Flame propagation characteristics in hydrogen-air mixtures

Wookyung Kim

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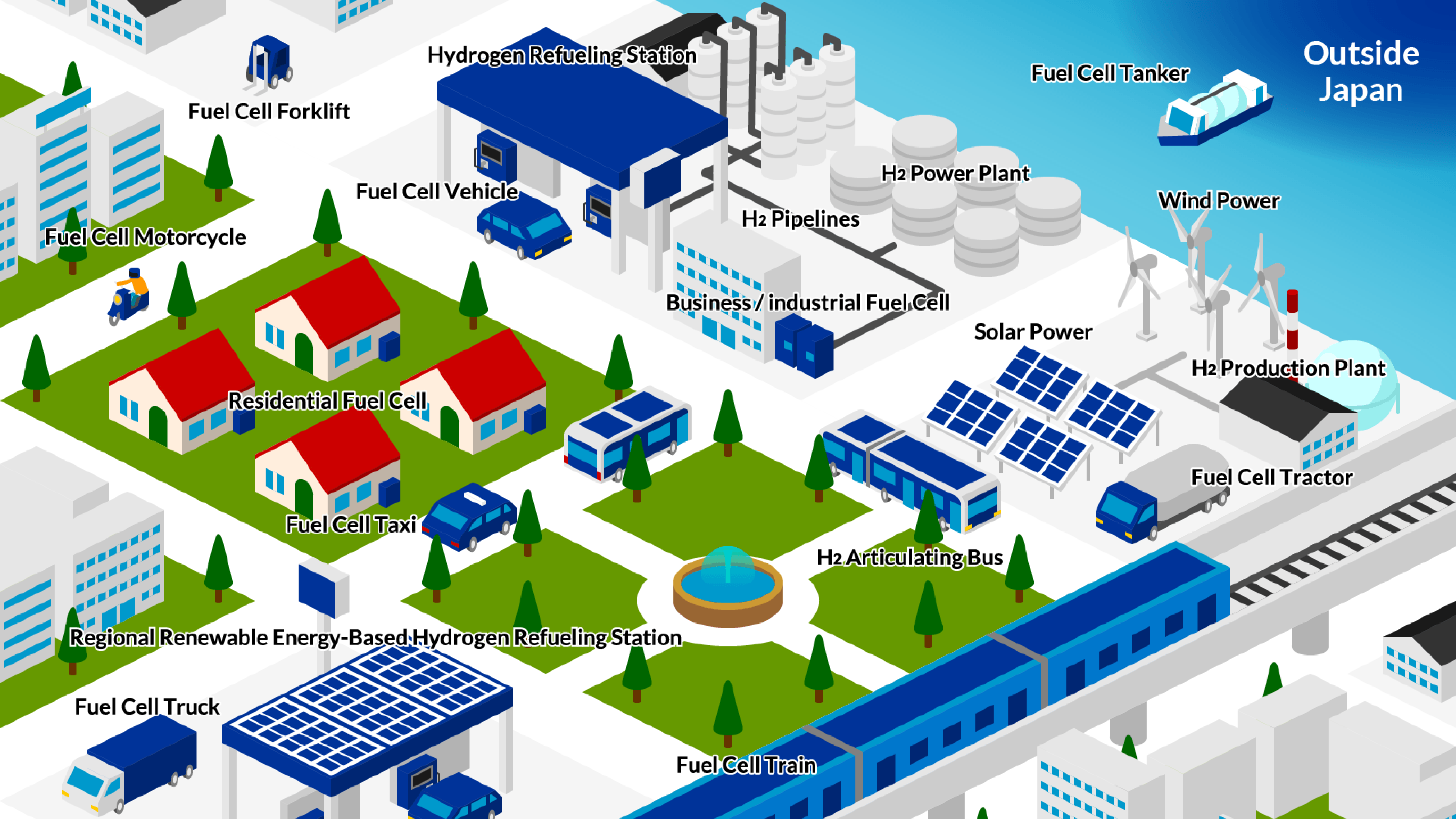
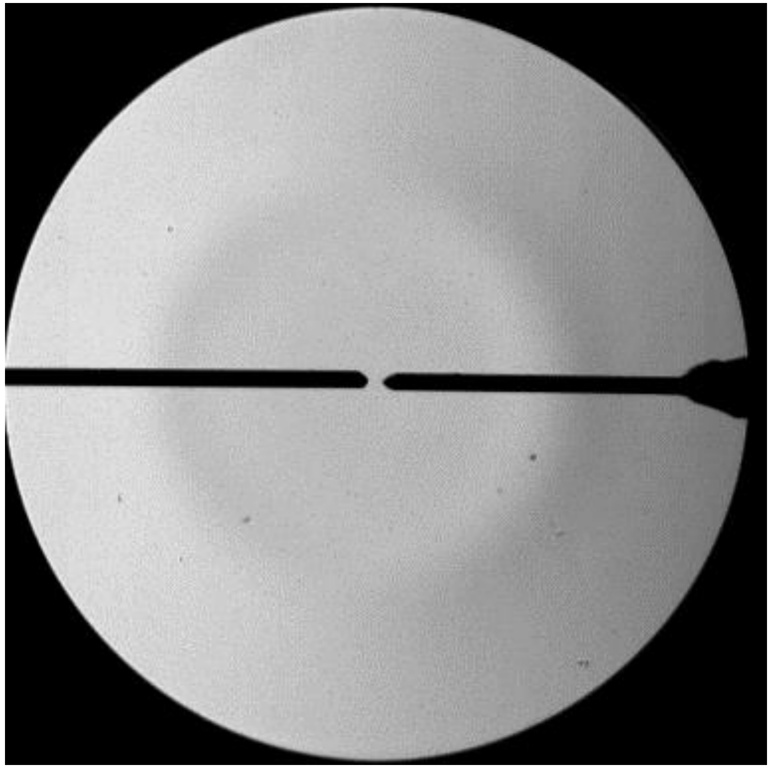
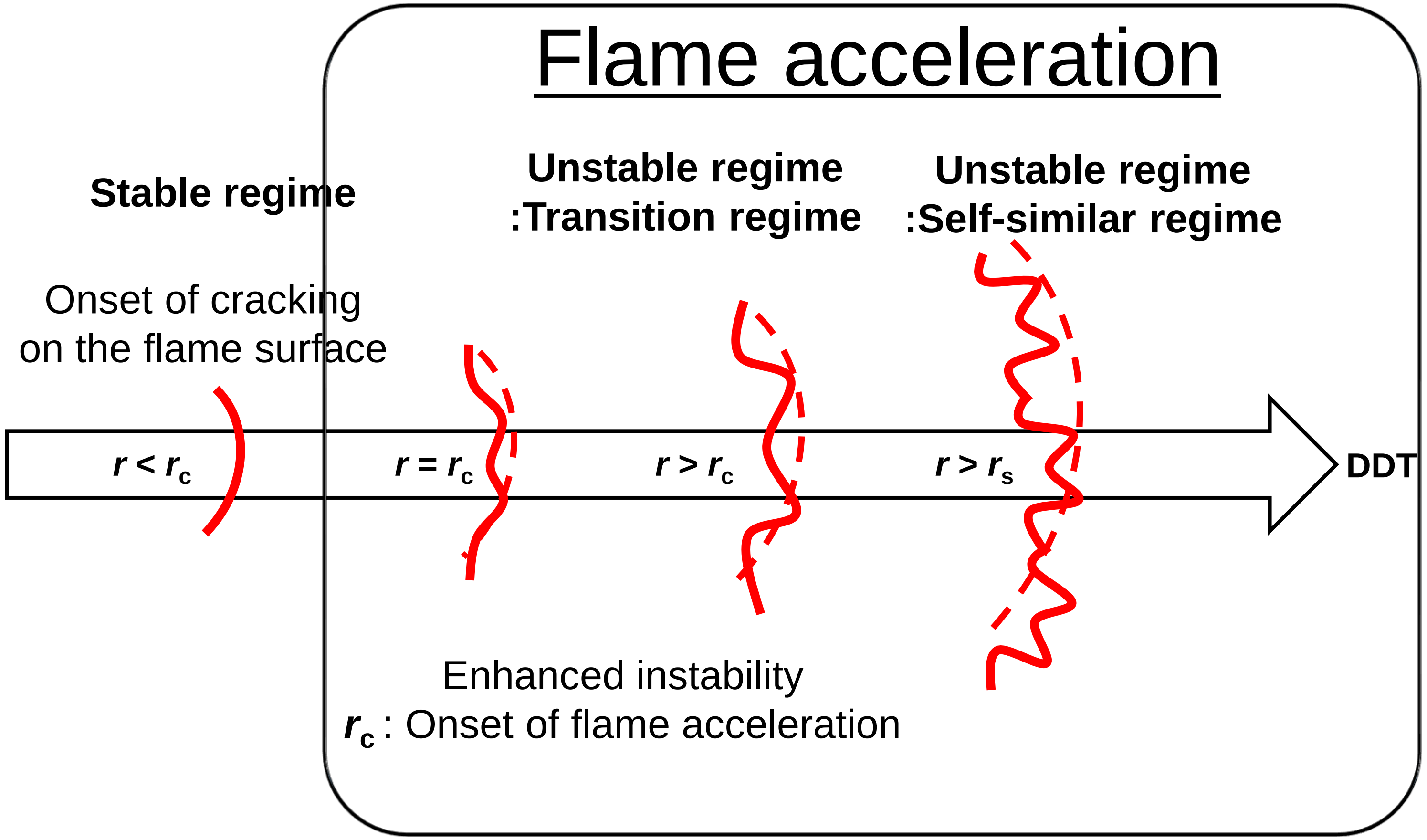
13TH CIMAC CASCADES (2024.08.15) QINGDAO, CHINA


Outside Japan
Fuel Cell Tanker
Hydrogen Refueling Station
Fuel Cell Forklift
Fuel Cell Vehicle
H2 Power Plant
Wind Power
H2 Pipelines
Fuel Cell Motorcycle
Business / industrial Fuel Cell
Solar Power
H2 Production Plant
Residential Fuel Cell
Fuel Cell Tractor
Fuel Cell Taxi
H2 Articulating Bus
Regional Renewable Energy-Based Hydrogen Refueling Station
Fuel Cell Truck
Fuel Cell Train

How does a flame propagate?





Flame acceleration

Stable regime

Onset of cracking
on the flame surface

Unstable regime
:Transition regime

Unstable regime
:Self-similar regime

Enhanced instability
r_c : Onset of flame acceleration

Flame acceleration

Cellular instabilities

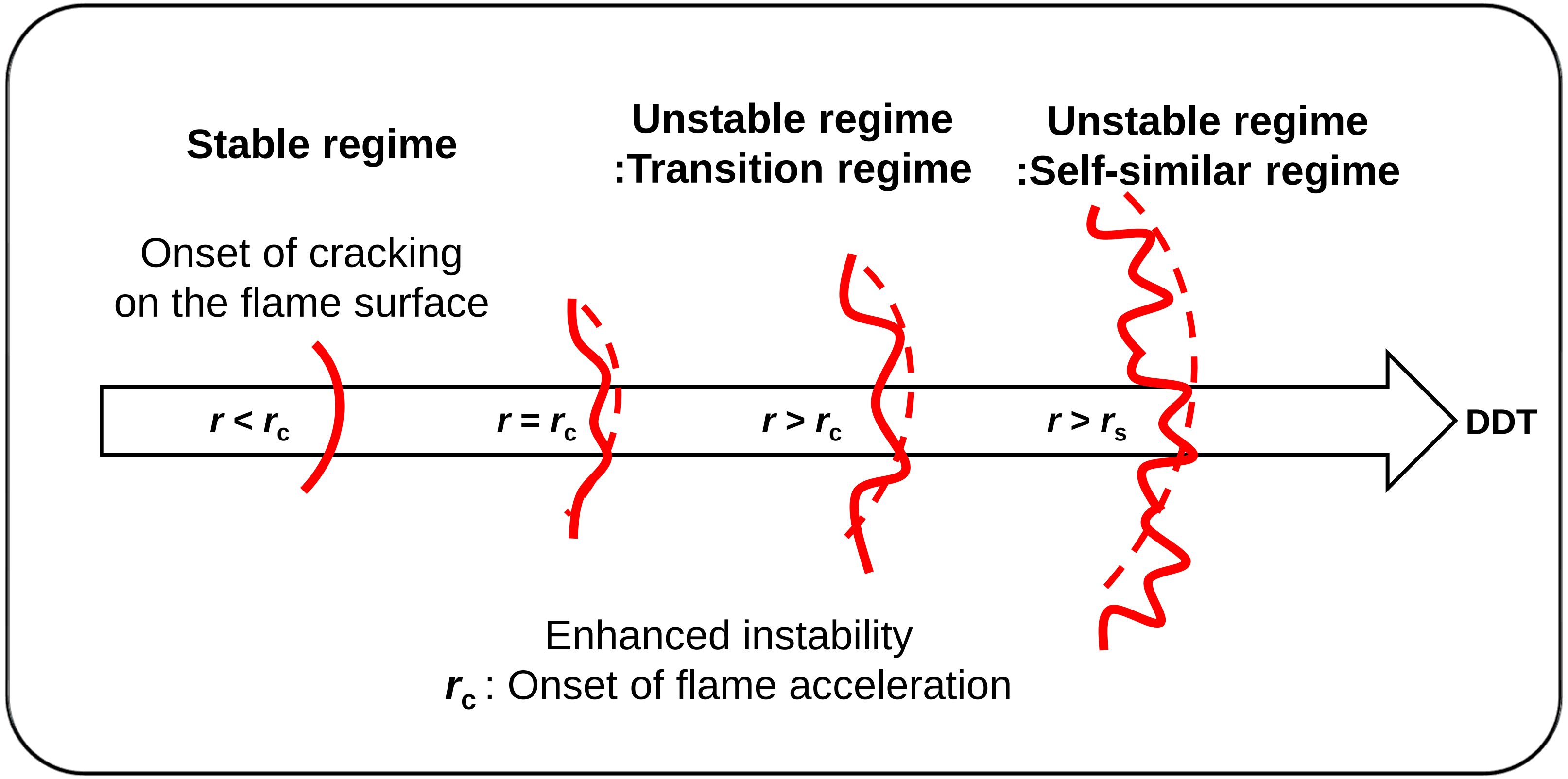
- Darrieus–Landau instability
- Diffusive-thermal instability

Wrinkled flame front

Larger surface area

Flame acceleration

$r \propto t^{\alpha}$



Stable regime

Unstable regime
:Transition regime

Unstable regime
:Self-similar regime

Onset of cracking
on the flame surface

$r < r_c$

$r = r_c$

$r > r_c$

$r > r_s$

DDT

Enhanced instability
r_c : Onset of flame acceleration

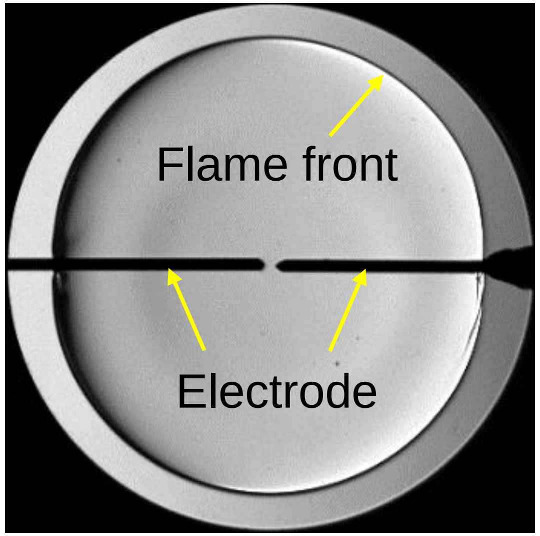
- W. Kim et al., *International Journal of Hydrogen Energy*, 43 (2018) 12556-15564,
- W. Kim et al., *Journal of Loss Prevention in the Process Industries,* 60 (2019) 264-268.
- W. Kim et al., *International Journal of Hydrogen Energy*, 45 (2020) 25608-25614.

Flame acceleration

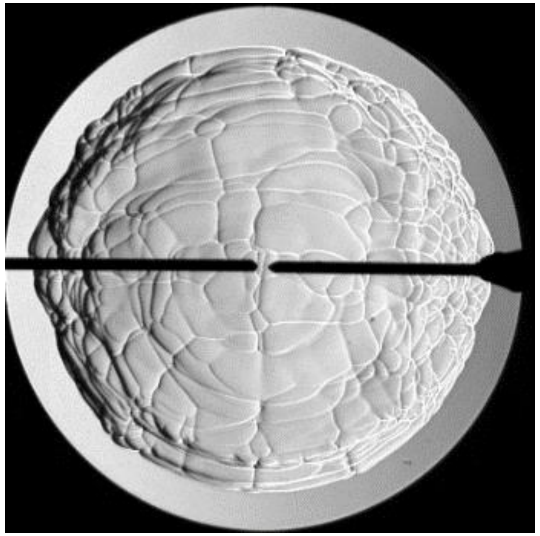
Cellular instabilities

- Darrieus–Landau instability
- Diffusive-thermal instability

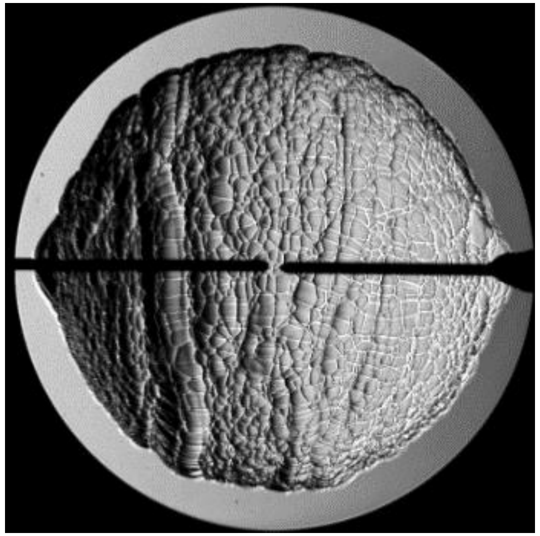
$P_\mathrm{i} = 0.1\ \mathrm{MPa},\ \phi = 2.0$
$Le > 1,\ \delta = 0.31\ \mathrm{mm}$



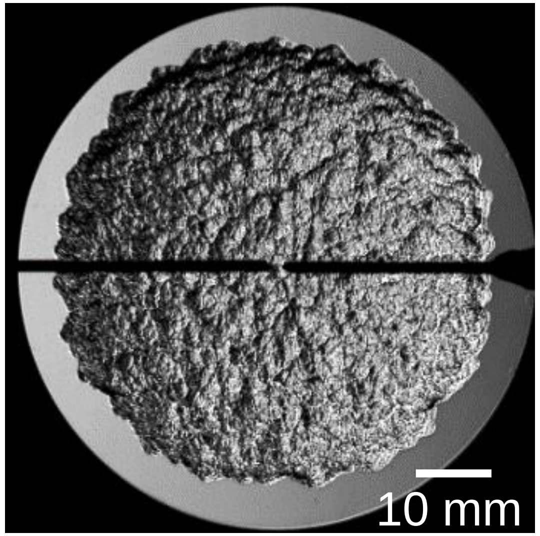
$P_\mathrm{i} = 0.1\ \mathrm{MPa},\ \phi = 0.5$
$Le < 1,\ \delta = 0.49\ \mathrm{mm}$



$P_\mathrm{i} = 0.5\ \mathrm{MPa},\ \phi = 2.0$
$Le > 1,\ \delta = 0.04\ \mathrm{mm}$



$P_\mathrm{i} = 0.5\ \mathrm{MPa},\ \phi = 0.5$
$Le < 1,\ \delta = 0.17\ \mathrm{mm}$



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- W. Kim et al., *International Journal of Hydrogen Energy*, 45 (2020) 25608-25614.

Flame acceleration

Cellular instabilities

- •Darrieus–Landau instability
- •Diffusive-thermal instability

Wrinkle

Larger

Flame acceleration

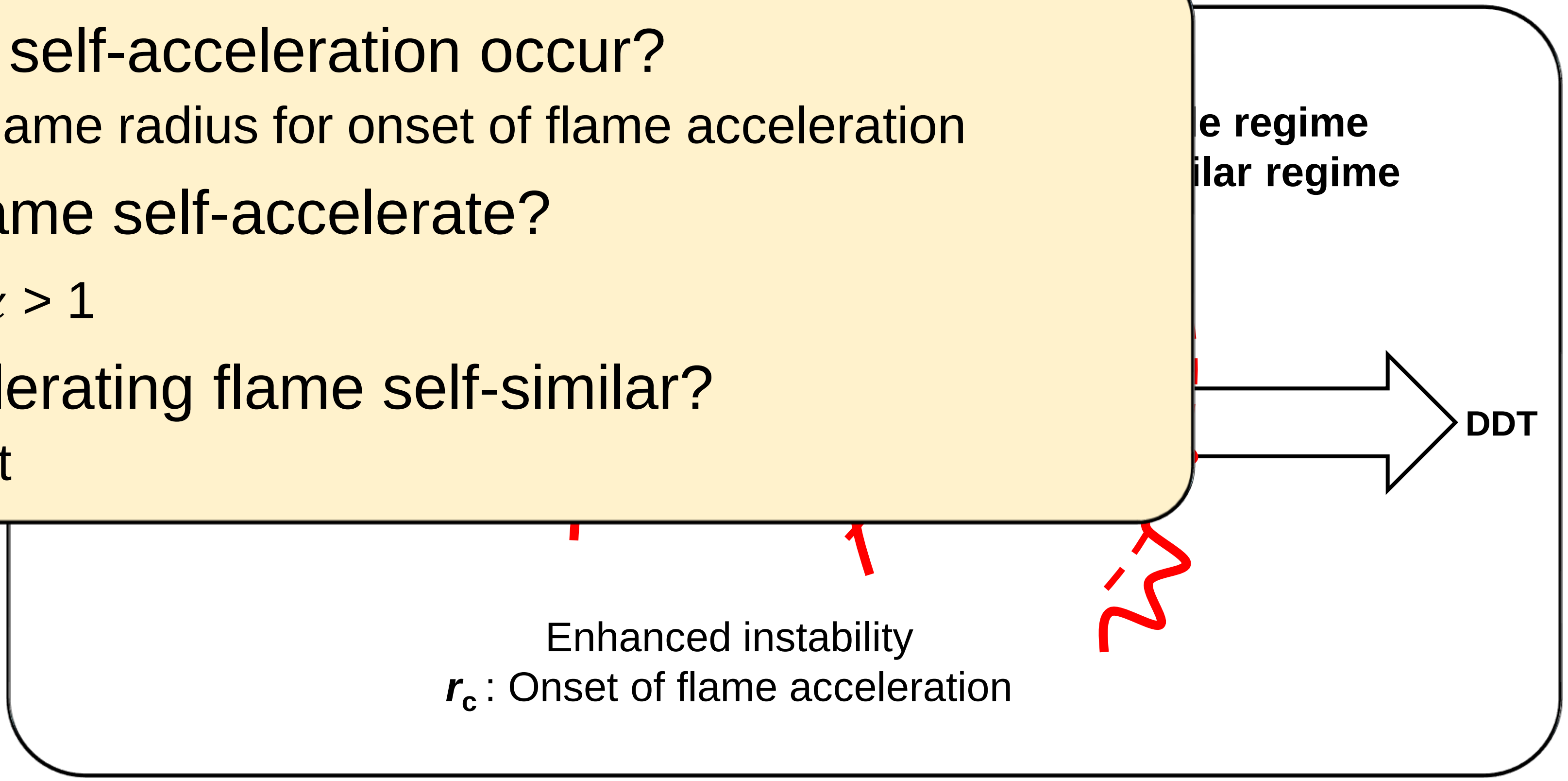
$r \propto t^{\alpha}$

- When does self-acceleration occur?

  r_c : Critical flame radius for onset of flame acceleration
- Does the flame self-accelerate?

  $r \propto t^{\alpha}$ i.e. $\alpha > 1$
- Is self-accelerating flame self-similar?

  α = constant



Enhanced instability

r_c : Onset of flame acceleration

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- W. Kim et al., *Journal of Loss Prevention in the Process Industries,* 60 (2019) 264-268.
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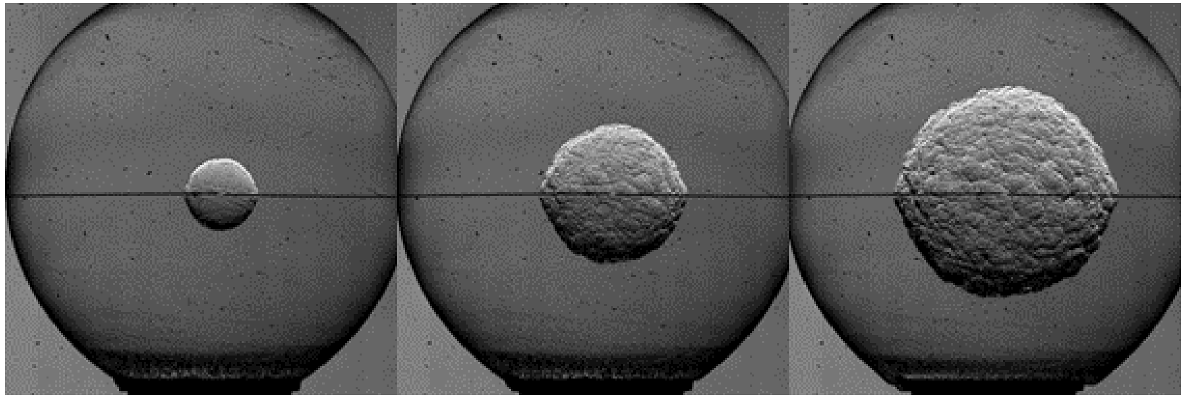
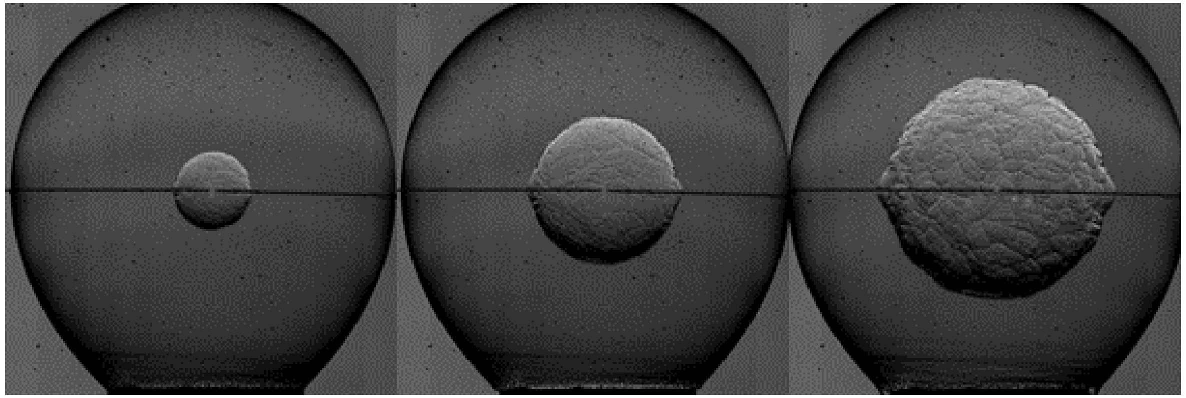
Hydrogen-oxygen flame



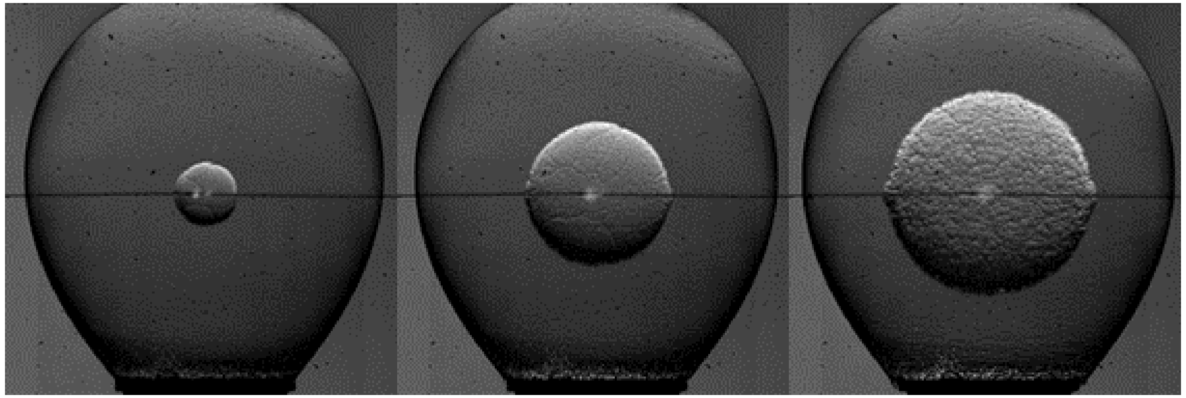
$r = 10.7$ mm, $t = 0.65$ ms $r = 20.1$ mm, $t = 1.20$ ms $r = 30.1$ mm, $t = 1.70$ ms

$\phi = 0.2$



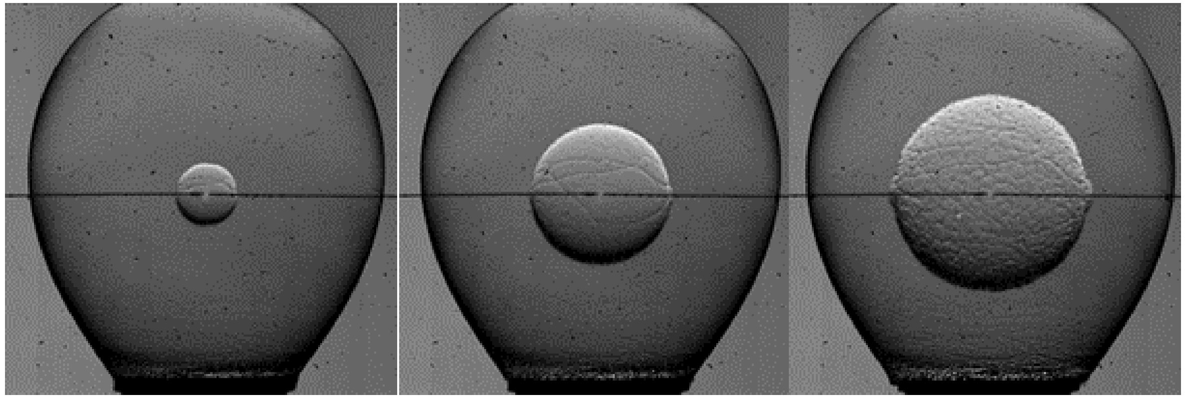
$r = 10.6$ mm, $t = 0.20$ ms $r = 19.5$ mm, $t = 0.35$ ms $r = 29.0$ mm, $t = 0.50$ ms

$\phi = 0.6$



$r = 9.71$ mm, $t = 0.15$ ms $r = 20.8$ mm, $t = 0.30$ ms $r = 29.3$ mm, $t = 0.40$ ms

$\phi = 1.0$

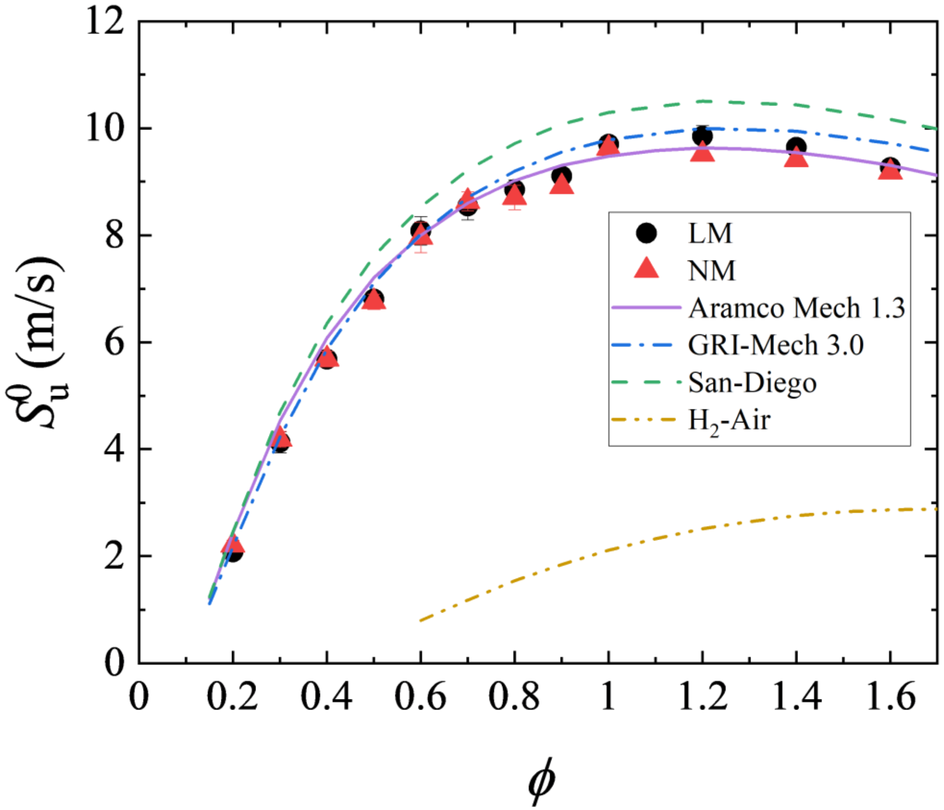


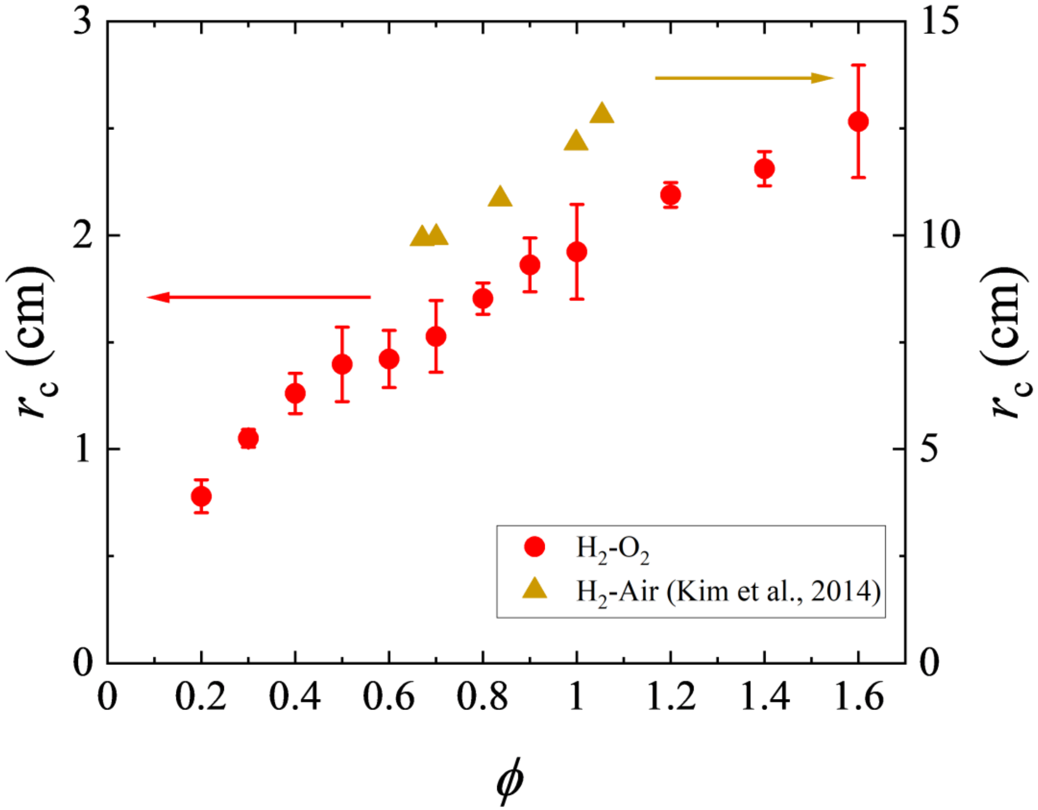
$r = 9.51$ mm, $t = 0. 15$ ms $r = 20.3$ mm, $t = 0.30$ ms $r = 28.0$ mm, $t = 0.40$ ms

$\phi = 1.4$

- K. Tanaka, A. Ueda, Y. Kim, W. Kim, *Process safety and environmental protection*, 183 (2024) 645-652

Onset of self-acceleration





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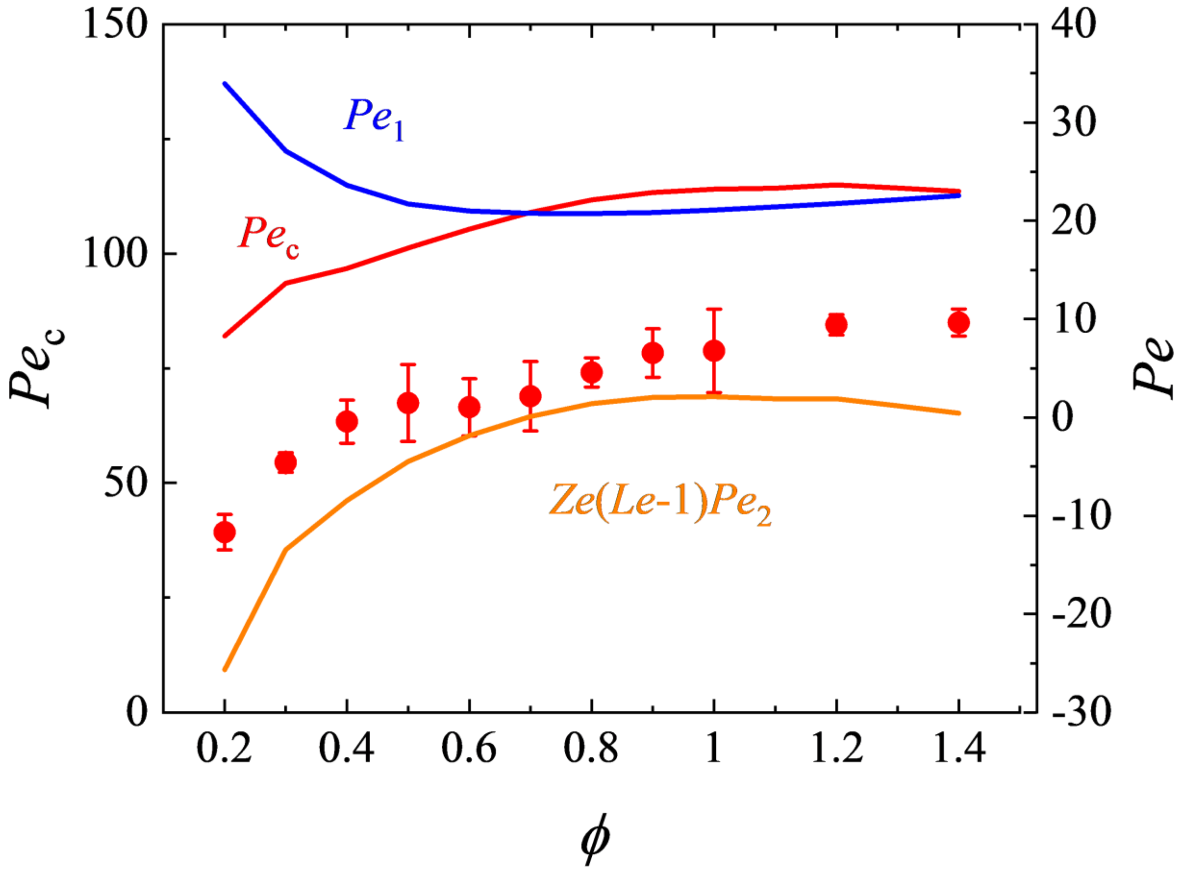
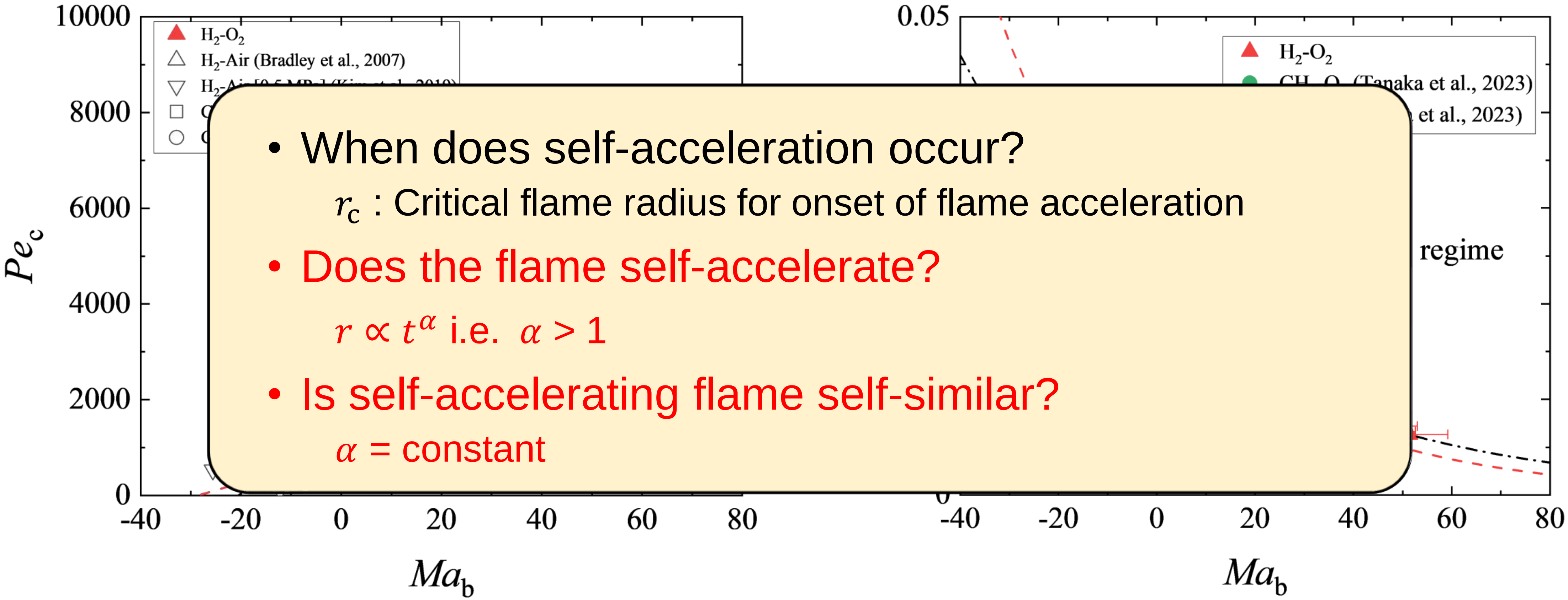


- For the linear analysis of Bechtold and Matalon, Pe_c expressed the influences due to Darrieus–Landau and diffusive-thermal instabilities.

$$Pe_c = Pe_1(\sigma) + Ze(Le - 1)\,Pe_2(\sigma)$$

G. Jomaas et al. J. Fluid Mech. 583 (2007) 1–26, JK. Bechtold, & M. Matalon, Combust. Flame, 67 (1987) 77-90.

Onset of self-acceleration



- When does self-acceleration occur?

  r_c : Critical flame radius for onset of flame acceleration

- Does the flame self-accelerate?

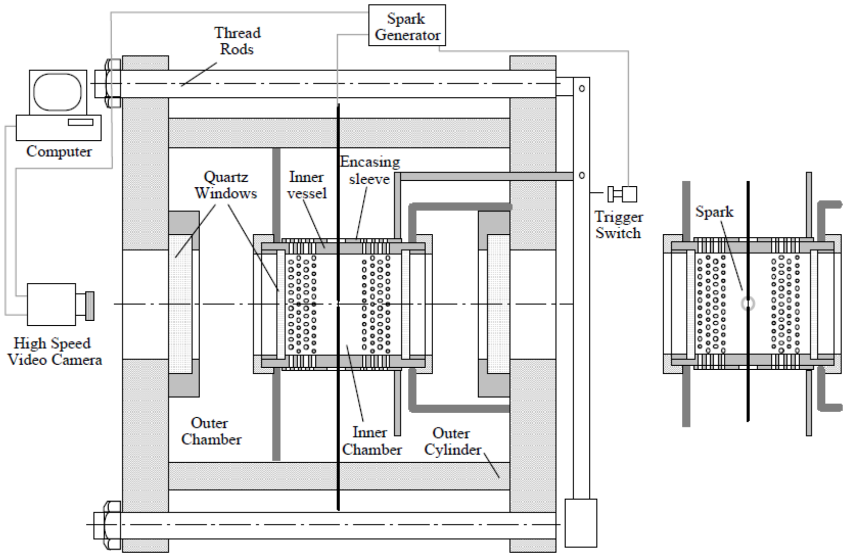
  $r \propto t^{\alpha}$ i.e. $\alpha > 1$

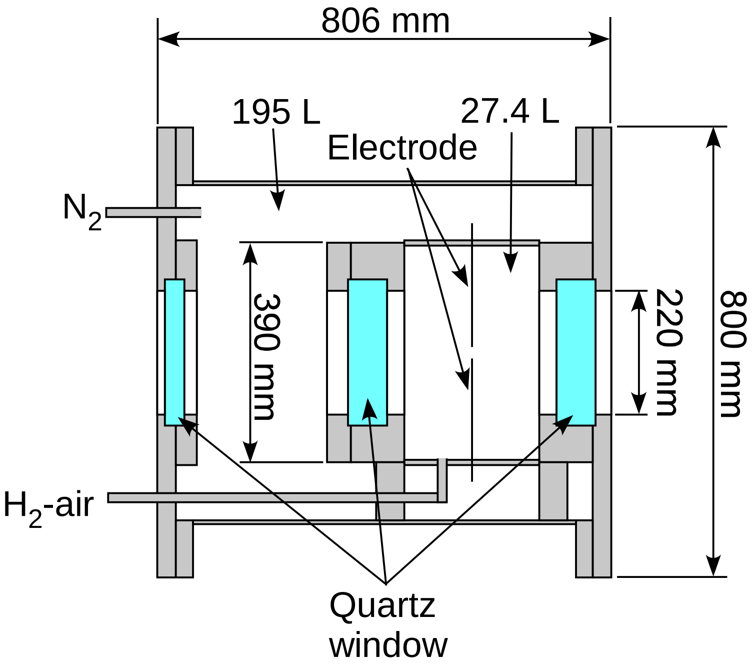
- Is self-accelerating flame self-similar?

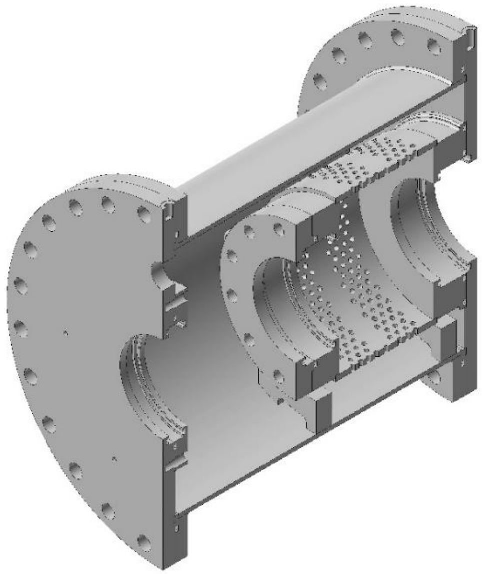
  α = constant

- D Bradley et al., Combustion and Flame 149 (2007) 162-172
- W Kim et al., International Journal of Hydrogen Energy 43(2019) 12556-12564
- C. R. Bauwens et al Proceedings of the Combustion Institute 35 (2015) 2059-2066.
- A Ueda et al., Journal of the Energy Institute, 110 (2023) 101335

Experimental setup







- **Princeton Univ.**

1. Dual chamber
2. Inner cylinder (ϕ 82.55 mm x 127 mm)
3. Outer cylinder (ϕ 273.05 mm x 304.8 mm)
4. V = 0.679L, Up to 60 atm
5. Flame radius 25 mm

- **Hiroshima Univ.**

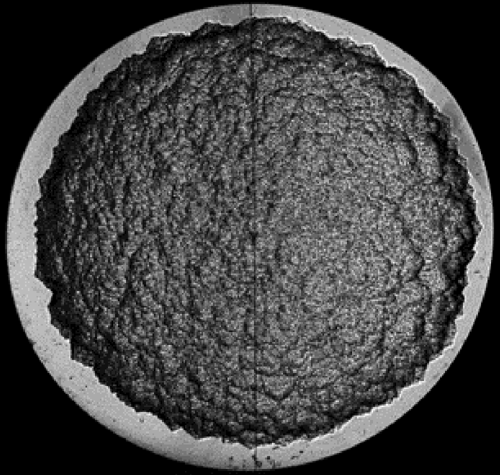
1. Dual chamber
2. Inner cylinder (V = 27.4 L)
3. Outer cylinder (V = 195L)
4. Up to 10 atm
5. Flame radius 110 mm

S.D. Tse, D. Zhu and C.K. Law Rev. Sci. Instrum., 75 (2004) 233-239

Cellular flame images

Princeton Univ.
P_i = 0.5 MPa
ϕ = 0.6
r = 15.4 mm

Hiroshima Univ.
P_i = 0.5 MPa
ϕ = 0.6
r = 100 mm



- The flame radius r = 100 mm, measured by large dual-chamber in Hiroshima Univ. is much larger than r = 15.4 mm of Princeton Univ.

Jomaas G. et al. J. Fluid Mech. 583 (2007) 1–26

Cellular flame images

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P_i = 0.5 MPa
ϕ = 0.6
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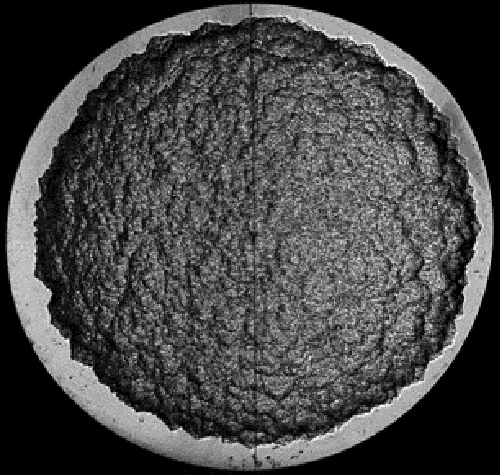

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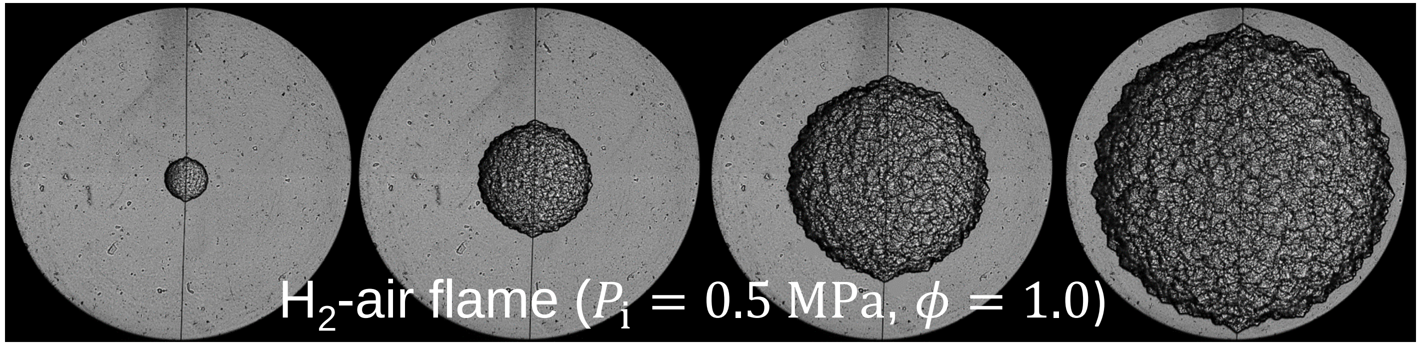
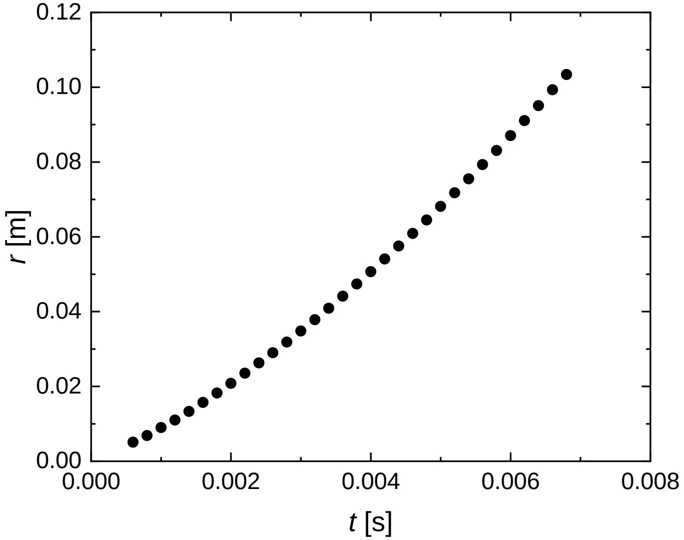
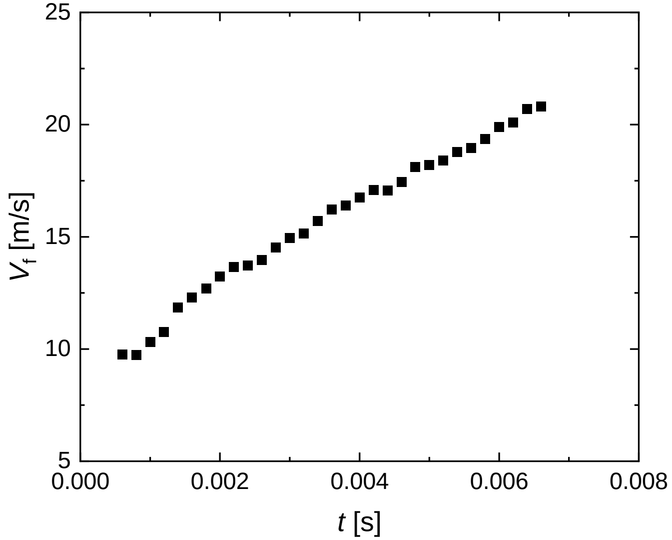
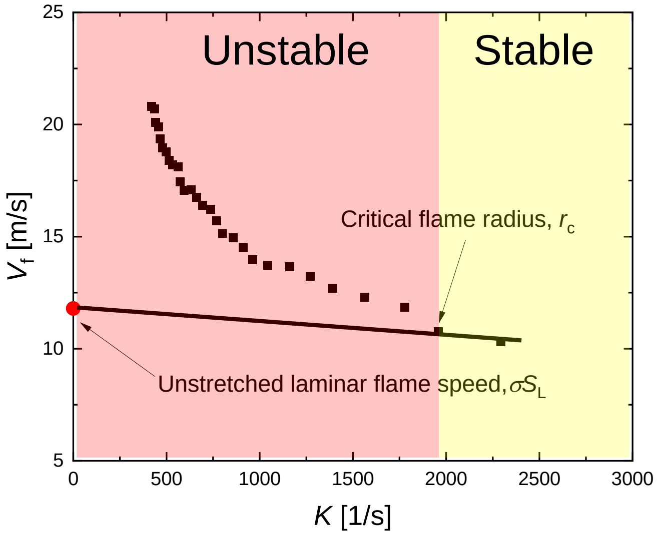
Onset of self-acceleration



H_2-air flame ($P_i = 0.5$ MPa, $\phi = 1.0$)

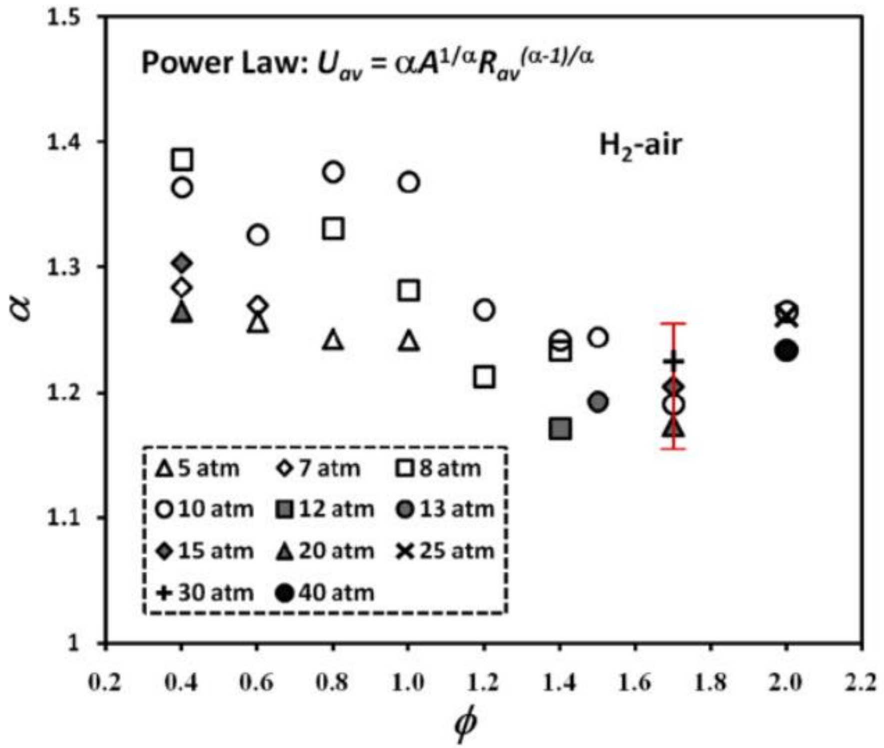


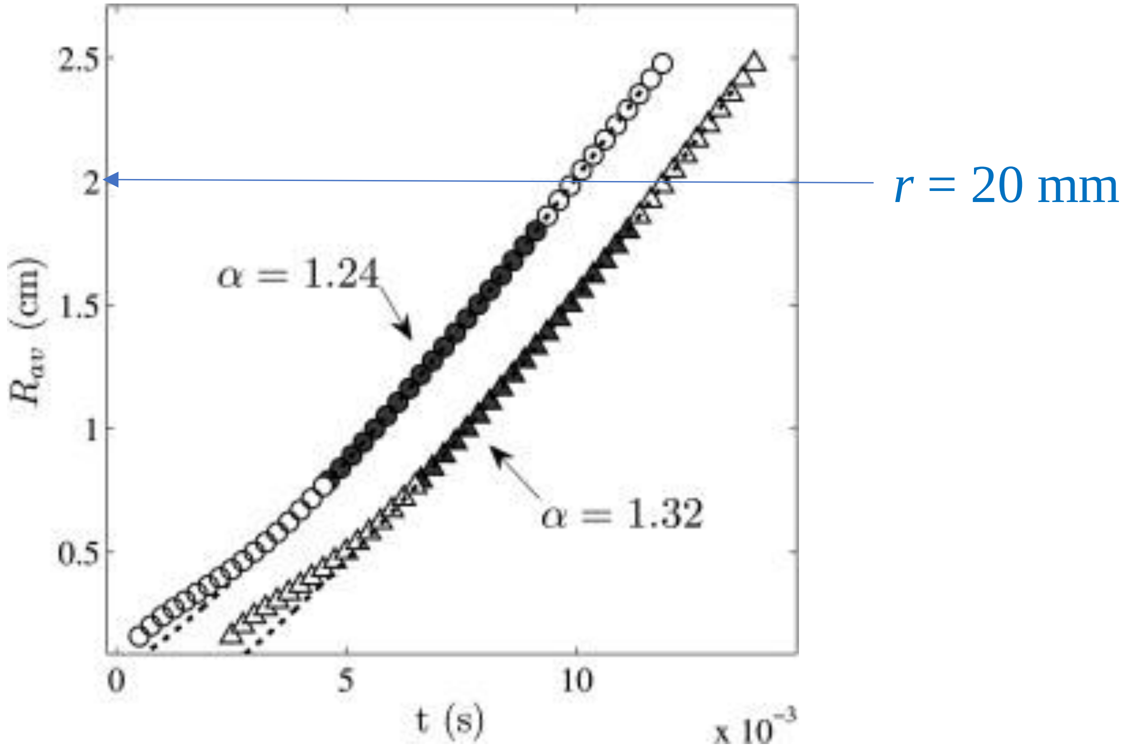




- Spherical expanding flame self-accelerates in stoichiometric H_2-air mixture.

Acceleration exponent, $r \propto t^{\alpha} (r \gg r_c)$





r = 20 mm

- The increasing tendency of α with a decrease in ϕ, and α values increased with initial pressure.
- The α values seem to depend on the mixture and initial pressure.
- Nevertheless, this result demonstrates that the evaluated values of α were underestimated, because the evaluation range might be located in the transition regime to self-turbulization.

[12] F. Wu, G. Jomass, C.K.Law, *Proceedings of the Combustion Institute*, 34 (2013) 937-945

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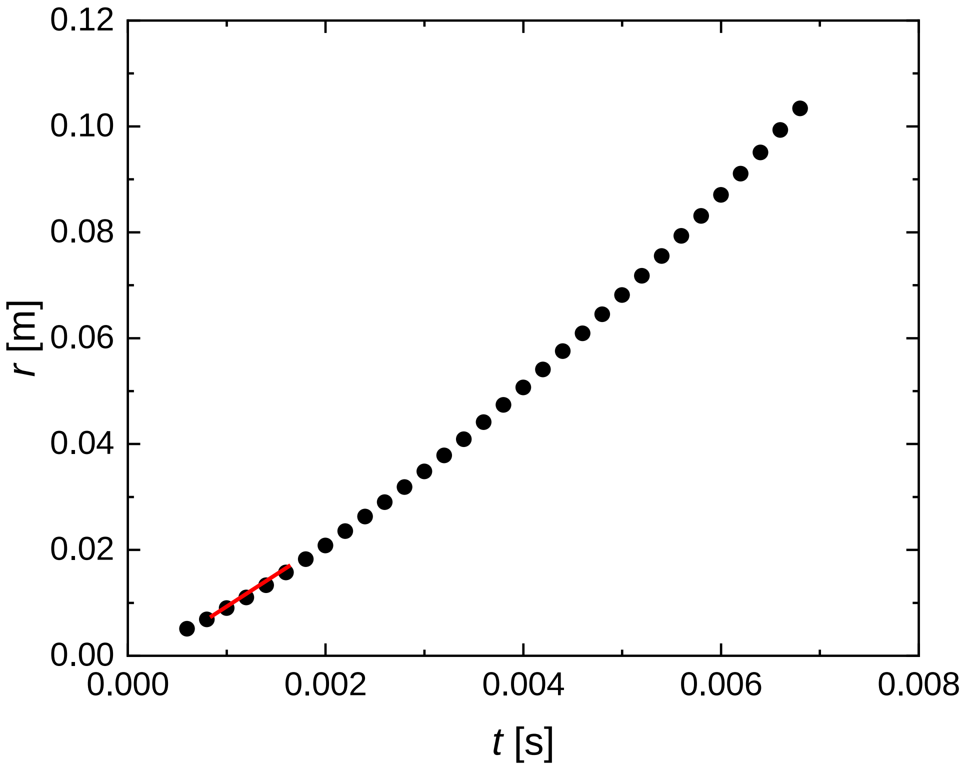

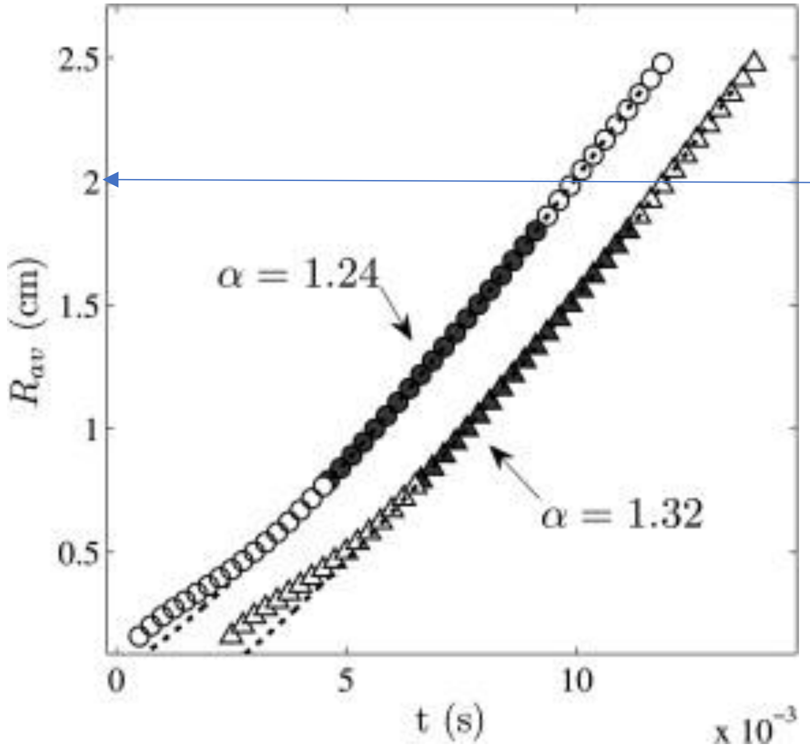

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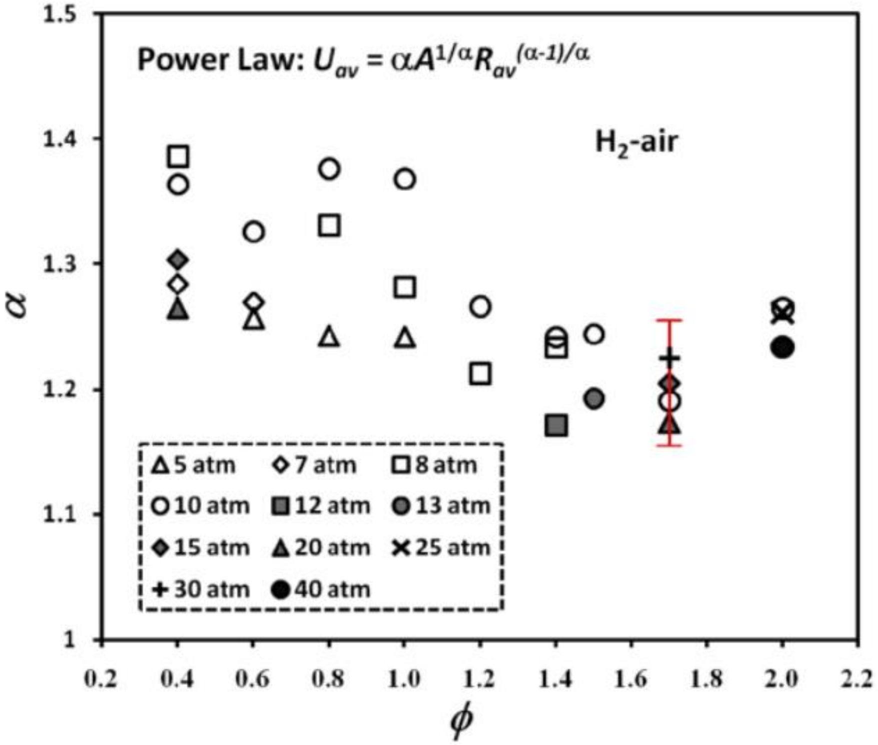

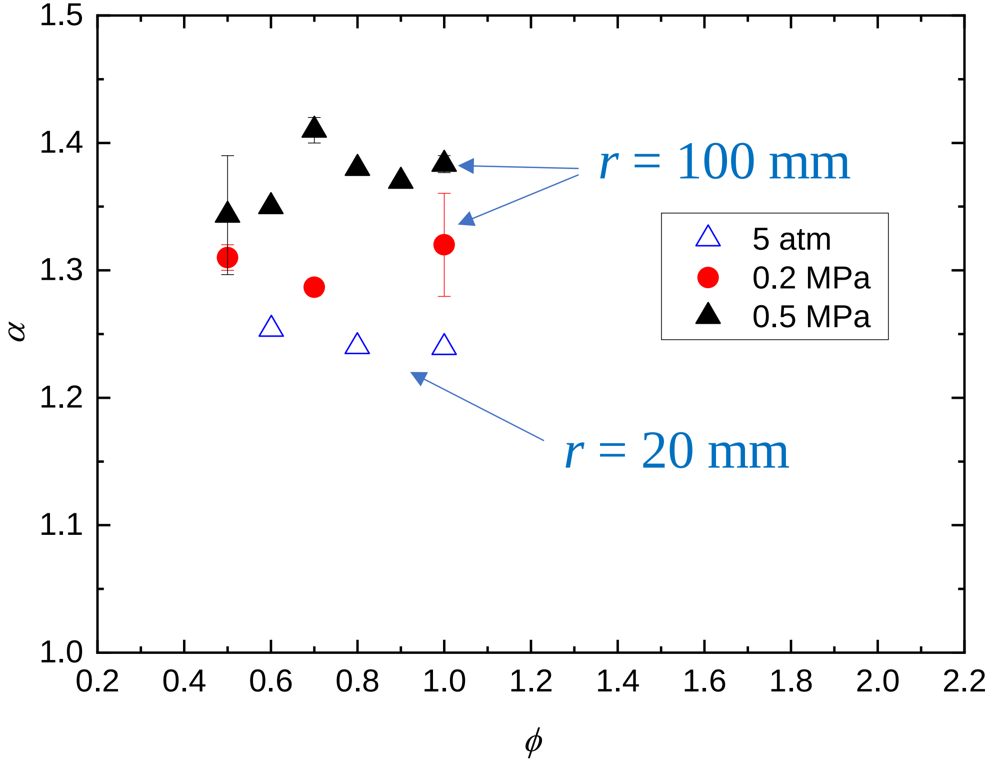

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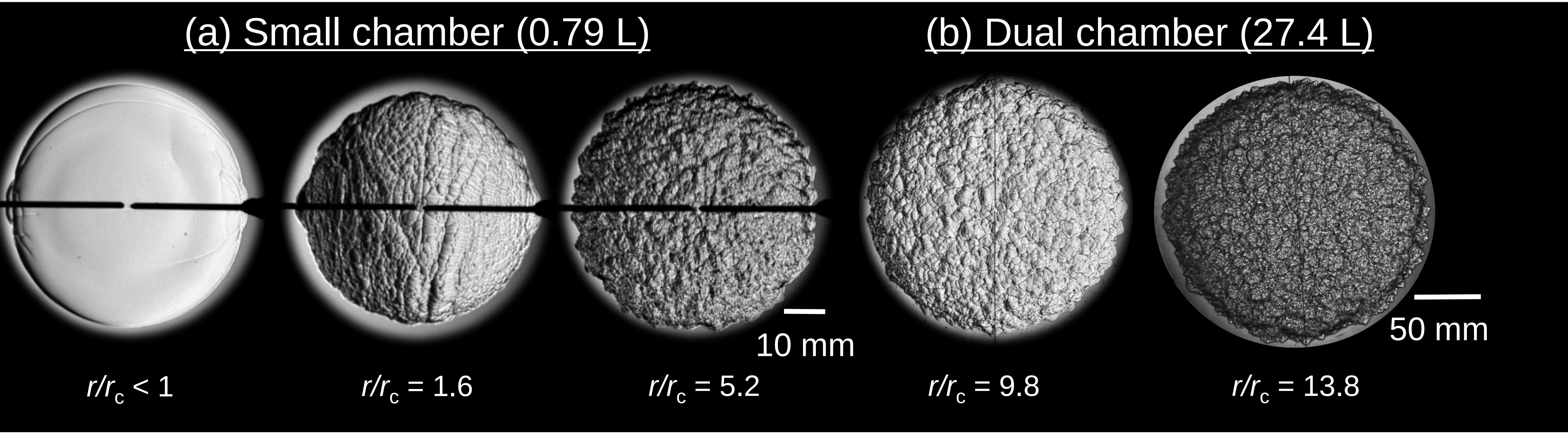

- The α increased and saturated $\alpha = 1.4$ with an increase in r/r_c.
- The transition regime to self-similar propagation has been observed at $r/r_c > 10$.
- Self-similarity is observed, in which the value of α remains nearly constant with further increase in r/r_c.

[6] W. Kim et al., *International Journal of Hydrogen Energy*, 43 (2018) 12556-15564, [8] W. Kim et al., *International Journal of Hydrogen Energy*, 45 (2020) 25608-25614.

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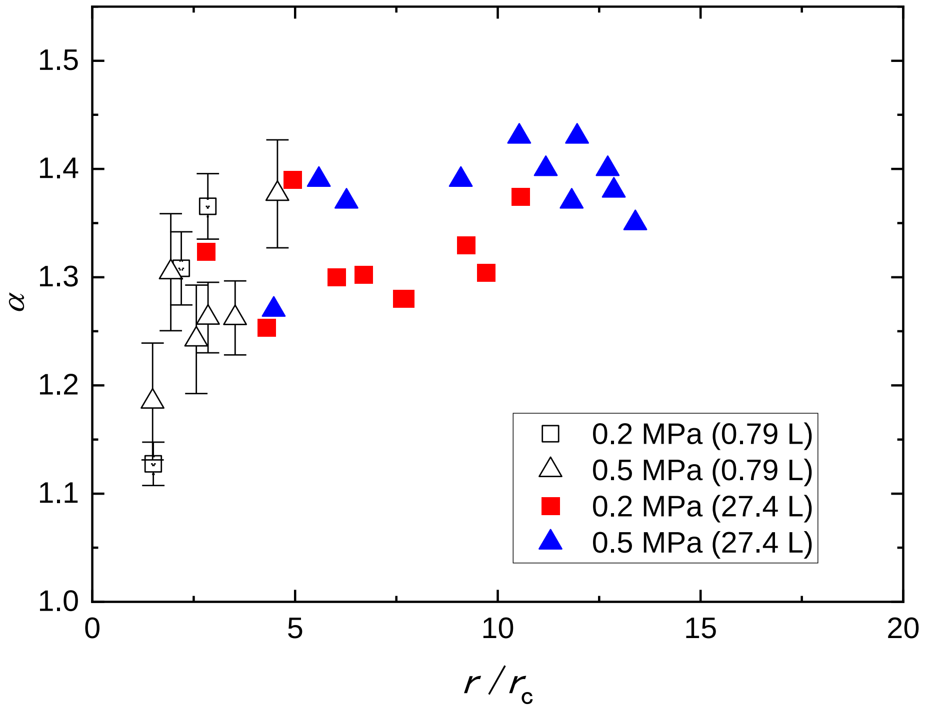

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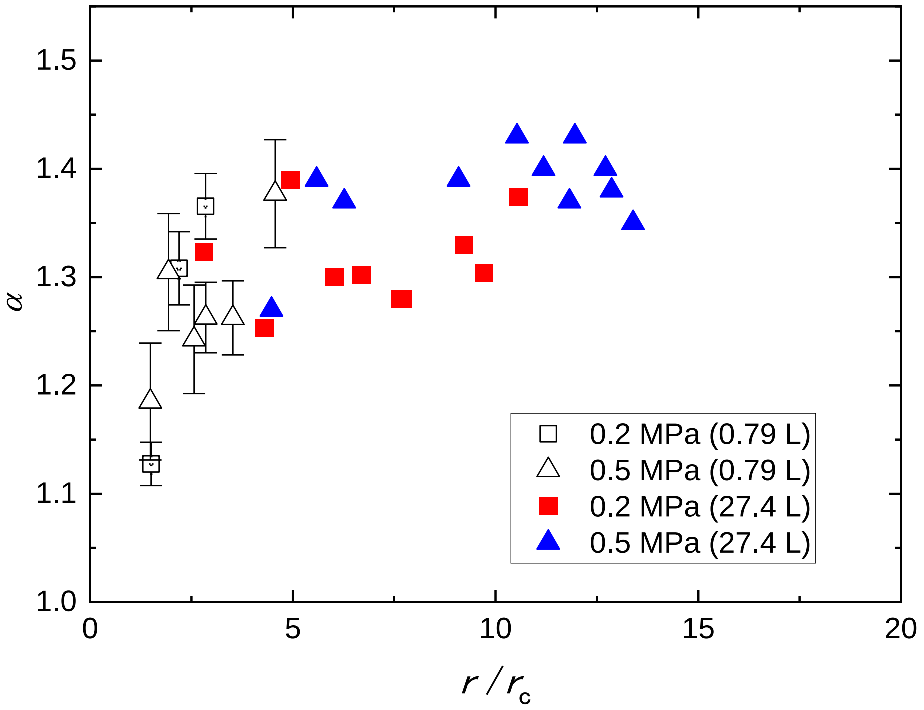

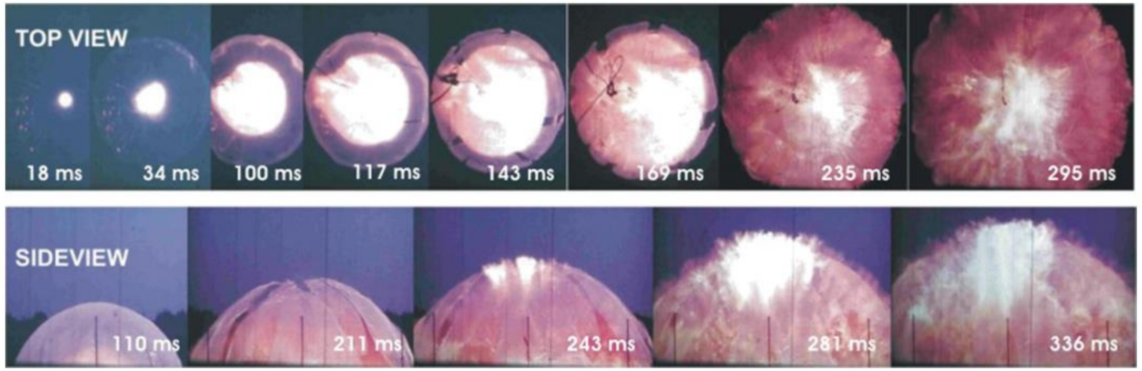

Large-scale near stoichiometric hydrogen-air flame in a 20 m diameter hemisphere.

- The α increased and saturated $\alpha = 1.4$ with an increase in r/r_c.
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[13] V Molkov et al., J. Phys. D: Appl. Phys. 39 (2006) 4366–4376, [14] V Molkov et al. Int. J. Hydrog. Energ 32 (2007) 2198–2205 [15] Y.A. Gostintsev et al., Combust Explo Shock Waves, 24 (1988) 563-569

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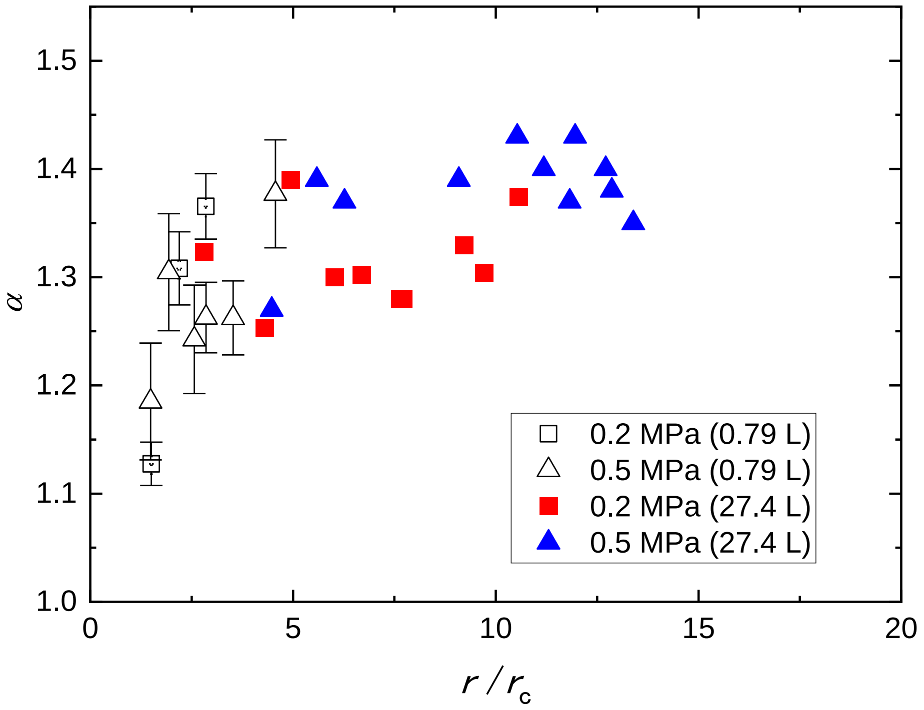

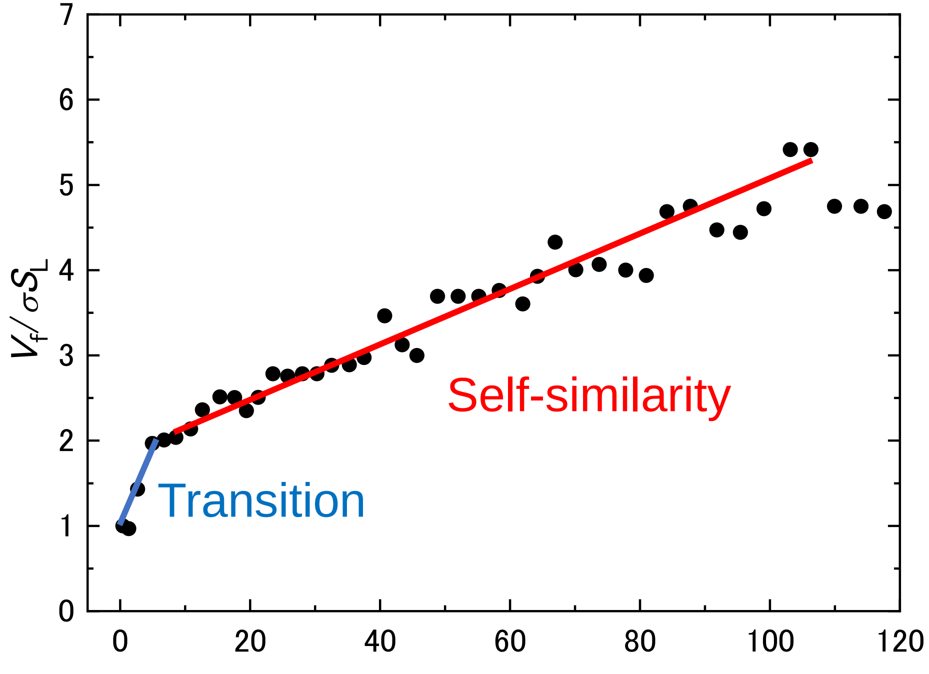

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<u>Onset of self-similarity</u>

- *Molkov*, $r/r_c = 8.6$ ($r_{cs} = 1$ m)
- *Gostinsev*, $r/r_c = 8.6\text{-}10.3$ ($r_{cs} = 1\text{-}1.2$ m)
- $r_c = 0.116$ m
- $\alpha = 1.42$

[13] V Molkov et al., J. Phys. D: Appl. Phys. 39 (2006) 4366–4376, [14] V Molkov et al. Int. J. Hydrog. Energ 32 (2007) 2198–2205 [15] Y.A. Gostintsev et al., Combust Explo Shock Waves, 24 (1988) 563-569

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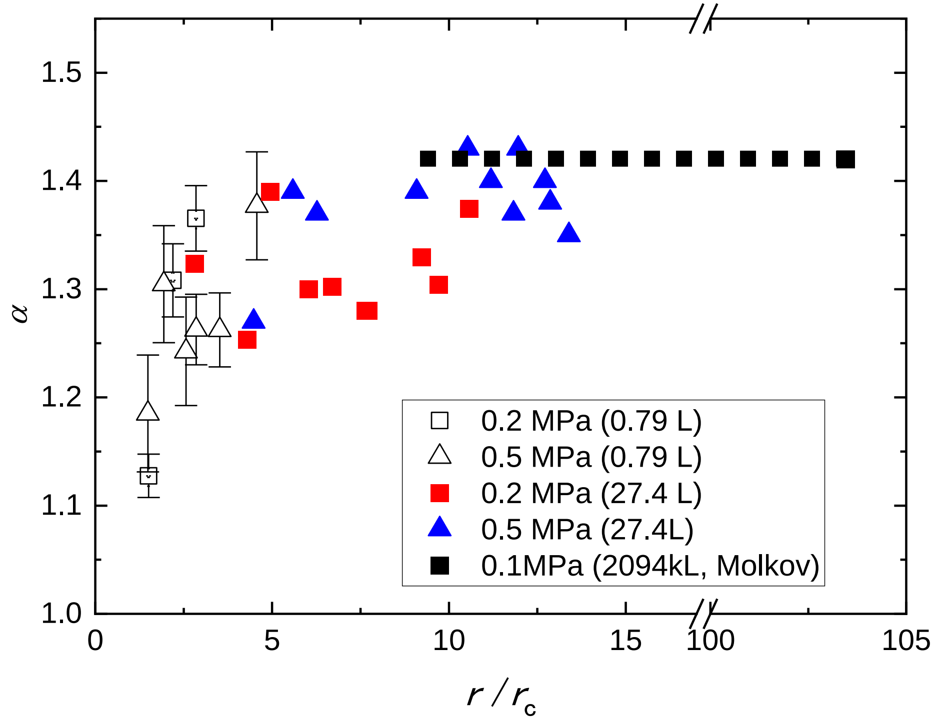

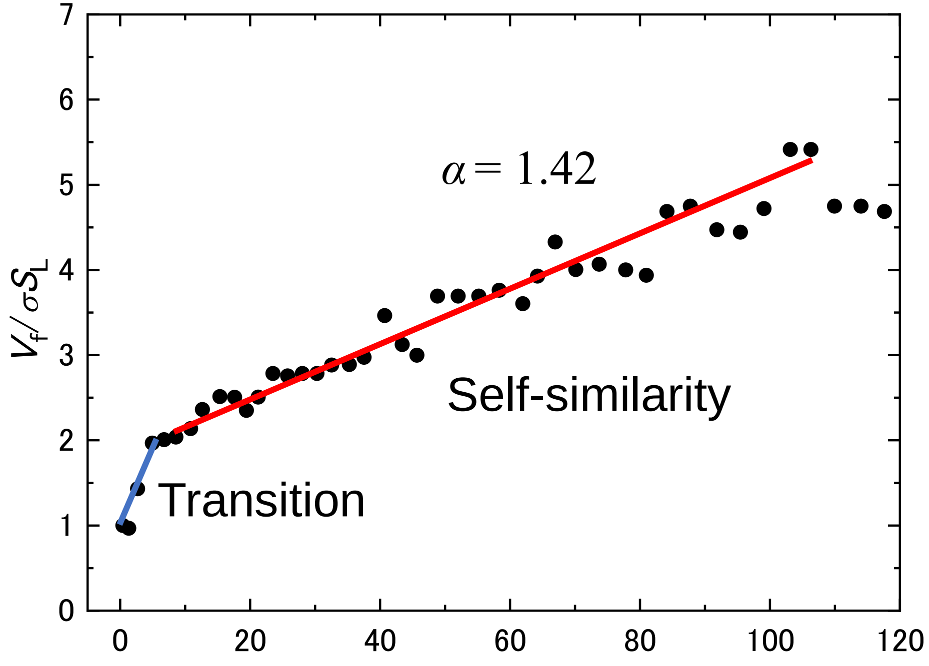

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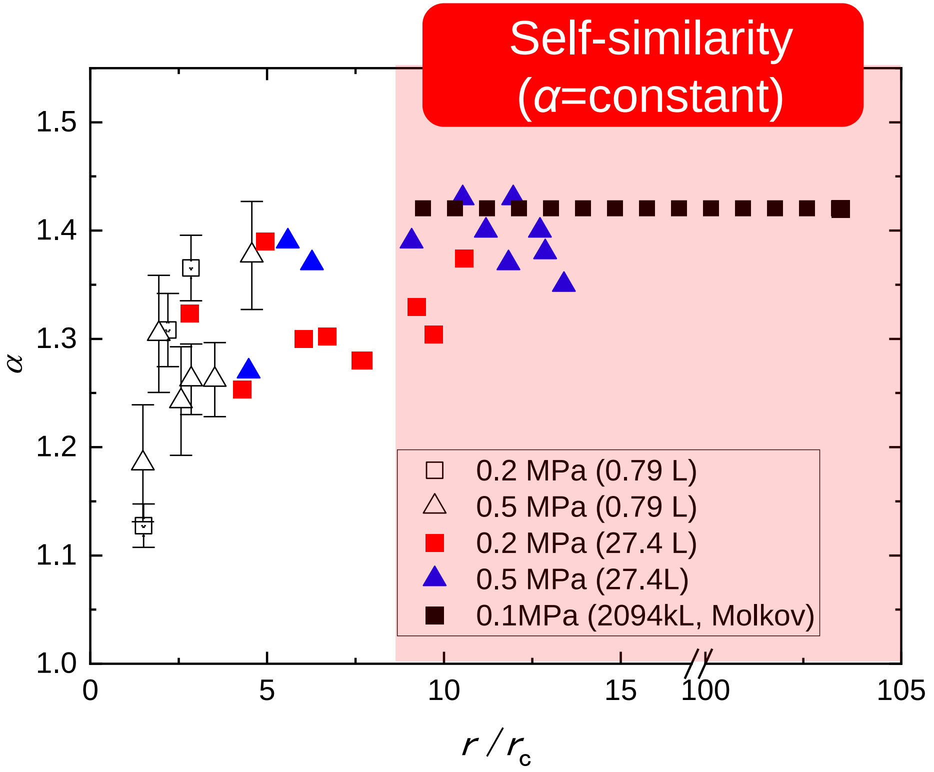

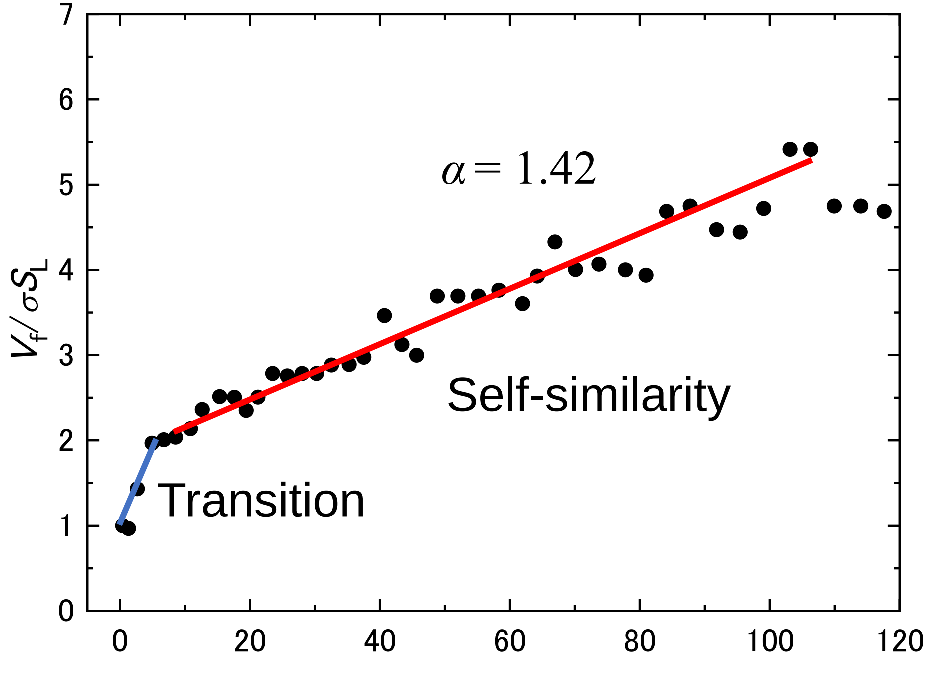

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increase in r/r_c.

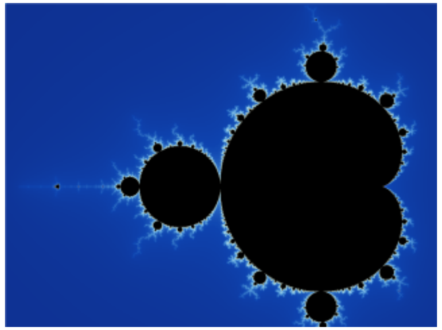
Onset of self-similarity

- $r_{\mathrm{c}} = 0.116$ m
- *Molkov*, $r/r_{\mathrm{c}} = 8.6$ ($r_{\mathrm{cs}} = 1$ m)
- *Gostinsev*, $r/r_{\mathrm{c}} = 8.6\text{-}10.3$ ($r_{\mathrm{cs}} = 1\text{-}1.2$ m)
- $\alpha = 1.42$

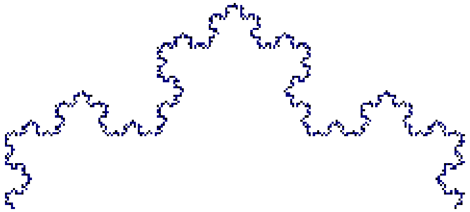
[13] V Molkov et al., J. Phys. D: Appl. Phys. 39 (2006) 4366–4376, [14] V Molkov et al. Int. J. Hydrog. Energ 32 (2007) 2198–2205 [15] Y.A. Gostintsev et al., Combust Explo Shock Waves, 24 (1988) 563-569

Self-acceleration and Self-similarity

-Fractal pattern in nature-



Mandelbrot set

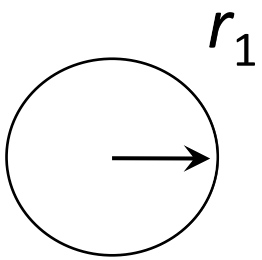


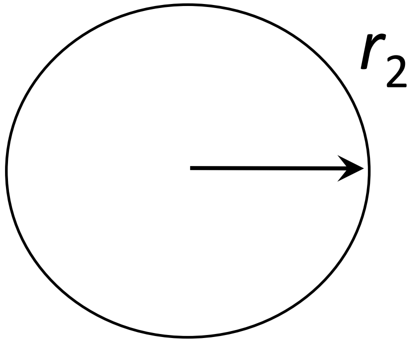
Koch curve

"Clouds are not spheres, mountains are not cones, coastlines are not circles, and bark is not smooth, nor does lightning travel in a straight line."(Mandelbrot, 1983).

→ **Fractals** are typically **self-similar patterns**, where self-similar means they are "**the same from near as from far**". Fractals may be exactly the same at every scale

Self-similar formation for Homologous sphere





$$L = \pi r_1$$

$$A = 4\pi r_1{}^2$$

$$V = \frac{4\pi r_1{}^3}{3}$$

$$\xrightarrow{\times\left(\frac{r_2}{r_1}\right)^D}$$

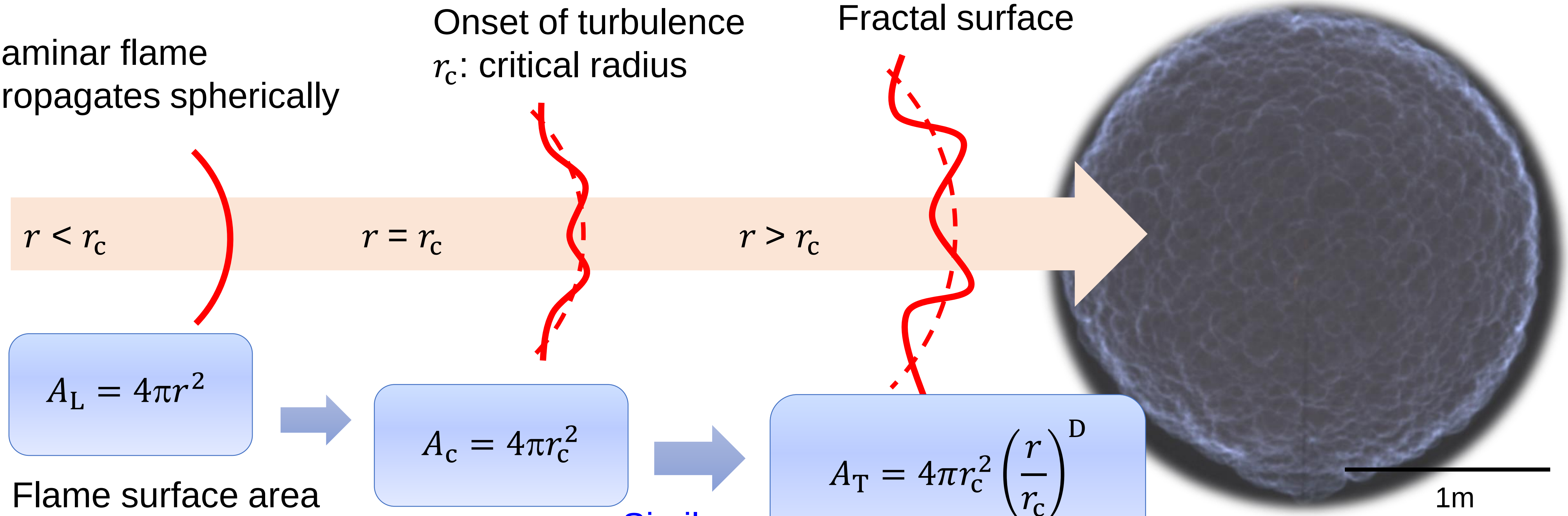
$$L = \pi r_2$$

$$A = 4\pi r_2{}^2$$

$$V = \frac{4\pi r_2{}^3}{3}$$

$D = 2 + d$: Fractal dimension

Modification of the flame surface area



Laminar flame
propagates spherically

Onset of turbulence
r_c: critical radius

Fractal surface

$r < r_c$

$r = r_c$

$r > r_c$

$A_L = 4\pi r^2$

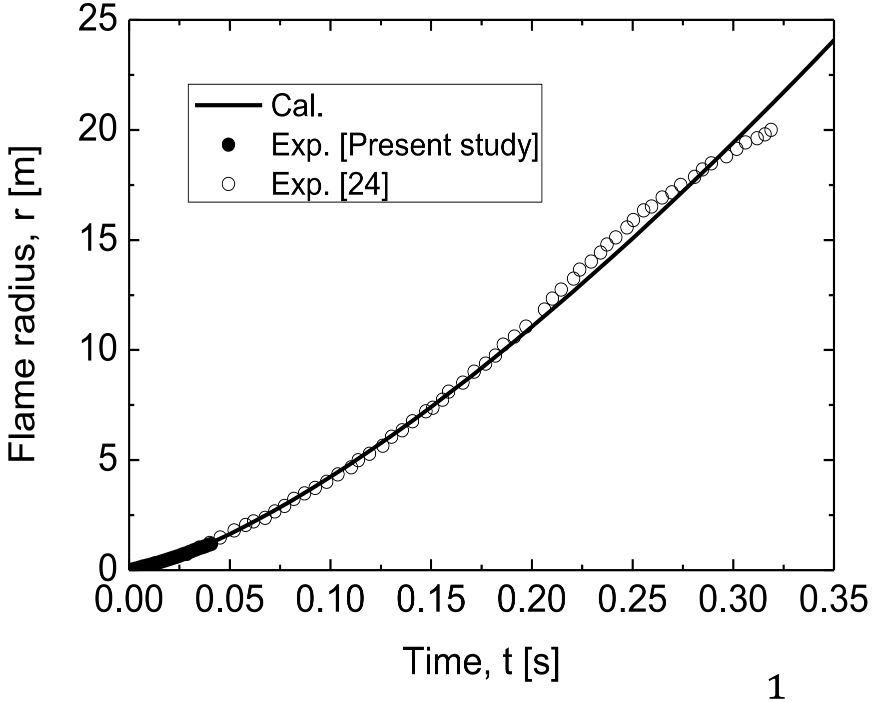
Flame surface area

$A_c = 4\pi r_c^2$

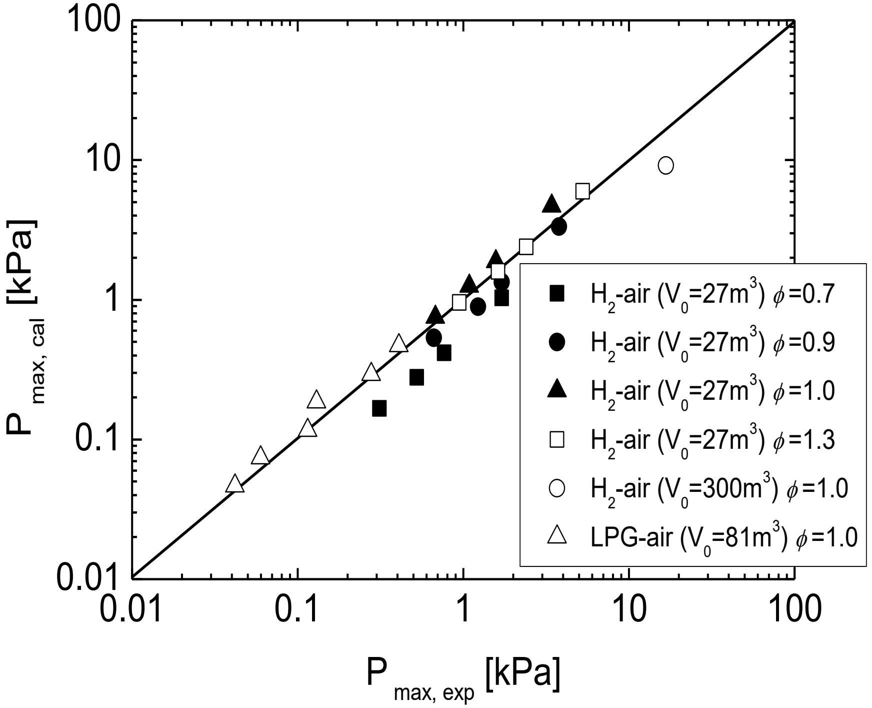
$A_T = 4\pi r_c^2 \left(\frac{r}{r_c}\right)^D$

Similar
transformation

Estimation models



$$r = \left(\frac{1-d}{r_{\mathrm{cl}}^{d}}\varepsilon S_{\mathrm{L}} t + d r_{\mathrm{cl}}^{1-d}\right)^{\frac{1}{1-d}}$$

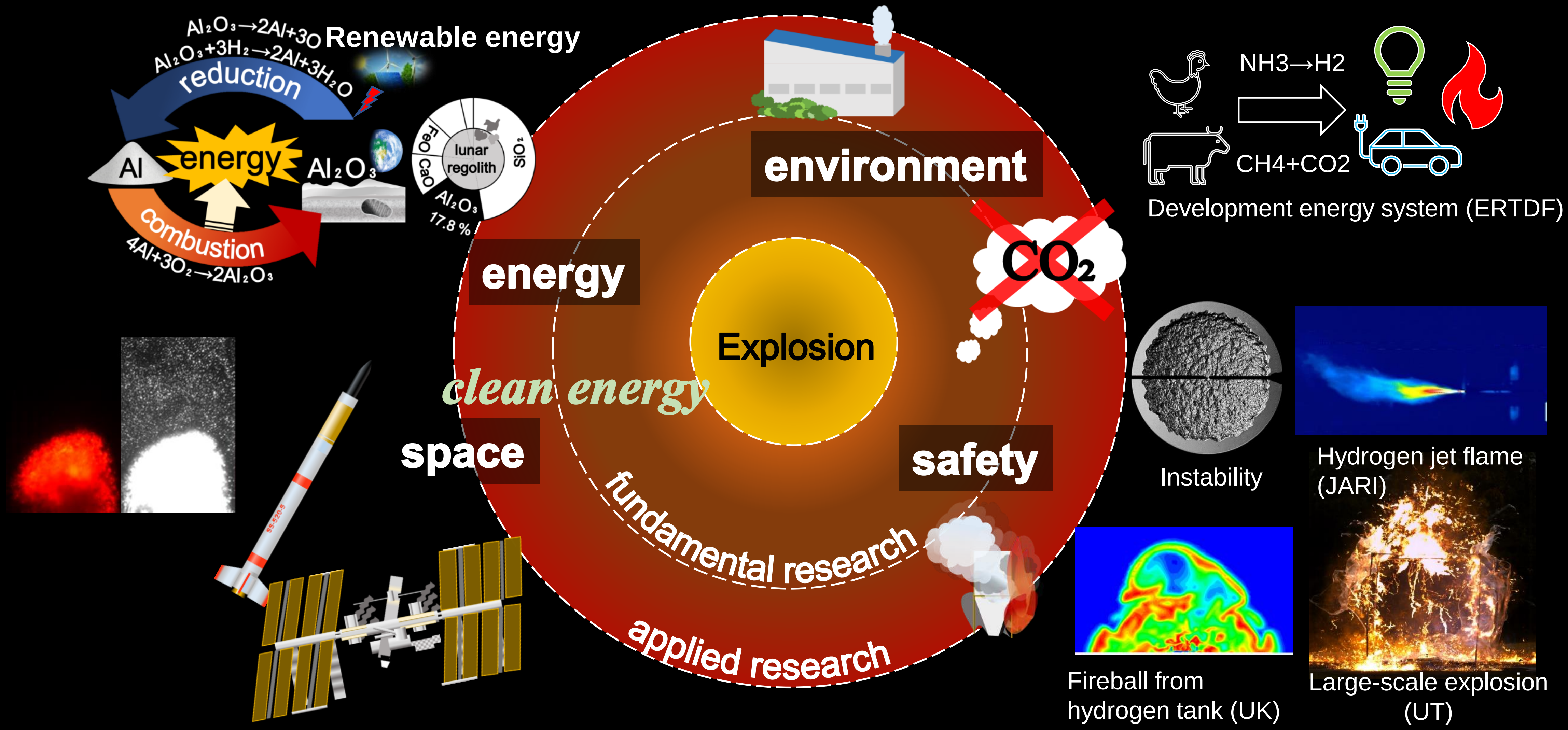


$$p_{\max} = \frac{\rho}{R}(d+2)\varepsilon^{2} S_{\mathrm{L}}^{2}\frac{r_{\mathrm{q}}^{2d+1}}{r_{\mathrm{cl}}^{2d}}$$

◆ These models were in agreement with large-scale gas explosions.

- W. Kim et al., Int. J. Hydrogen Energy, 40 (2015) 11087-11092,
- V Molkov et al., J. Phys. D: Appl. Phys. 39 (2006) 4366–4376

-Understanding explosion from industry to space-



Development energy system (ERTDF)

Instability

Hydrogen jet flame (JARI)

Fireball from hydrogen tank (UK)

Large-scale explosion (UT)