On the accurate determination of laminar burning velocity from constant-volume propagating spherical flames

Zheng Chen, Yiqing Wang

College of Engineering, Peking University

北京大學
Peking University

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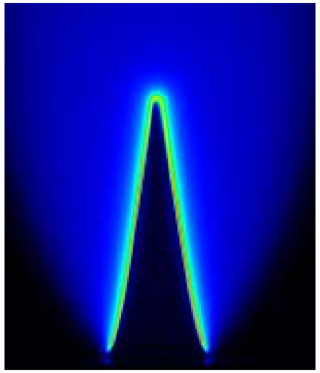
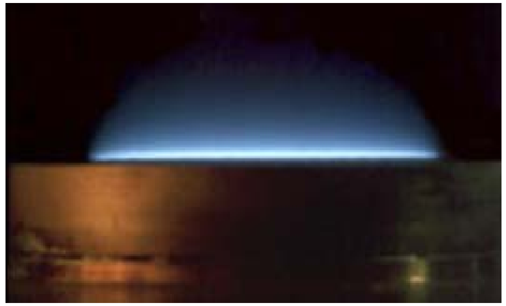
Laminar flame speed measurements





Stationary flame method:

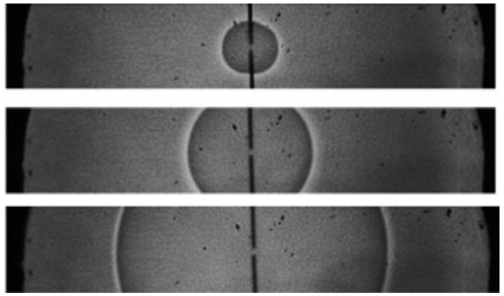
- ☐ Bunsen flame
- ☐ flat flame (heat flux method)
- ☐ counterflow or stagnation flame

Propagating flame method:

- ☐ cylindrical tube method
- ☐ soap bubble method
- ☐ propagating spherical flame method

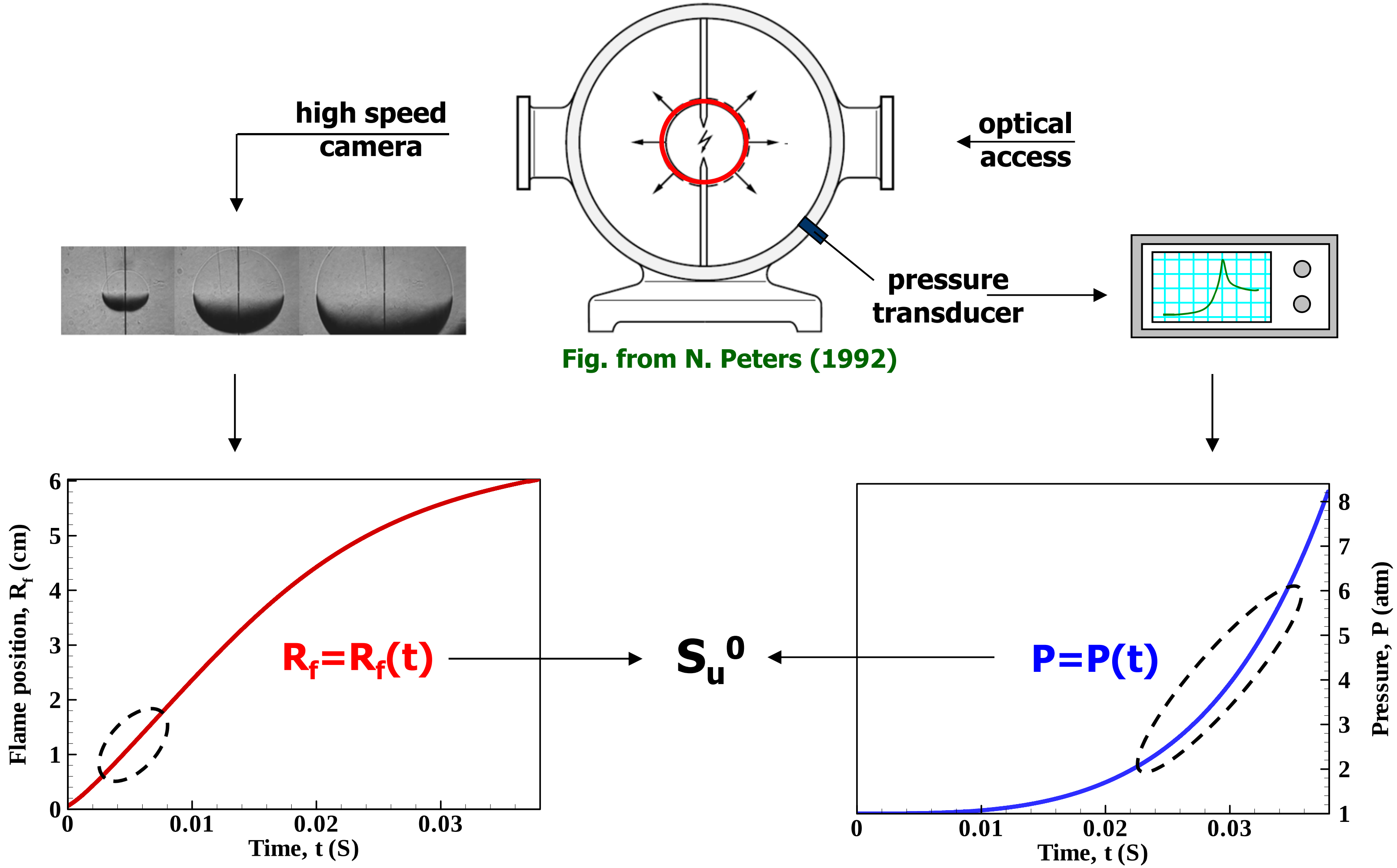
↑

High pressure & temperature !



Figures from Egolfopoulos et al., Prog. Energy Comb. Sci. 43 (2014).

Propagating spherical flame method



Constant-Pressure Method

small flame, negligible P rise

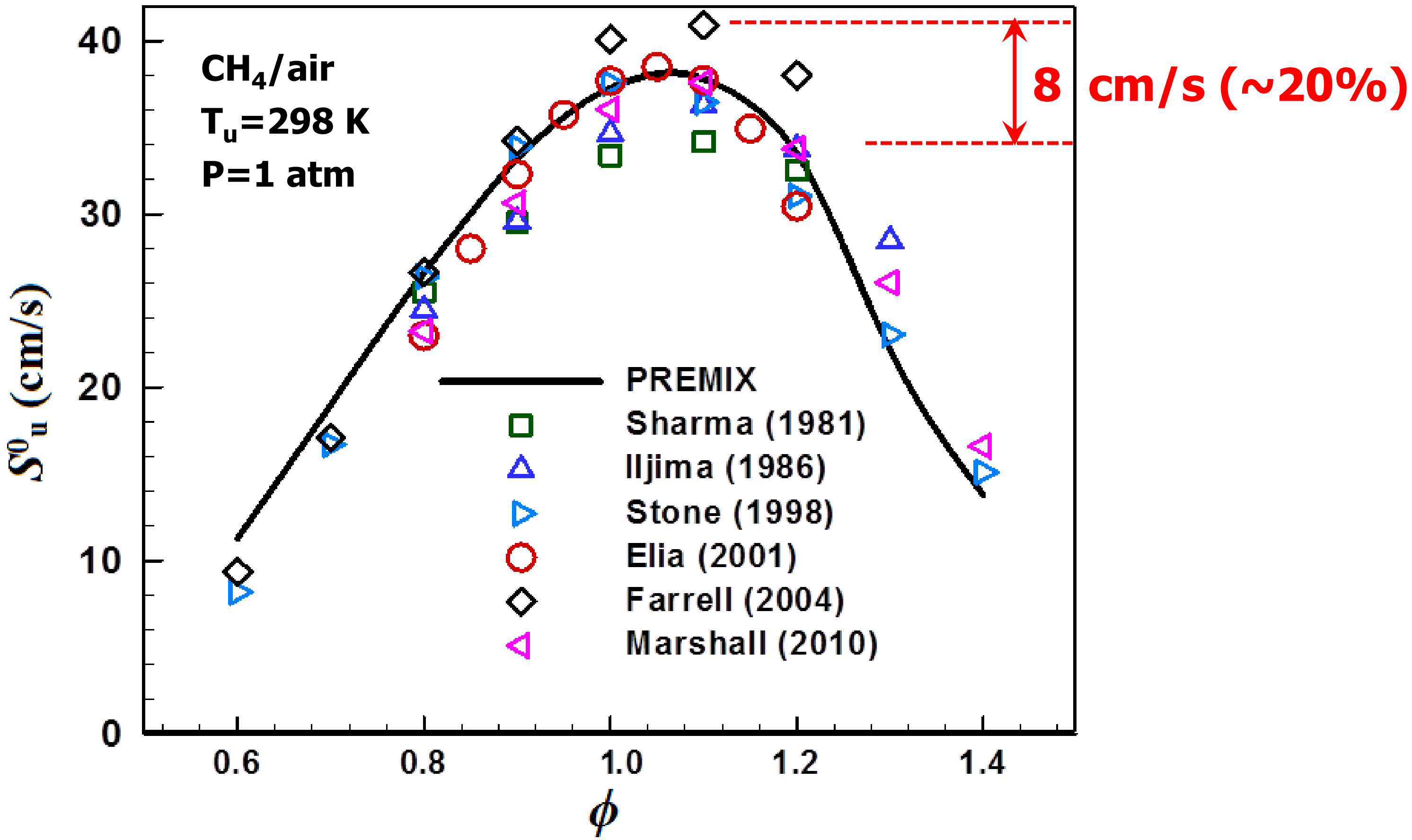
Both S_u^0 and Markstein length

Constant-Volume Method

large flame with P rise

Engine-relevant T_u and P

Data from the constant-volume method

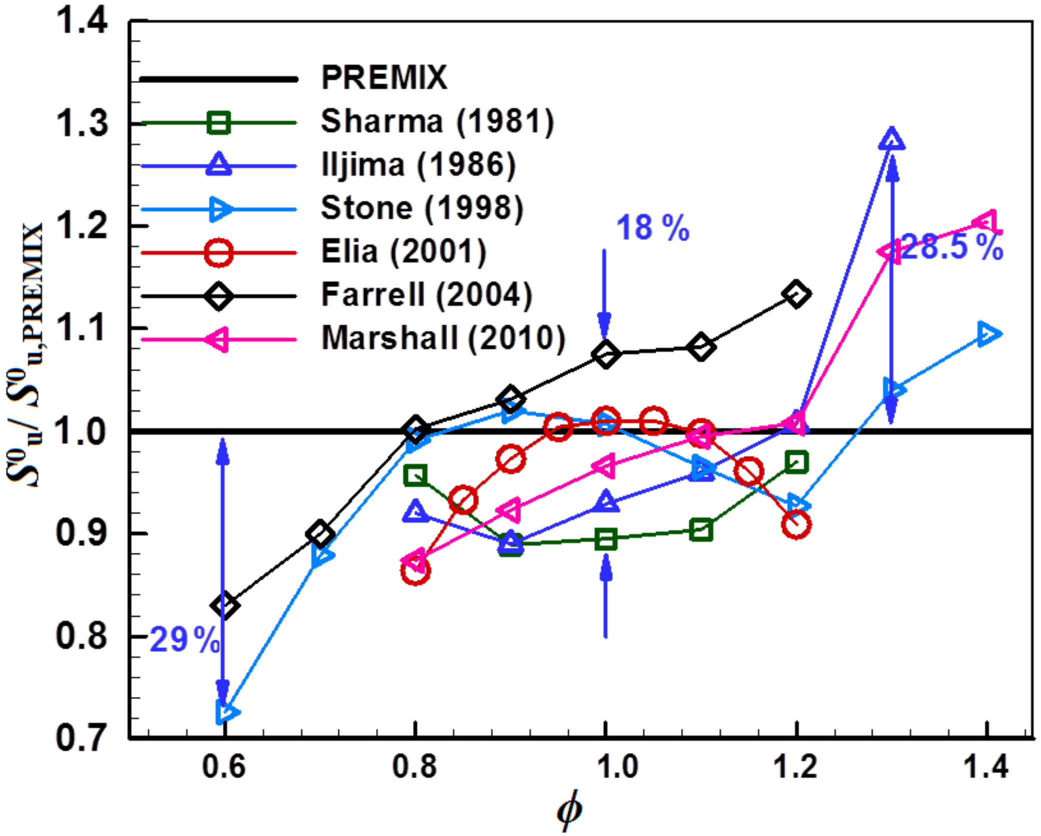


- **Same constant-volume method for the same fuel CH_4**
- **Large discrepancy !**

M. Faghih, Z. Chen, The constant-volume propagating spherical flame method for laminar flame speed measurement, Science Bulletin, 61 (2016) 1296-1310.

Discrepancy among S_u^0 measured by OPF

CH_4/air, T_u=298 K, P=1 atm

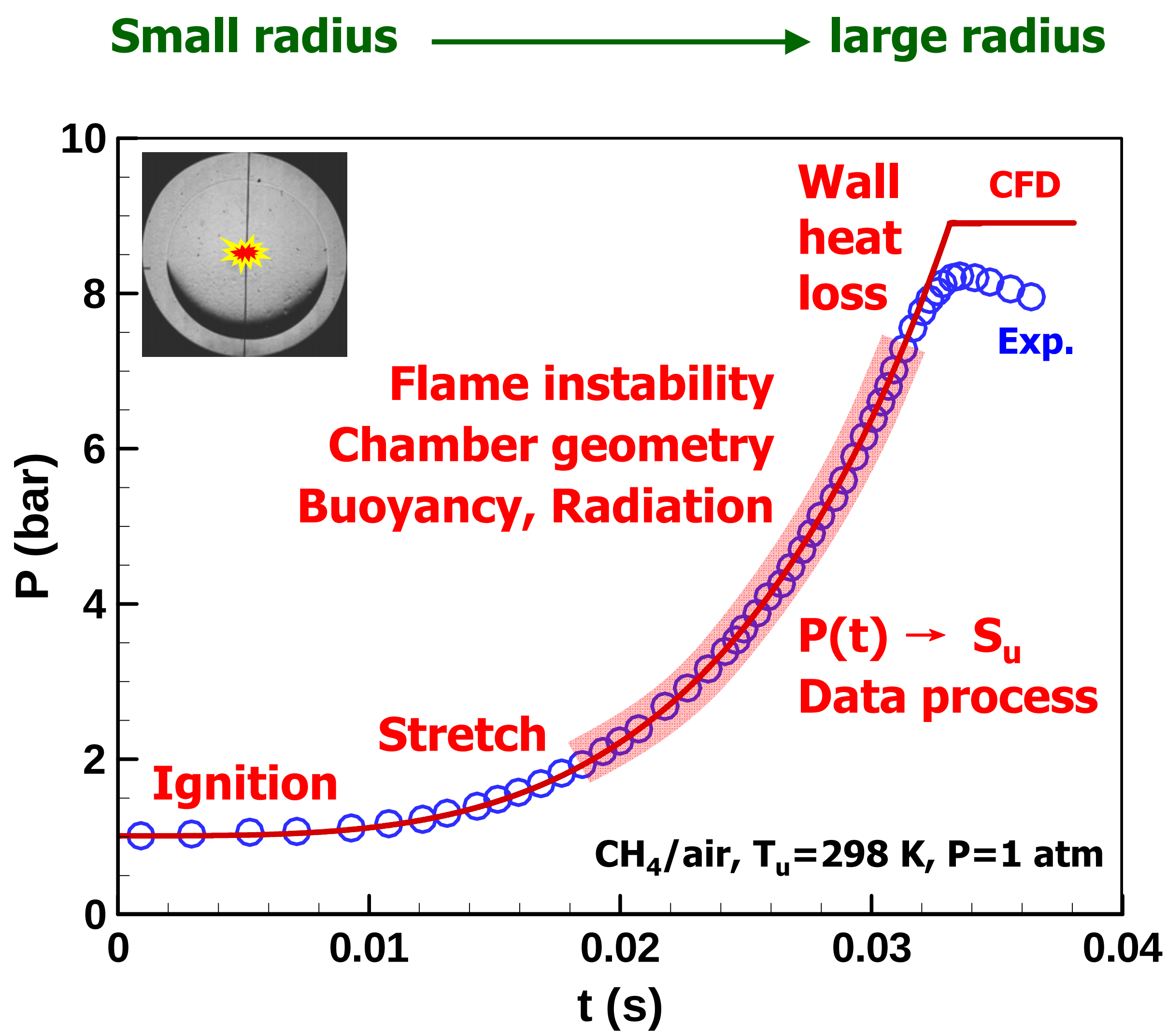


Normalized by prediction of GRI Mech 3.0

- **Large discrepancy, 18%, at ϕ=1**
- **Large discrepancy at very lean or rich conditions**

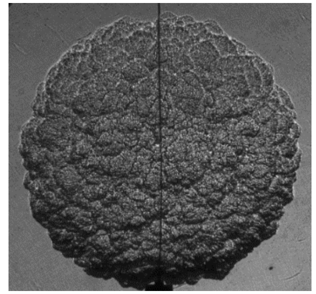
M. Faghih, Z. Chen, The constant-volume propagating spherical flame method for laminar flame speed measurement, Science Bulletin, 61 (2016) 1296-1310.

Possible causes for uncertainty



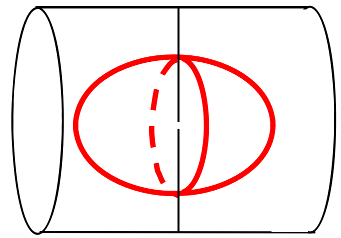
Symbols: Exp. (Movileanu et al. 2009); Line: CFD

Flame instability

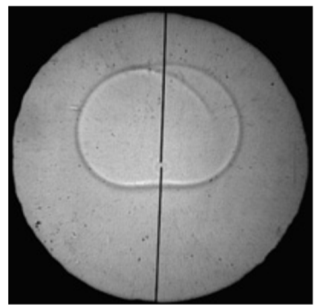


(Jomaas et al. 2013)

Cylindrical chamber



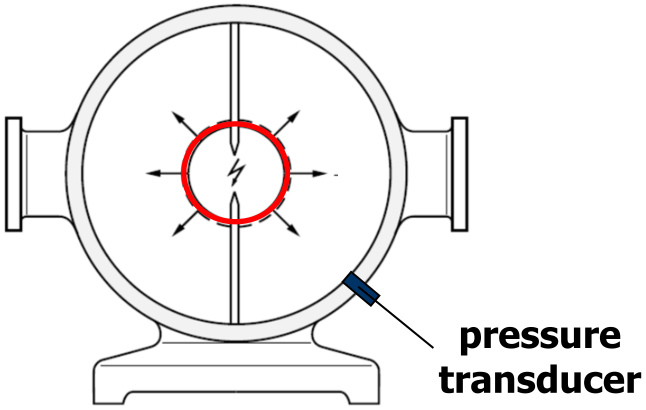
Buoyancy



(Qiao et al. 2007)

Data process

- **Assumptions**
  - 1D spherical flame, no instability
  - ideal gas, uniform pressure distribution
  - isentropic compressed of unburned gas
  - negligible radiation and buoyancy …



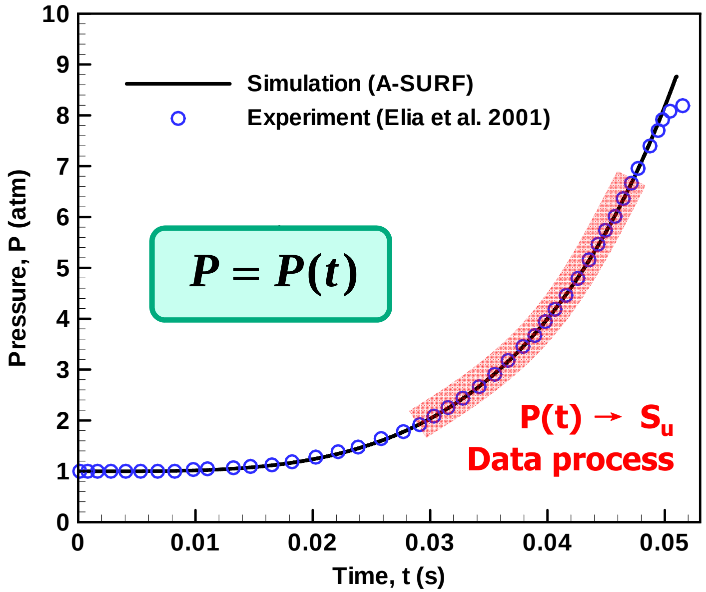
(N. Peters 1992)

$$S_u = \frac{dR_f}{dt} - \frac{R_W^3 - R_f^3}{3P\gamma_u R_f^2}\frac{dP}{dt}$$

$$\frac{R_f}{R_W} = \left[1-(1-x)\left(\frac{P_0}{P}\right)^{1/\gamma_u}\right]^{1/3}$$

$$S_u = \frac{R_W}{3}\left[1-(1-x)\left(\frac{P_0}{P}\right)^{1/\gamma_u}\right]^{-2/3}\left(\frac{P_0}{P}\right)^{1/\gamma_u}\frac{dx}{dt}$$

$$S_u = S_u(P) \qquad T_u / T_{u,0} = (P/P_0)^{(1-1/\gamma_u)}$$



x: burned mass fraction, $x=m_b/m_0$, $x=x(P)$

Data process

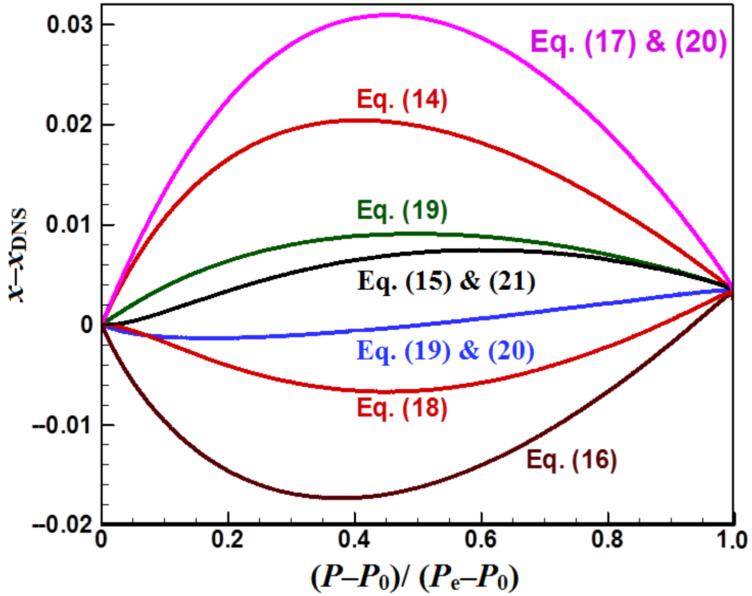
CH$_4$/air, ϕ=1, T_{u0}=300 K, P_0=1 atm

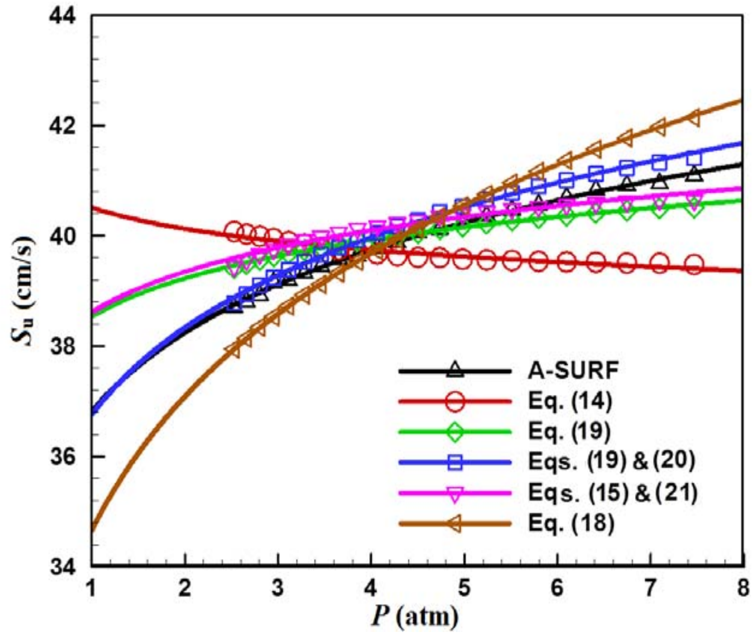
$$S_u = \frac{R_W}{3}\left[1-(1-x)\left(\frac{P_0}{P}\right)^{1/\gamma_u}\right]^{-2/3}\left(\frac{P_0}{P}\right)^{1/\gamma_u}\frac{dx}{dt}$$

x: burned mass fraction, $x=m_b/m_0$, $x=x(P)$

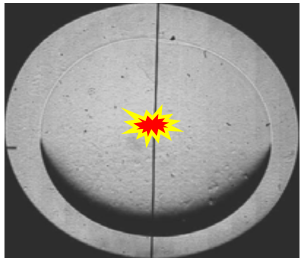
Correlation		Year	Eq. nos.
$x=\frac{(P-P_0)}{(P_e-P_0)}$	Lewis & von Elbe	1951	(14)
$x(P)=\frac{(\bar{T}_e/\bar{T}_b)\left(P/P_0-(P/P_0)^{(\gamma_u-1)/\gamma_u}\right)}{P_e/P_0-(\bar{T}_e/\bar{T}_b)(P/P_0)^{(\gamma_u-1)/\gamma_u}}$		1959	(15)
$x(P)=\frac{P-P_0(P/P_0)^{(\gamma_u-1)/\gamma_u}}{P_e-P_0(P/P_0)^{(\gamma_u-1)/\gamma_u}}$		1963	(16)
$x(P)=\frac{P^{1/\gamma_u}-P_0^{1/\gamma_u}}{P_e^{1/\gamma_b}P^{(1/\gamma_u-1/\gamma_b)}-P_0^{1/\gamma_u}}$		1969	(17)
$x(P)=\frac{\alpha\left[(P/P_0)^{1/\gamma_u}-1\right]}{(P/P_0)^{1/\gamma_u}-\alpha},\ \alpha=\frac{\rho_b^0}{\rho_0}+\frac{(1-\rho_b^0/\rho_0)(P/P_0-1)}{(P_e/P_0-1)}$		1980	(18)
$x=\frac{P-P_0f(P)}{P_e-P_0f(P)},\ f(P)=\frac{\gamma_b-1}{\gamma_u-1}+\frac{\gamma_u-\gamma_b}{\gamma_u-1}\left(\frac{P}{P_0}\right)^{(\gamma_u-1)/\gamma_u}$	Luijten et al.	2009	(19)
$x(P)=\frac{(\bar{T}_e/\bar{T}_b)\left(P/P_0-(P/P_0)^{(\gamma_u-1)/\gamma_u}\right)}{P_e/P_0-(\bar{T}_e/\bar{T}_b)(P/P_0)^{(\gamma_u-1)/\gamma_u}},\ \frac{\bar{T}_e}{\bar{T}_b}=\left(\frac{P_e}{P}\right)^{(\gamma^*-1)/\gamma^*},\ \gamma^*=\ln\left(\frac{P_e}{P_0}\left(1-\frac{T_{f,p}}{T_{f,v}}\right)\right)$		1994	(15), (21)
$x=\frac{P-P_0f(P)}{P_e-P_0f(P)},\ f(P)=\frac{\gamma_b-1}{\gamma_u-1}+\frac{\gamma_u-\gamma_b}{\gamma_u-1}\left(\frac{P}{P_0}\right)^{(\gamma_u-1)/\gamma_u},\ \gamma_{b,shift}=\frac{\gamma_b+8}{8}$		2016	(19), (20)

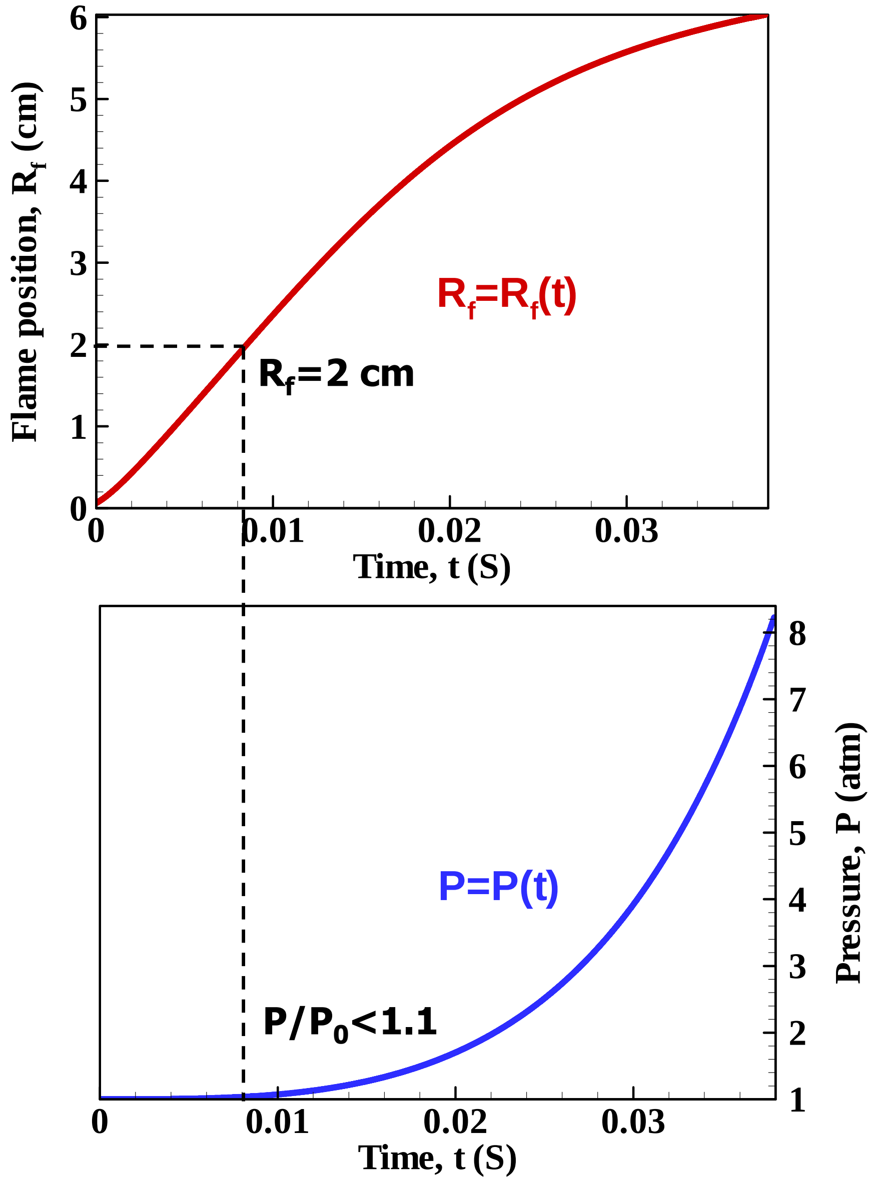
M. Faghih, Z. Chen, The constant-volume propagating spherical flame method for laminar flame speed measurement, Science Bulletin, 61 (2016) 1296-1310.





Ignition





- **Important for the constant-pressure method**
- **Negligible for the constant-volume method**

Stretch

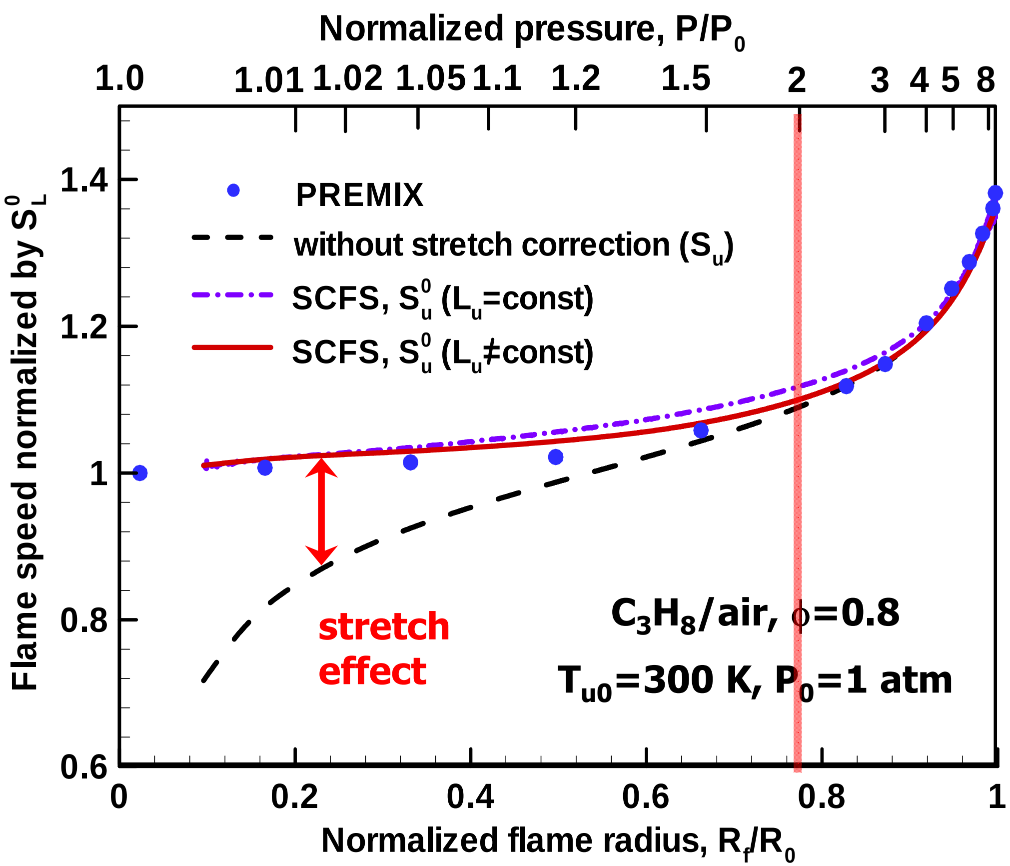
Chen et al. (2009CTM)

$$K = \frac{2}{R_f}\frac{dR_f}{dt}$$

$$S_u = S_u^0 - L_u K$$

$$\frac{S_u^0 - S_u}{S_u^0} \approx \frac{2L_u}{R_f}\left(\frac{\gamma_u - 1}{\gamma_u} + \frac{P_e}{\gamma_u P}\right)$$

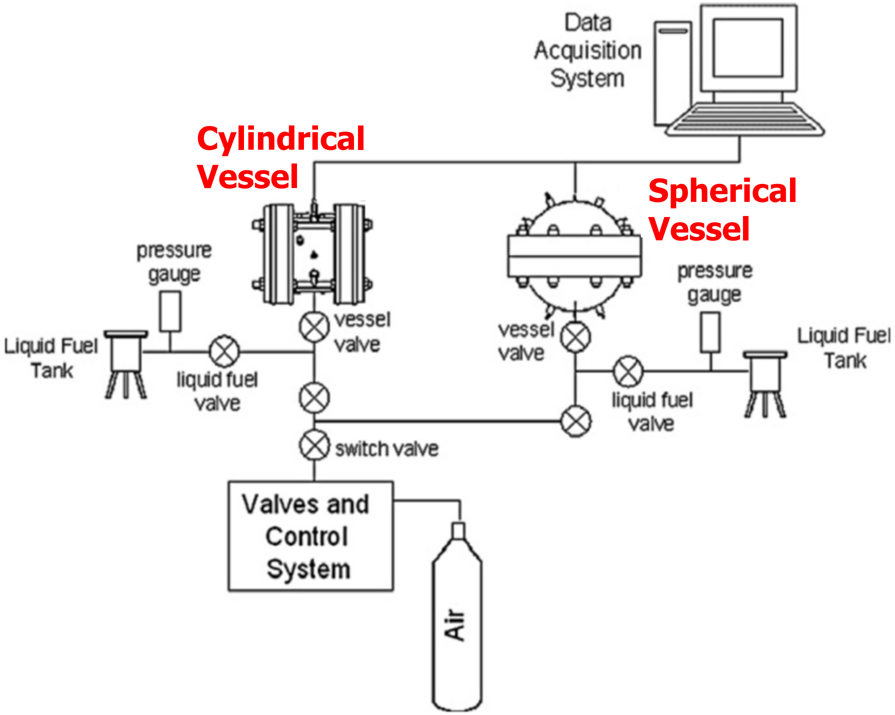
Stretch effect



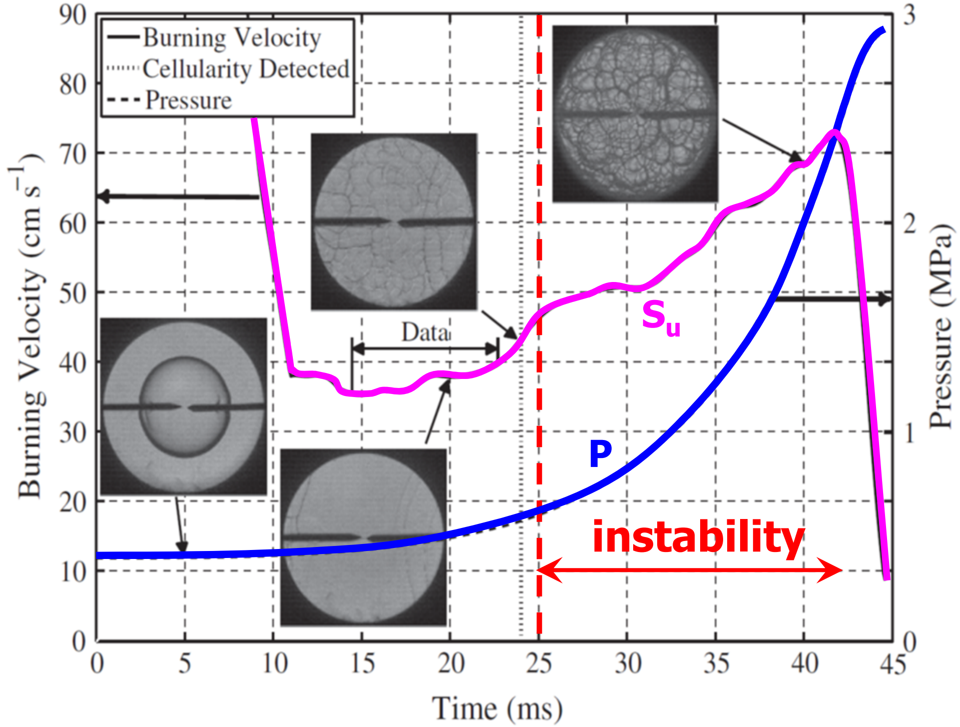
- Important only at the beginning; negligible for $P/P_0 > 2$
- Negligible for high pressures

Flame instability

18:17



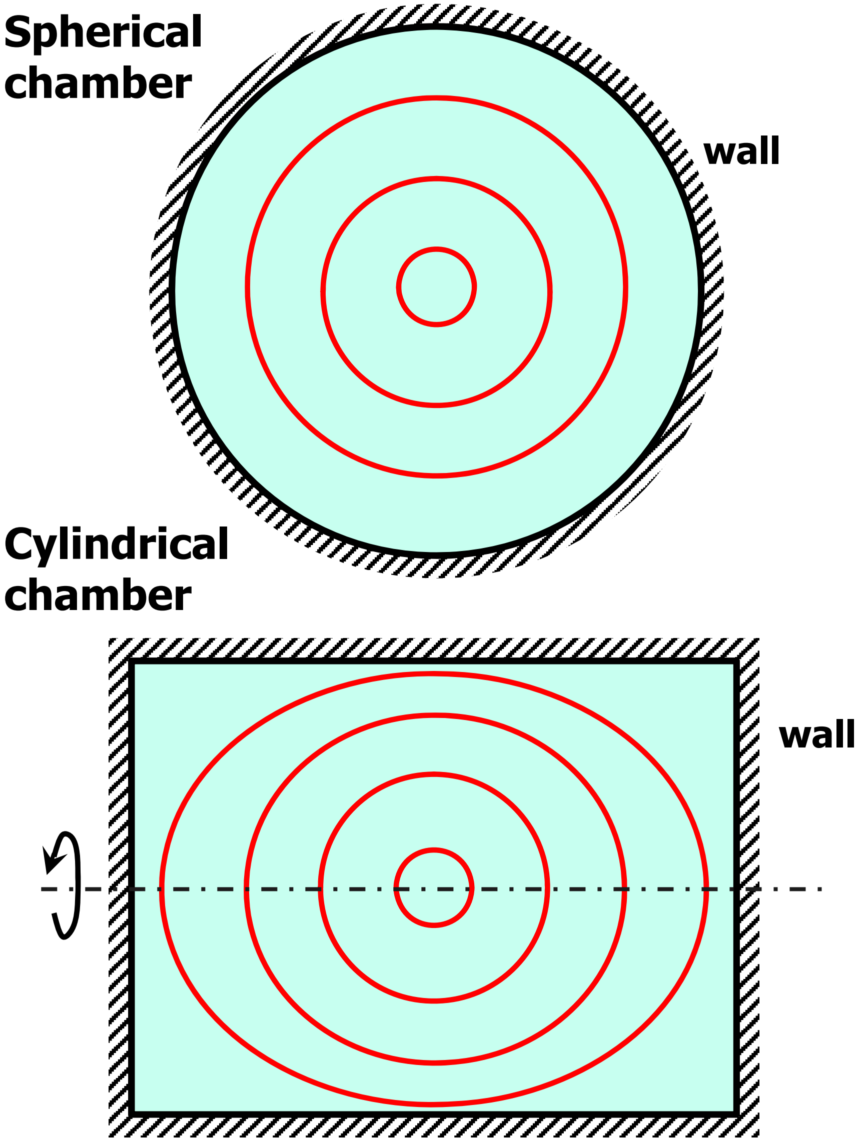
Moghaddas et al. (2012CNF)



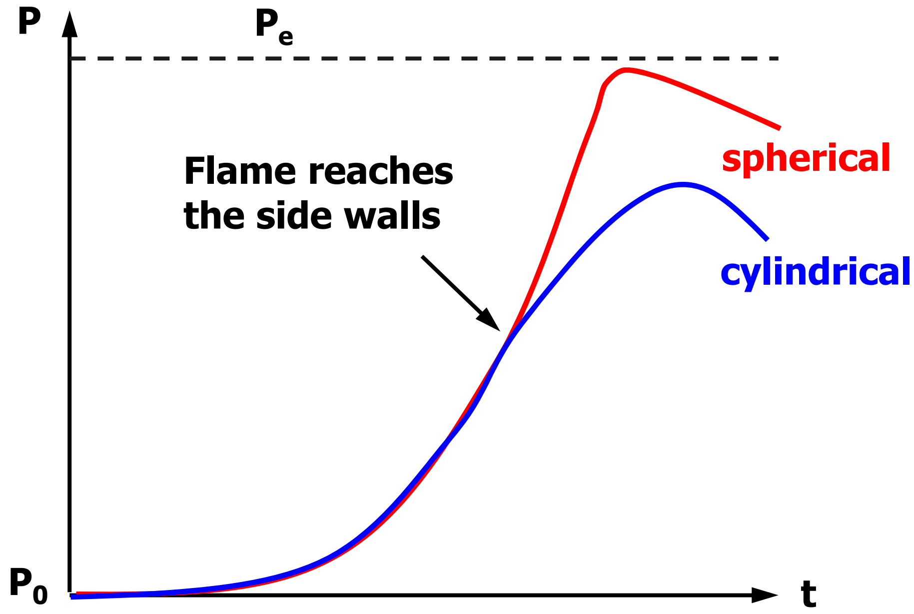
Marshall et al. (2011CNF)

- **Two facilities:**
  - ☐ **Cylindrical chamber, for full optical access and instability**
  - ☐ **Spherical chamber, to preserve sphericity and record P**
- **Single facility: spherical chamber + optical access (Fabien Halter)**

Chamber geometry

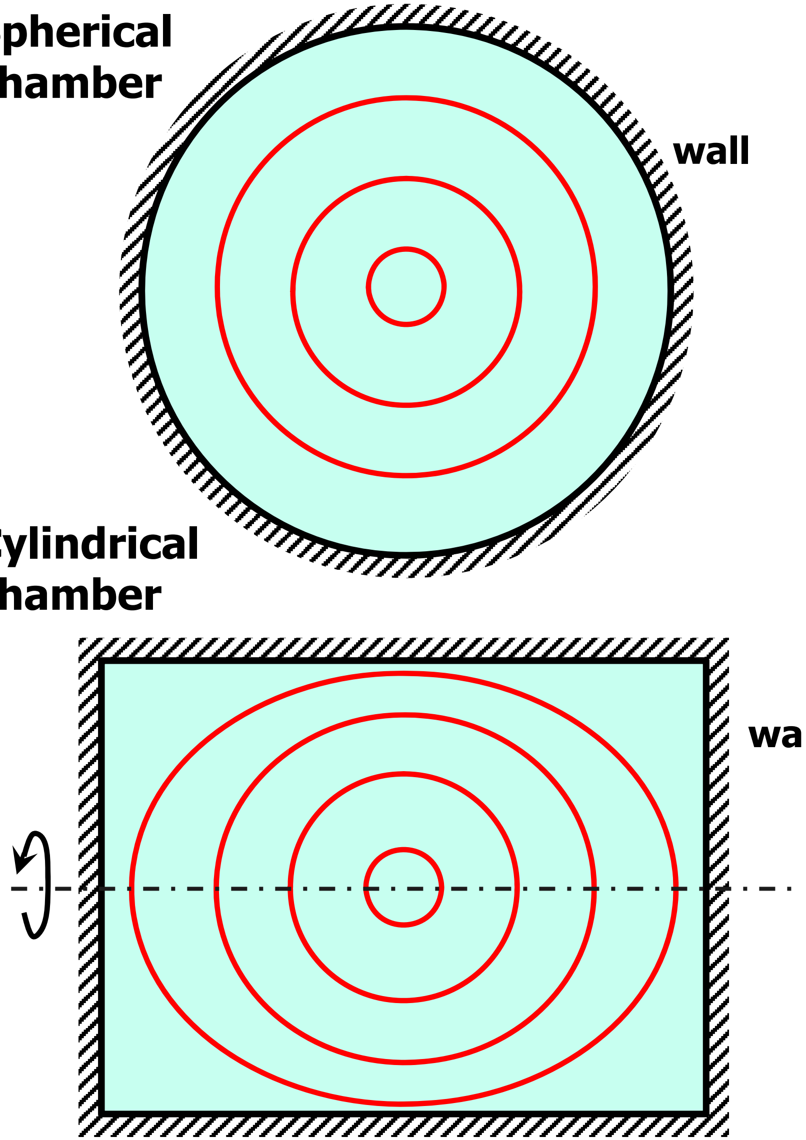


Burke et al. (2010CNF)



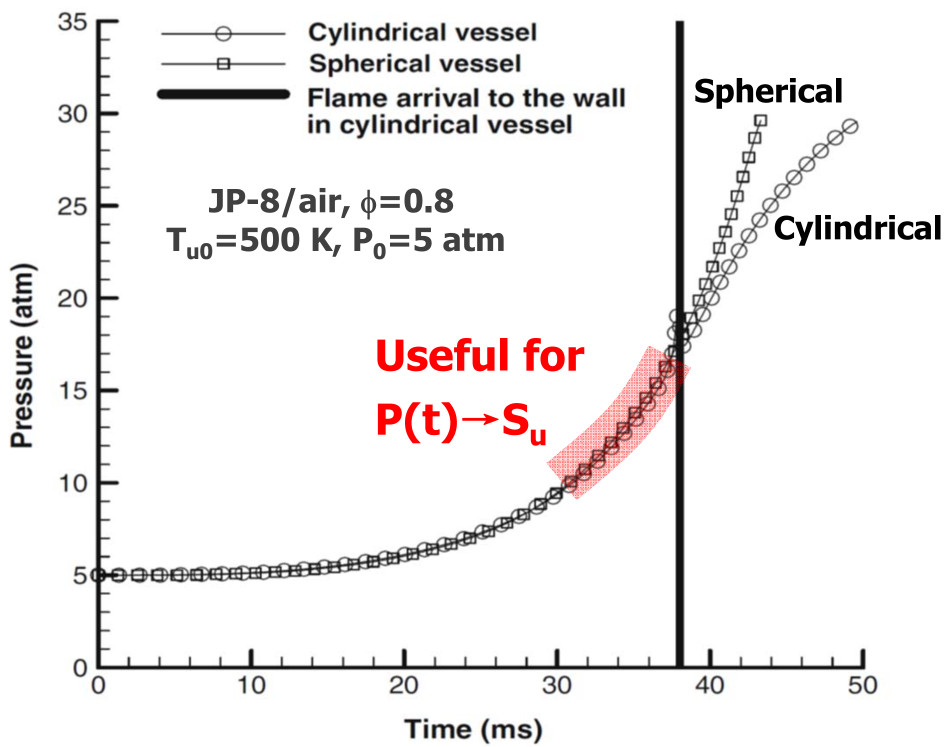
- For the cylindrical chamber, much lower P_{max} than P_e
- Very close pressure history before flame reaches wall

Chamber geometry



Burke et al. (2010CNF)

Exp. by Far et al. (2010Fuel)



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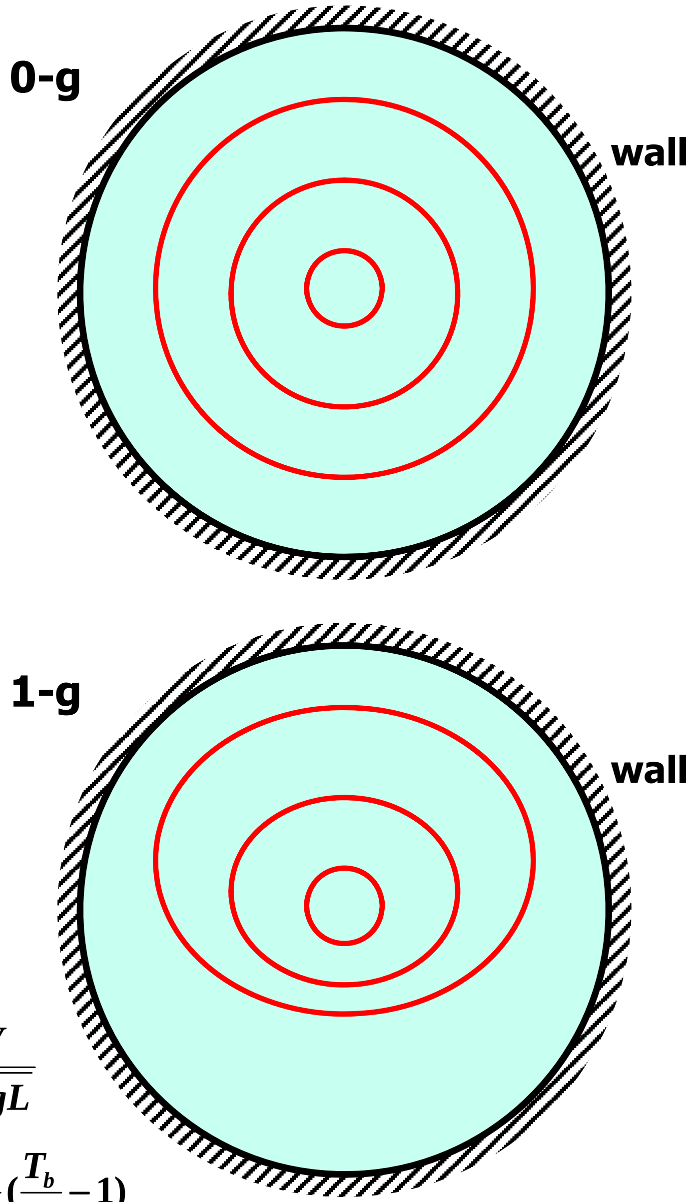
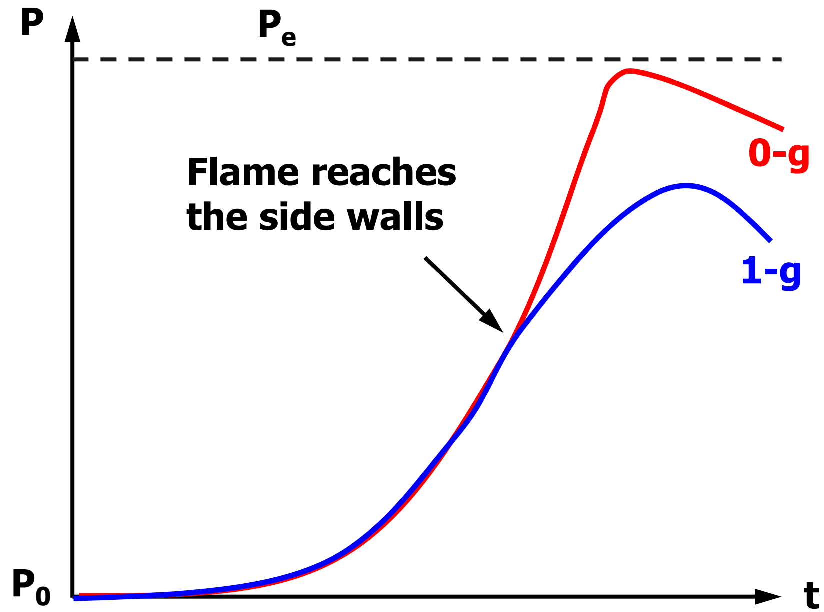
Buoyancy



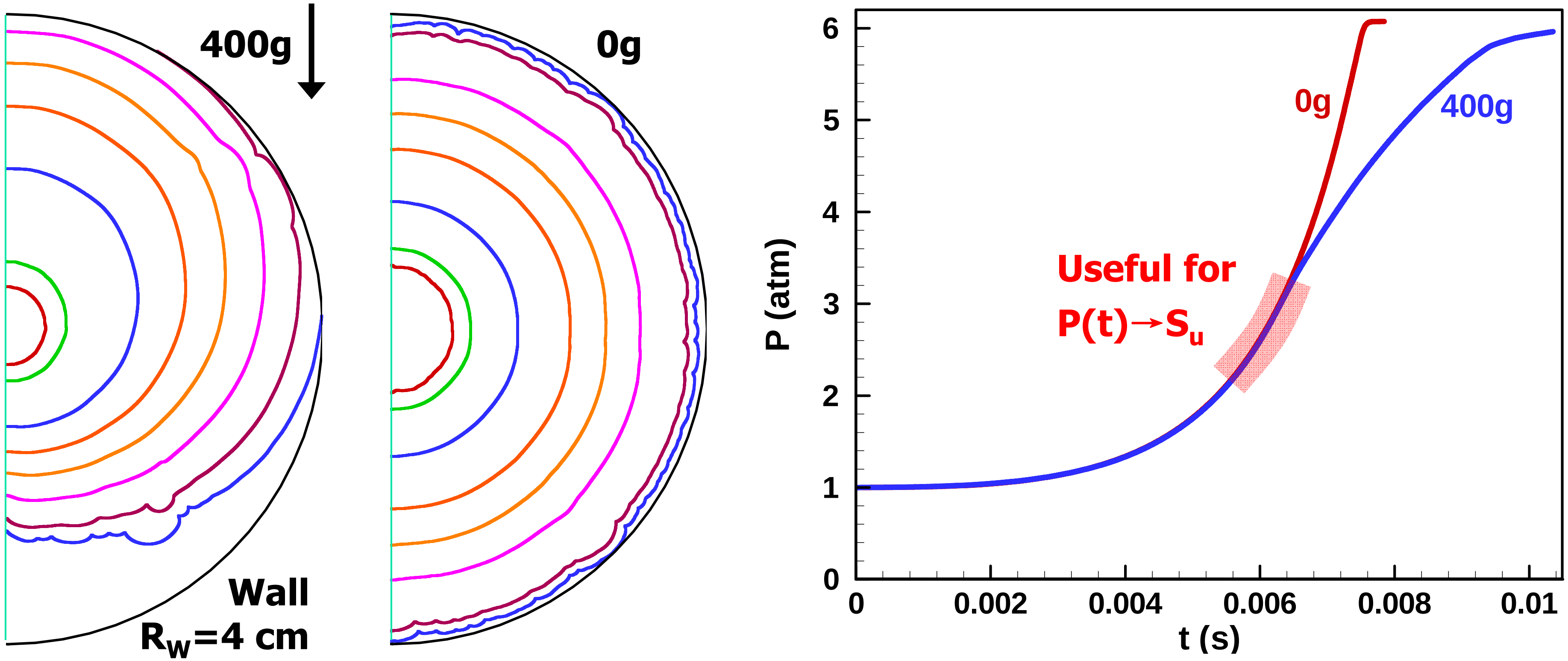
$$Fr = \frac{V}{\sqrt{gL}}$$

$$Ri = \frac{gL}{V^2}\left(\frac{T_b}{T_u} - 1\right)$$



- **Identical at 1-g and μ-g for S_u^0>15 cm/s (Ronney 1985)**
- **Similar pressure history before flame reaches wall**
- **Non-spherical ?**

Buoyancy

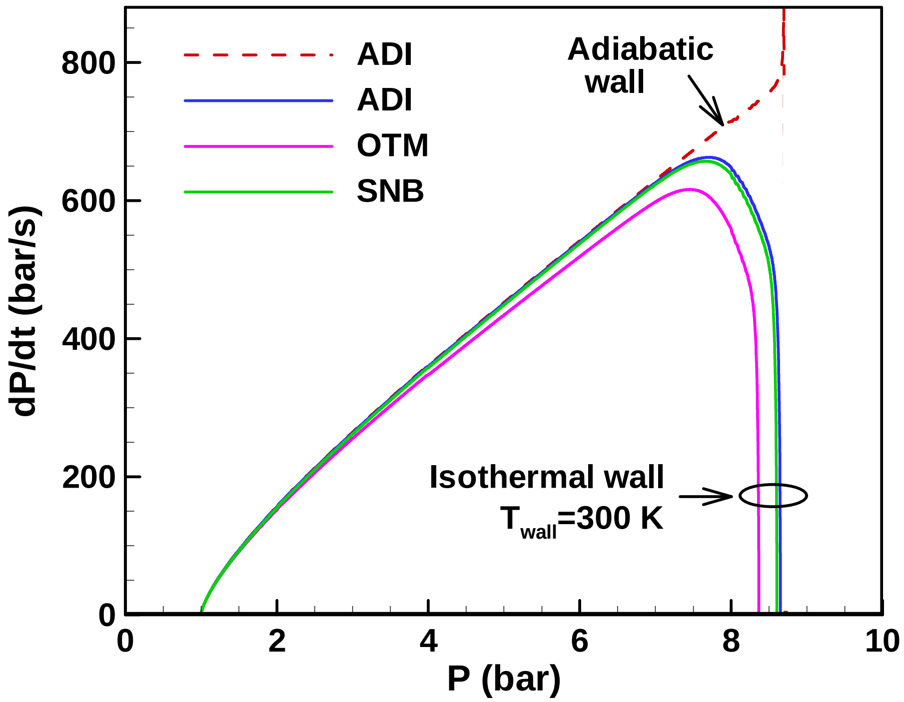


- 2D simulation by Fluent, $H_2:O_2:N_2$=6:1:4.96, T_0=300 K, P_0=1atm
- S_u=170 cm/s @ 400g is equivalent to S_u=8.5 cm/s @ 1g

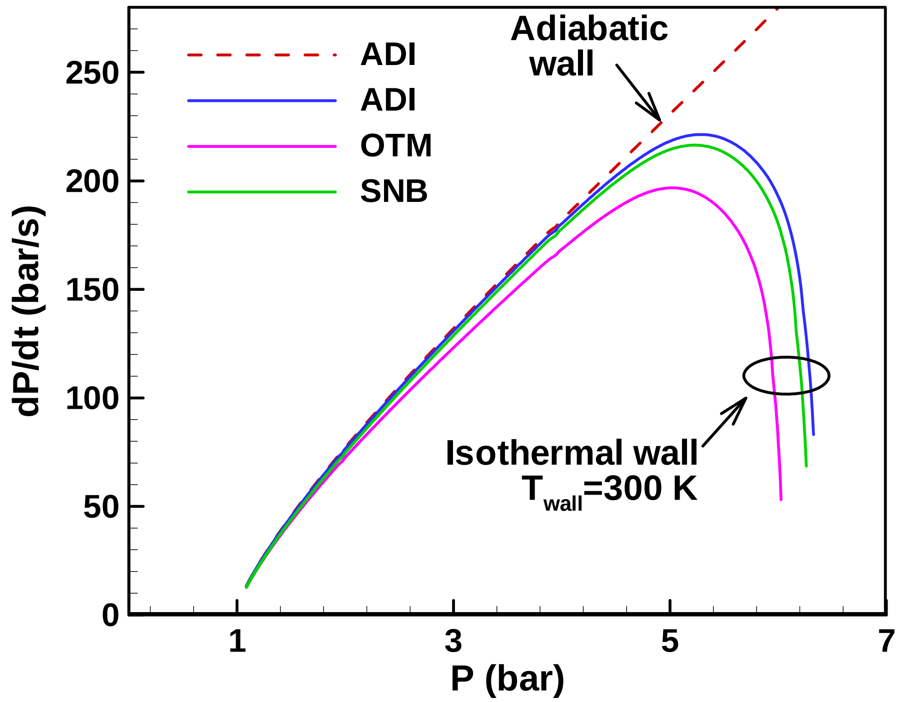
$$Ri = \frac{gL}{V^2}\left(\frac{T_b}{T_u} - 1\right)$$

Radiation

CH_4/air, ϕ=1.0, T_{u0}=300 K, P_0=1 bar



CH_4/air, ϕ=0.6, T_{u0}=300 K, P_0=1 bar

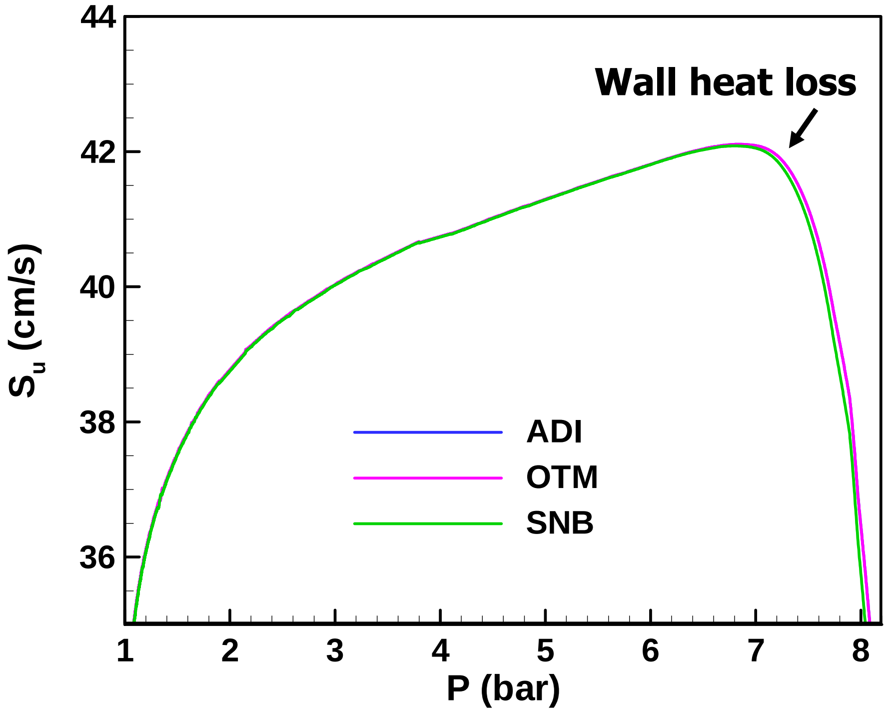


- **Negligible even for weak mixture: within 2%**
- **Radiation absorption reduces the difference**
- **Slow burning fuels, e.g.: refrigerants ?**

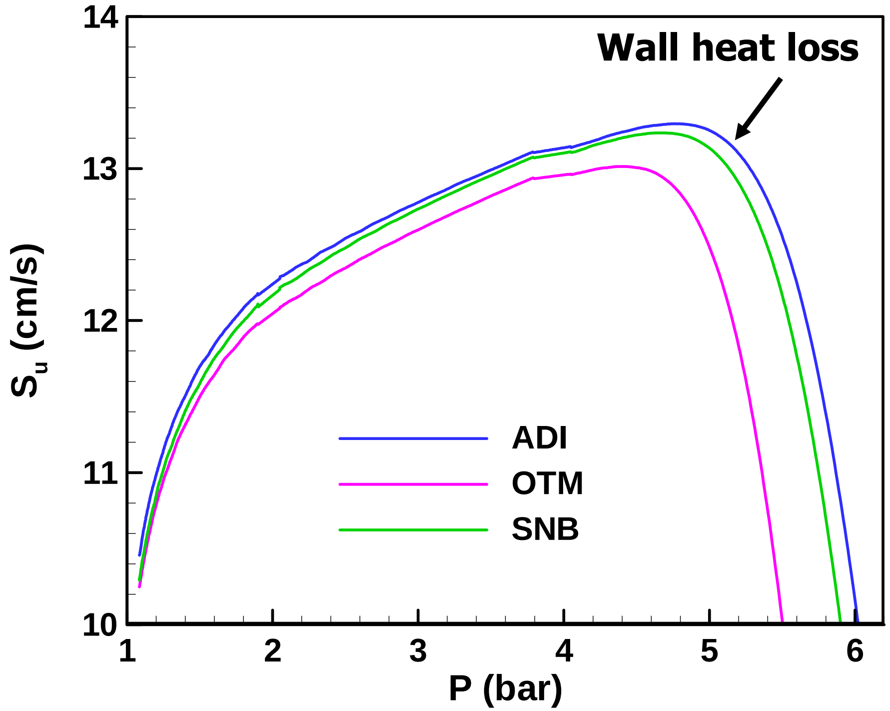
Radiation

$$S_u = \frac{R_W}{3}\left[1-(1-x)\left(\frac{P_0}{P}\right)^{1/\gamma_u}\right]^{-2/3}\left(\frac{P_0}{P}\right)^{1/\gamma_u}\frac{dx}{dt}$$

CH_4/air, ϕ=**1.0**, T_{u0}=300 K, P_0=1 bar



CH_4/air, ϕ=**0.6**, T_{u0}=300 K, P_0=1 bar



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Radiation

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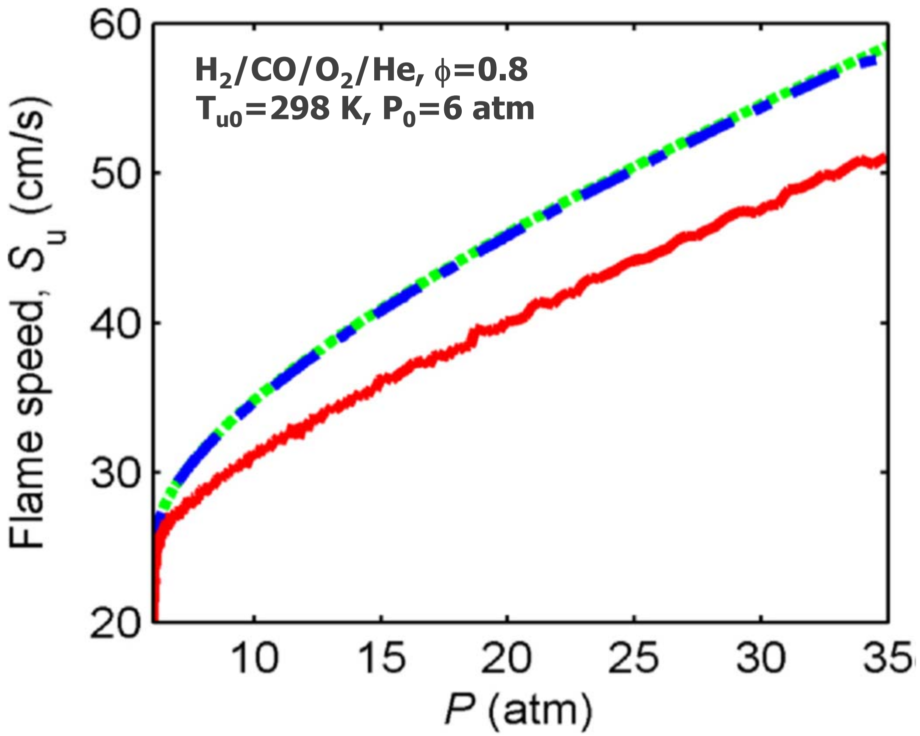
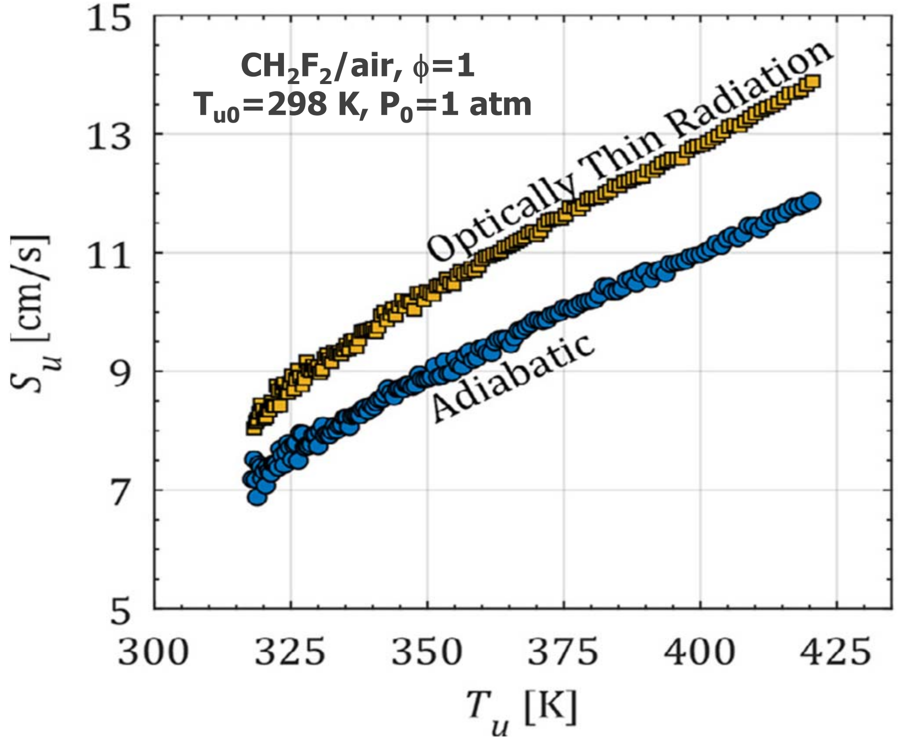


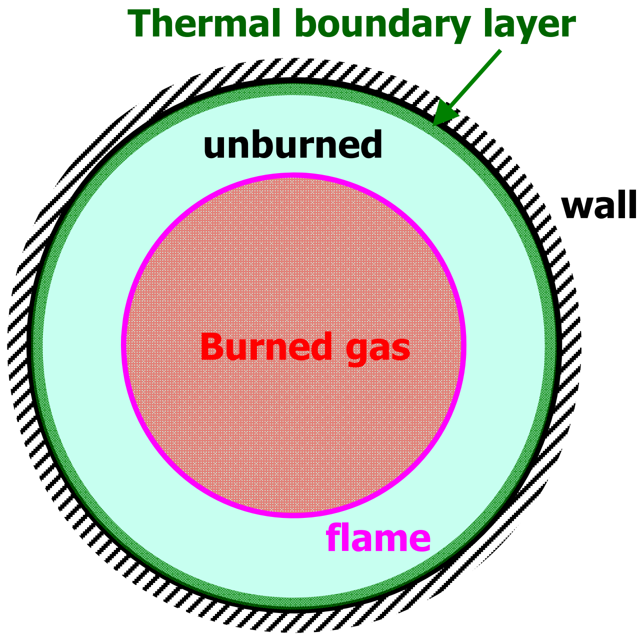
Xiouris et al. (2016CNF)

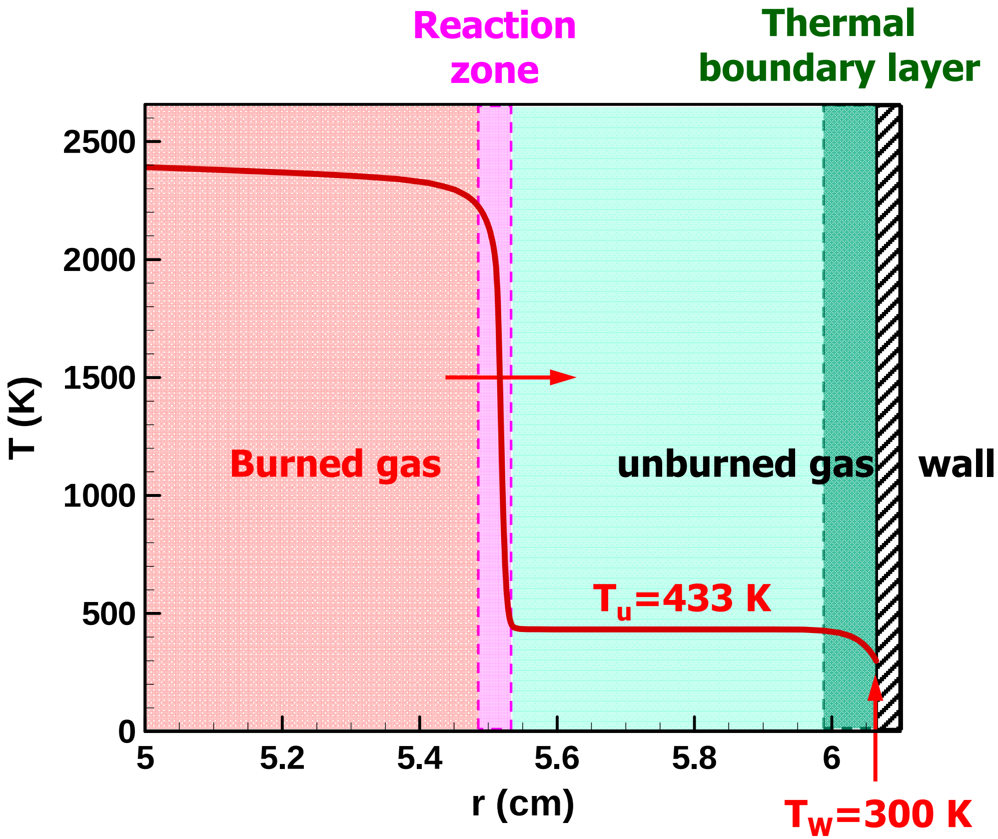


Burrell et al. (2019PCI)

- **"Neglecting radiation heat loss when interpreting experimental data could lead to uncertainty as large as 15%"**

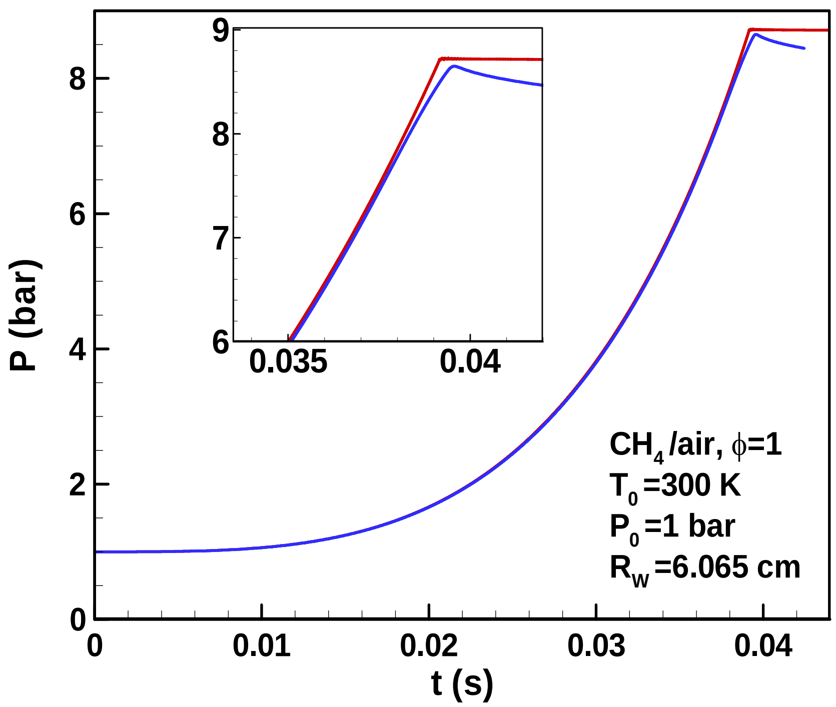
Wall heat loss

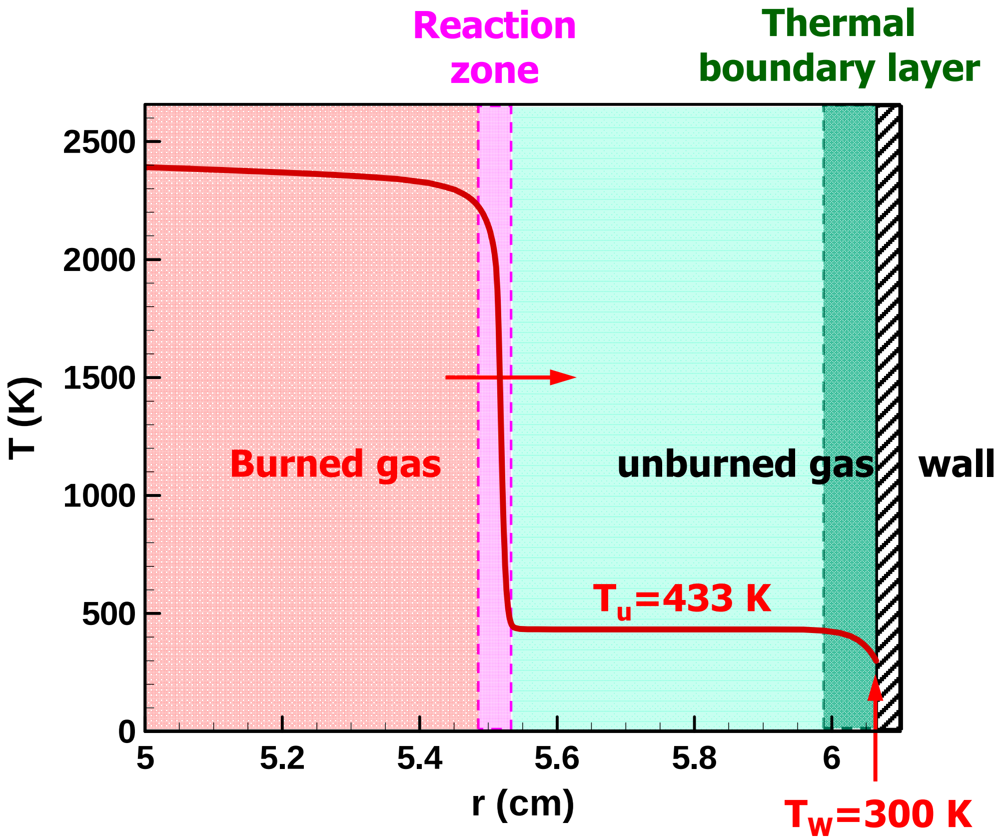




- **A thin thermal boundary layer develops near the wall**

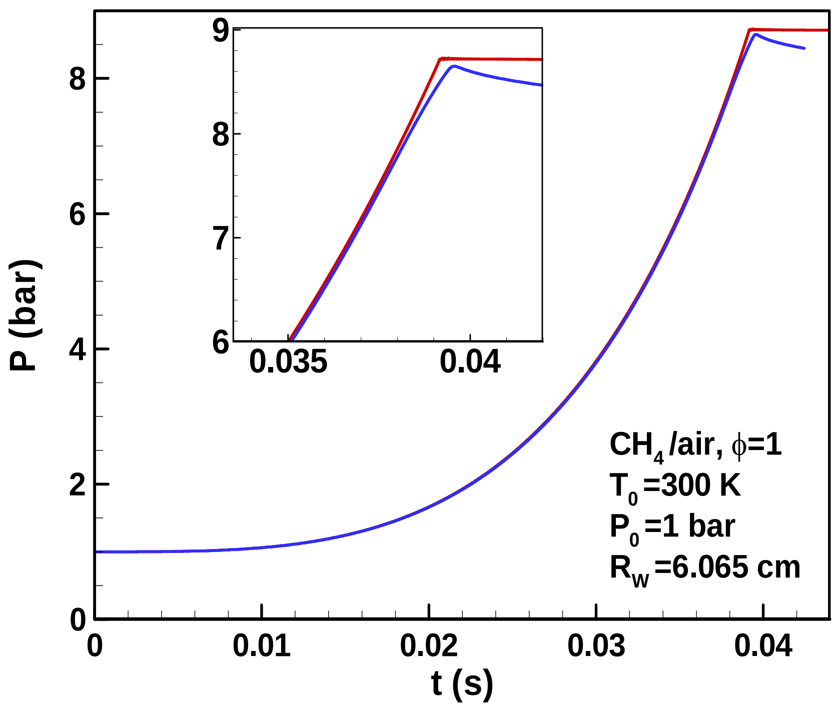
Wall heat loss

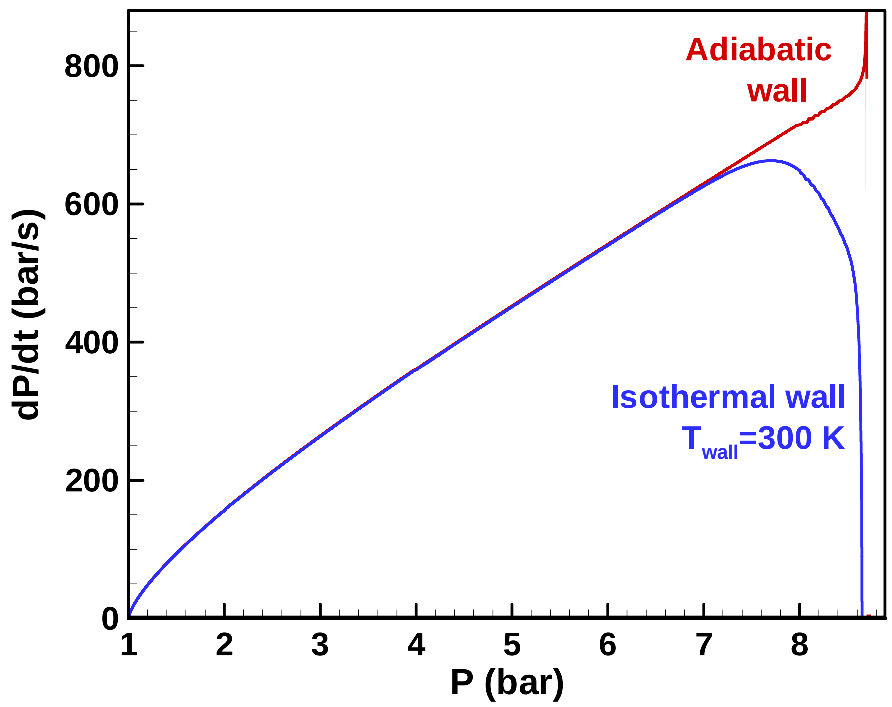




- A thin thermal boundary layer develops near the wall
- Heat loss to the wall results in pressure drop

Wall heat loss

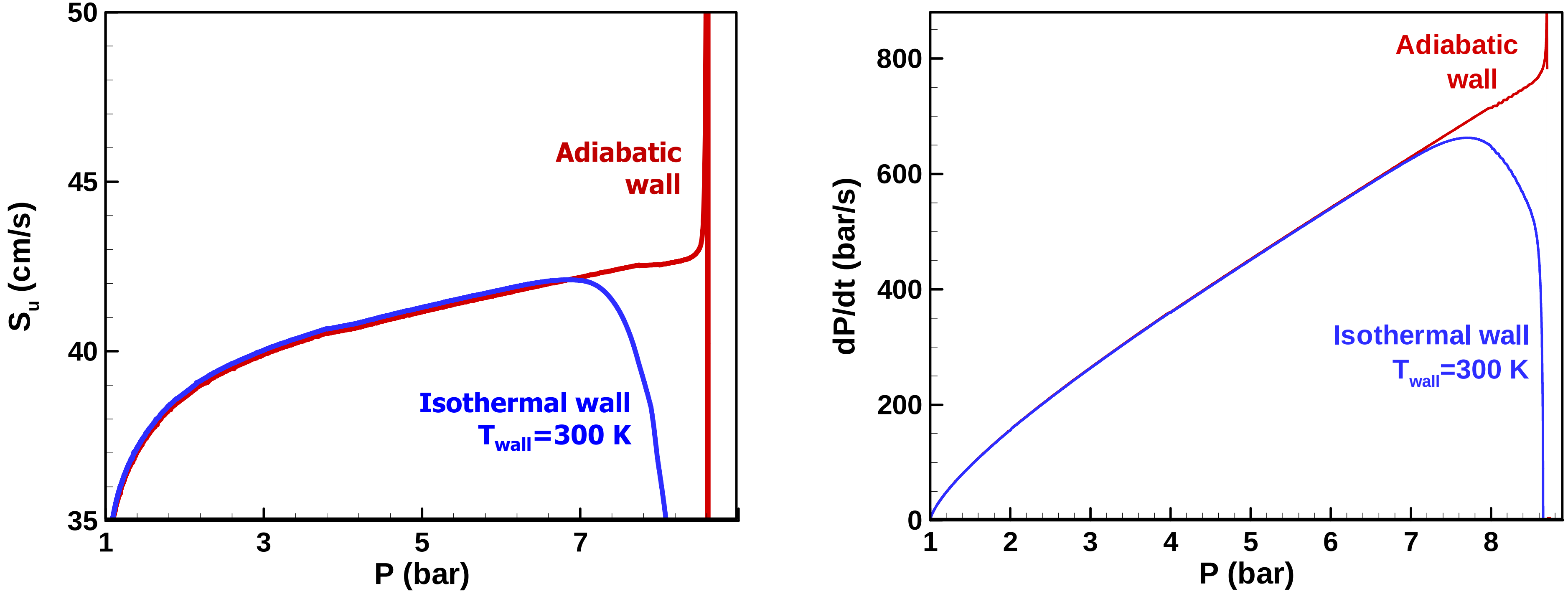




- A thin thermal boundary layer develops near the wall
- Heat loss to the wall results in pressure drop
- Useful data before $(dP/dt)_{max}$

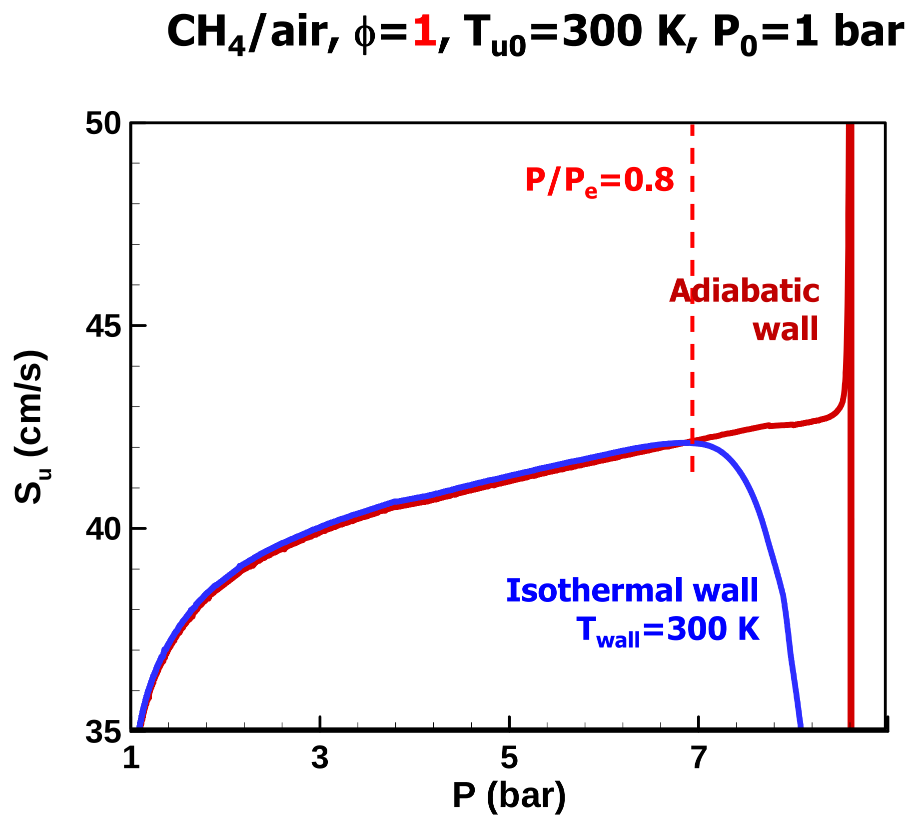
Wall heat loss

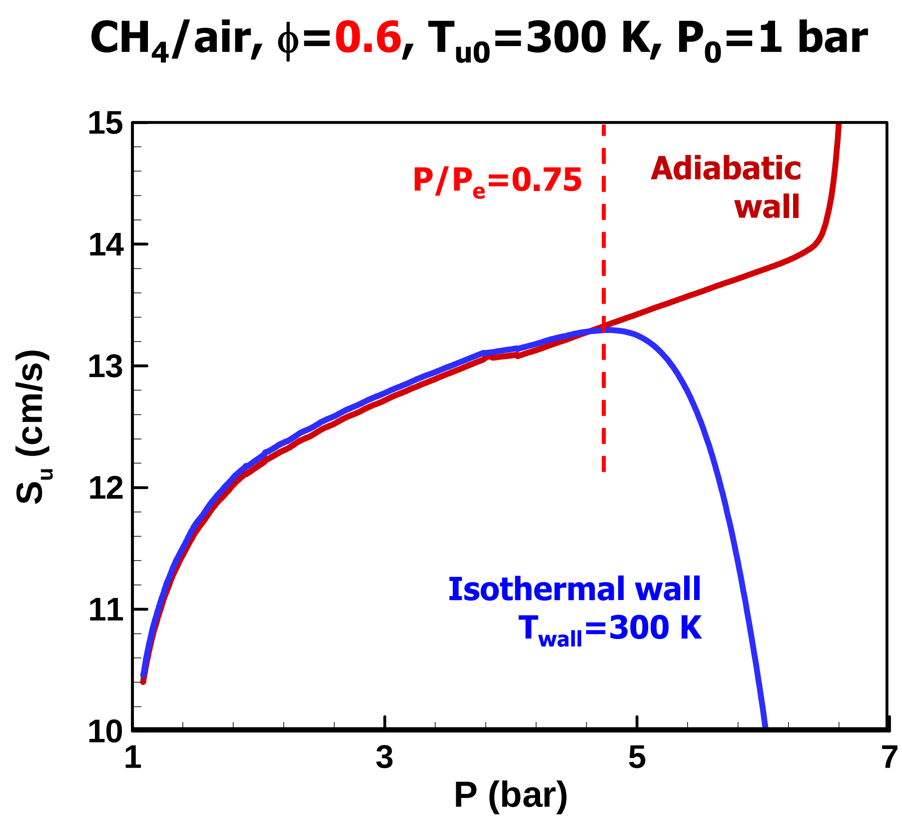
CH_4/air, ϕ=1, T_{u0}=300 K, P_0=1 bar



- **A thin thermal boundary layer develops near the wall**
- **Heat loss to the wall results in pressure drop**
- **Useful data before $(dP/dt)_{max}$**

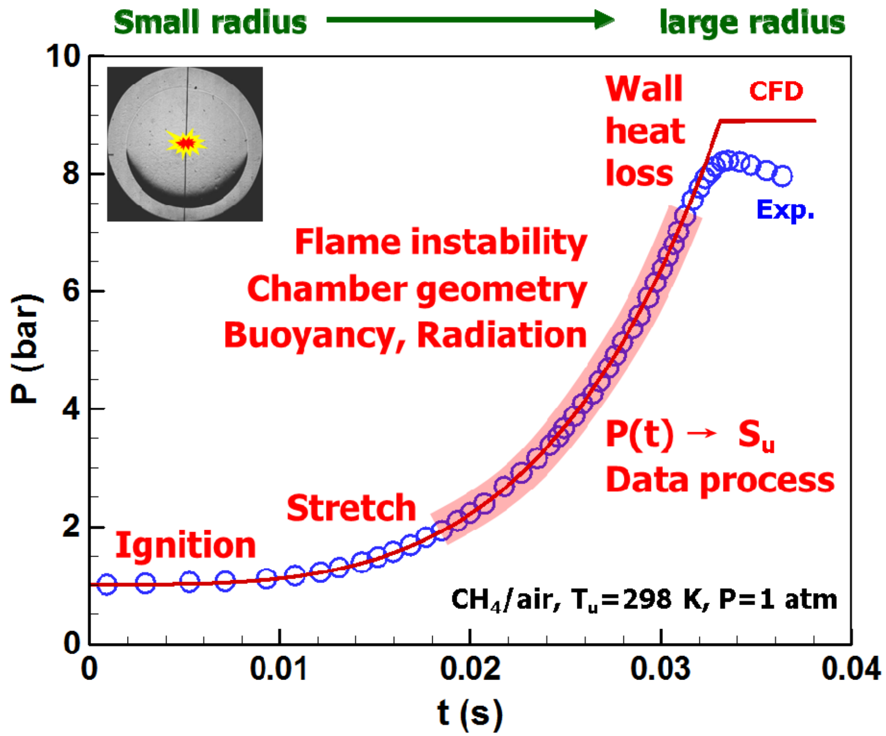
Wall heat loss



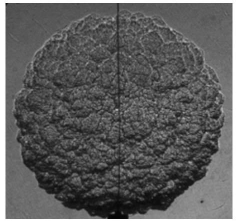


- A thin thermal boundary layer develops near the wall
- Heat loss to the wall results in pressure drop
- Useful data before $(dP/dt)_{max}$

Summary

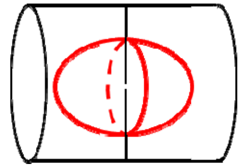


Flame instability

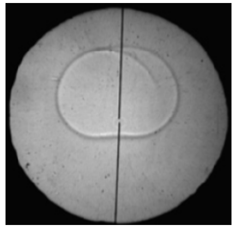


(Jomaas et al. 2013)

Cylindrical chamber

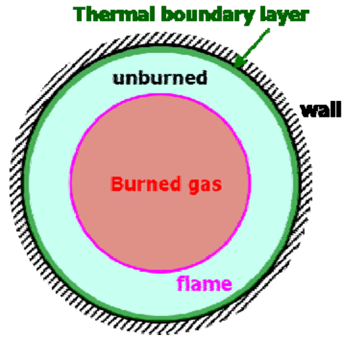


Buoyancy

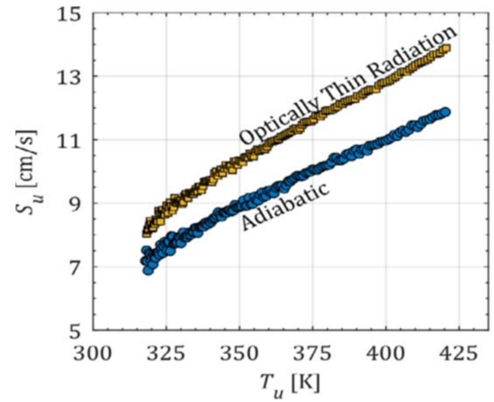


(Qiao et al. 2007)

Wall heat loss



Radiation



(Burrell et al. 2019)

- To avoid stretch effect: $P/P_0>2$ or $P>5$ atm
- To avoid wall heat loss: $P/P_e<0.75$
- Negligible radiation effect for: $S_u>10$ cm/s ?
- Negligible buoyancy effect for: $Ri=(T_b/T_u-1)gL/S_u^2$?
- Data processing, burned mass fraction: $x=m_b/m_0$

$$S_u = \frac{R_W}{3}\left[1-(1-x)\left(\frac{P_0}{P}\right)^{1/\gamma_u}\right]^{-2/3}\left(\frac{P_0}{P}\right)^{1/\gamma_u}\frac{dx}{dt}$$

$$S_u = \frac{dR_f}{dt} - \frac{R_W^3 - R_f^3}{3P\gamma_u R_f^2}\frac{dP}{dt}$$

Thank you !

On laminar burning velocity measurement using the constant-volume propagating spherical flames

Zheng Chen, Yiqing Wang

Peking University

Email: cz@pku.edu.cn