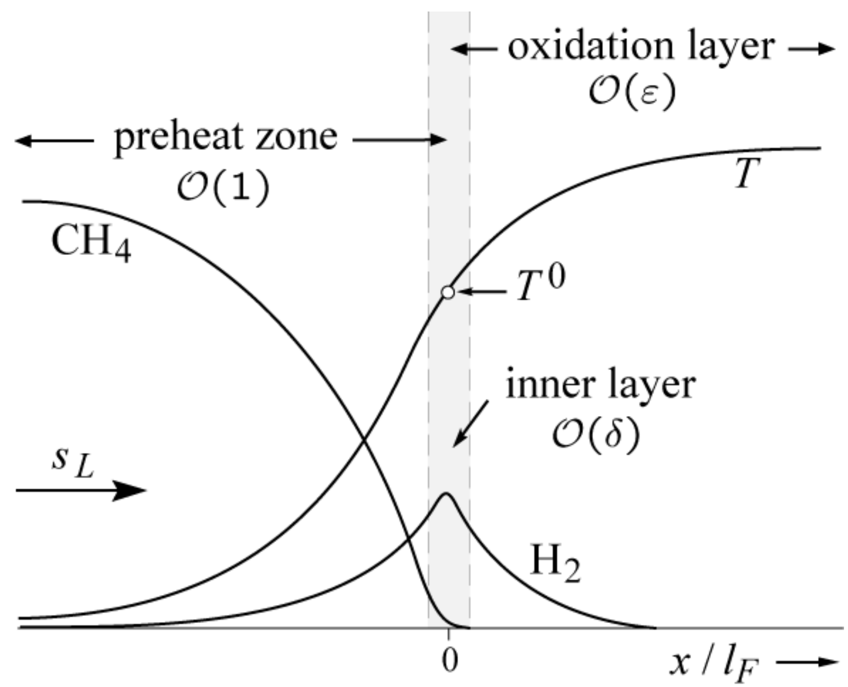


- This shows that hydrogen leakage may cause greater safety hazards than, for instance, hydrocarbons, which have flammability limits close to those of methane

Lean Flammability Limits of Hydrocarbon Flames

- Definition: Flammability is the ability of an ignited mixture to enable flame propagation without further heat addition

- This requires that a sufficient amount of fuel is available to reach a temperature that, in view of the flame structure, should exceed the inner layer temperature T^0
- Le Chatelier in 1891 was the first to point towards a criterion that relates the flammability limit to the thermodynamic properties of the fuel mixture.



- In 1898, Le Chatelier and Boudouard investigated experimental data and wrote:

  The flammability limit of most hydrocarbons corresponds to a heat of combustion close to 12.5 kcal.

- This is essentially Le Chatelier's famous *mixing rule*

- It determines an adiabatic flame temperature and should also be valid for mixtures of hydrocarbons with inerts

- The equation

$$s_L = Y_{Fu}^m A(T^0) \frac{T_u}{T^0} \left(\frac{T_b - T^0}{T_b - T_u} \right)^n$$

  shows that the burning velocity vanishes if the adiabatic flame temperature is equal to the inner layer temperature

- A lower theoretical bound for the lean flammability limit is therefore given by

$$T_b = T^0$$

- In view of this criterion, the adiabatic flame temperature identified by Le Chatelier and Boudouard corresponds to the inner layer temperature and thus describes a chemical rather than a thermodynamic property

- As the lean flammability limit is approached, the burning velocity drops sharply, but shows a finite value at the limiting point
- Egerton and Thabet and Powling report a value of 5 cm/s at atmospheric pressure using flat flame burners
- Experimental data for the lean flammability limit are always influenced by external disturbances, such as radiative heat loss or flame stretch

- We note that flame extinction occurs at a finite value of the burning velocity

- $T_b = T^0$ may be used to calculate the limiting fuel mass fraction $(Y_{\mathrm{F},u})_{l.l.}$ as a quantity that determines the flammability limit

- At the flammability limit, it is accurate enough to assume complete combustion and to determine T_b as a function of $Y_{\mathrm{F},u}$ and T_u (Lecture 2):

$$T_b - T_u = \frac{Q_{\mathrm{ref}} Y_{\mathrm{F},u}}{c_p \nu'_{\mathrm{F}} W_{\mathrm{F}}}$$

- Then, with $T_b = T^0$, one obtains

$$(Y_{\mathrm{F},u})_{l.l.} = \frac{(T^0 - T_u) c_p \nu'_{\mathrm{F}} W_{\mathrm{F}}}{Q_{\mathrm{ref}}}$$

$(Y_{\mathrm{F},u})_{l.l}$ decreases linearly with increasing T_u

Comparison of experimental data for the lean limit CH_4 mole fraction from Hustad & Sonju (1988) for different preheat temperatures with the two criteria