Bifurcations of stretched premixed flame stabilized by a hot wall

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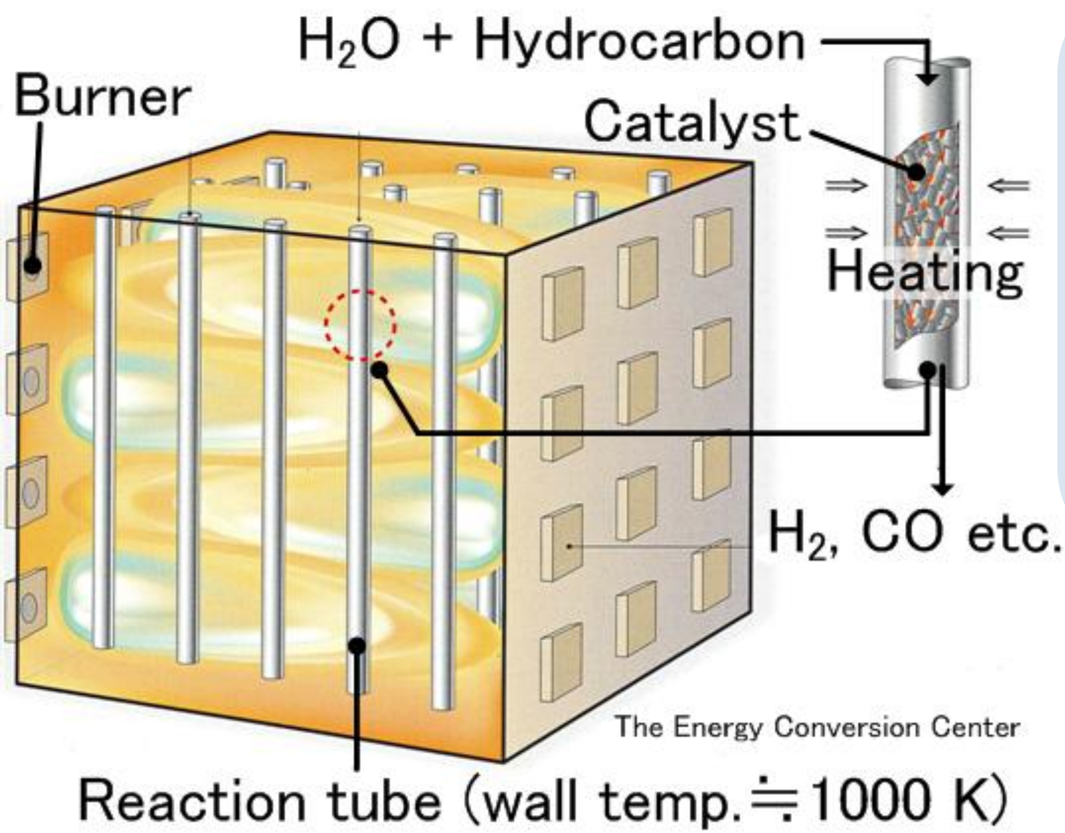
Background

HiCOT: high-temperature air combustion technology

Advantages:

significant CO_2 reduction, low NOx emission, homogeneous temperature, low acoustic noise, downsizing



Schematic of steam reformer

- Without HiCOT, flames should be far from reaction tubes
- With HiCOT, flames can be close to reaction tubes

↓

<u>Characteristics of flames near a hot wall</u>

Objectives

Flames interacting with a hot wall

Flame bifurcations have been shown using numerical computation and theoretical analysis
(Y. Ju & S. Minaev (2002))

↓

Flame bifurcations have not been shown experimentally

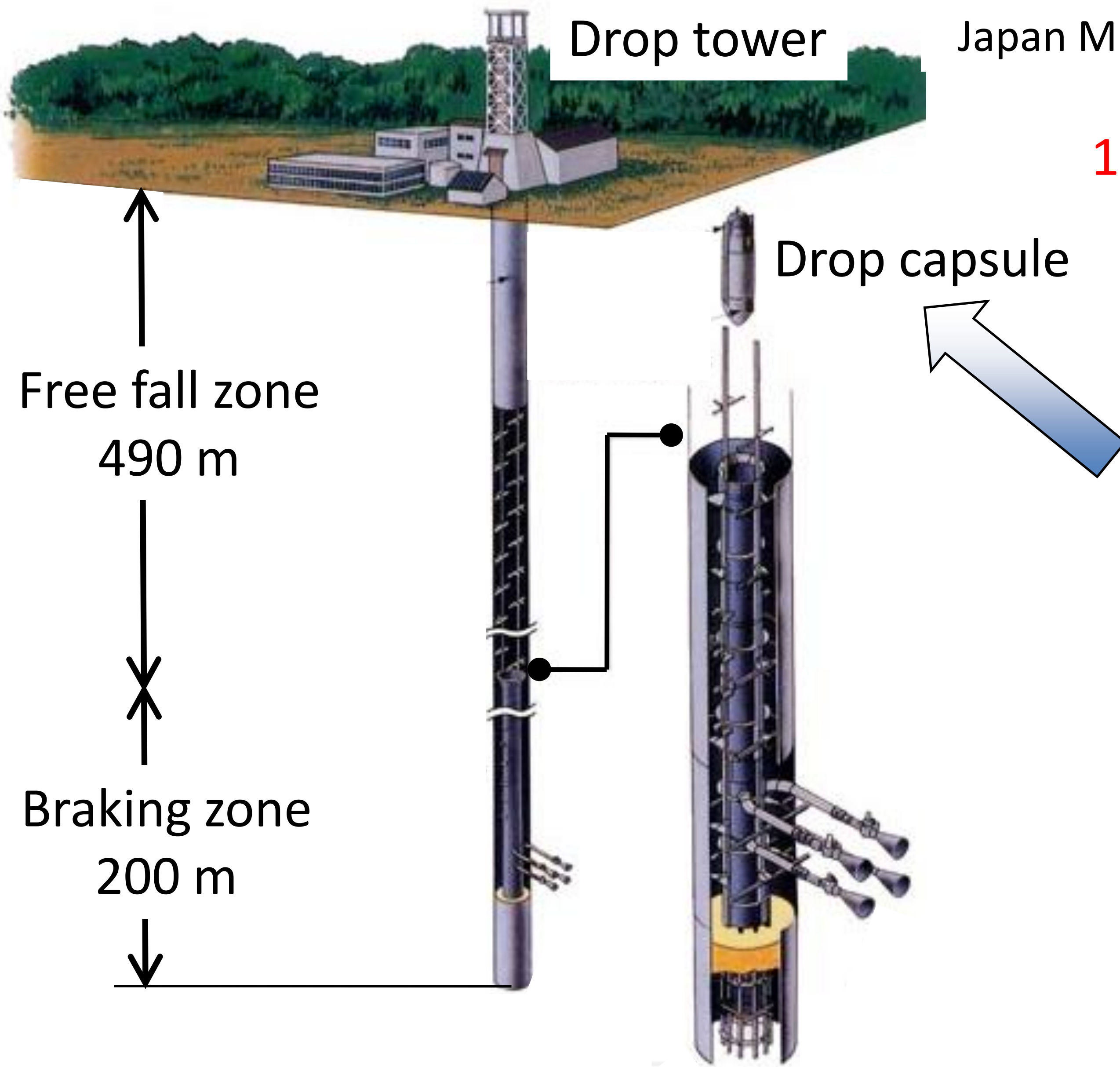
Flame structures have not been investigated in detail

- **Show flame bifurcations by microgravity experiments**
- **Investigate flame structures and flame bifurcations by numerical computations**

Experimental facility

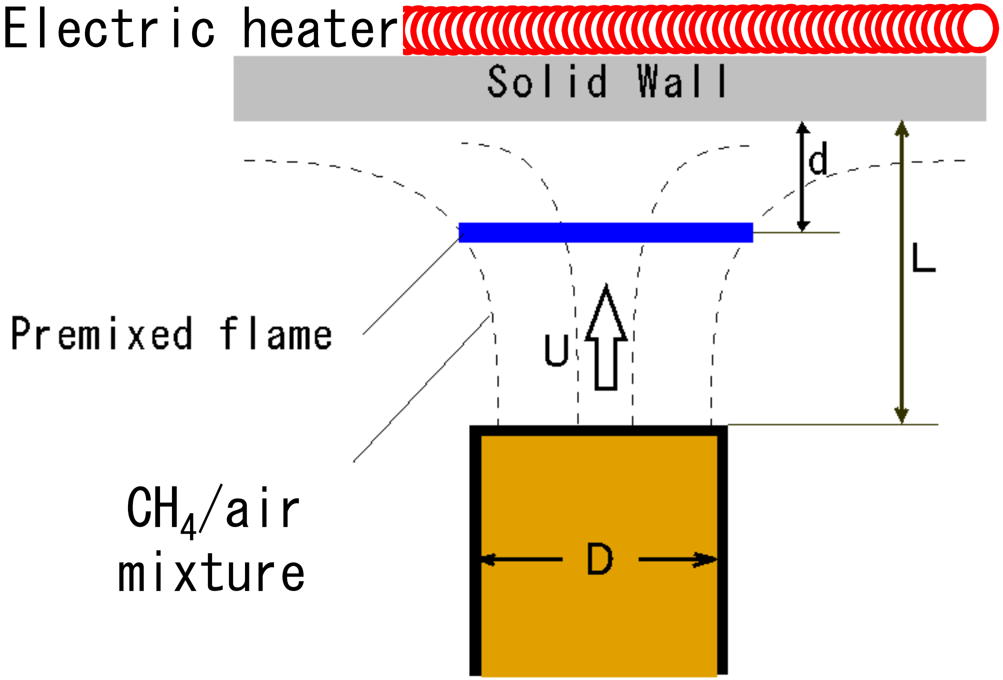
Japan Microgravity Center (JAMIC)

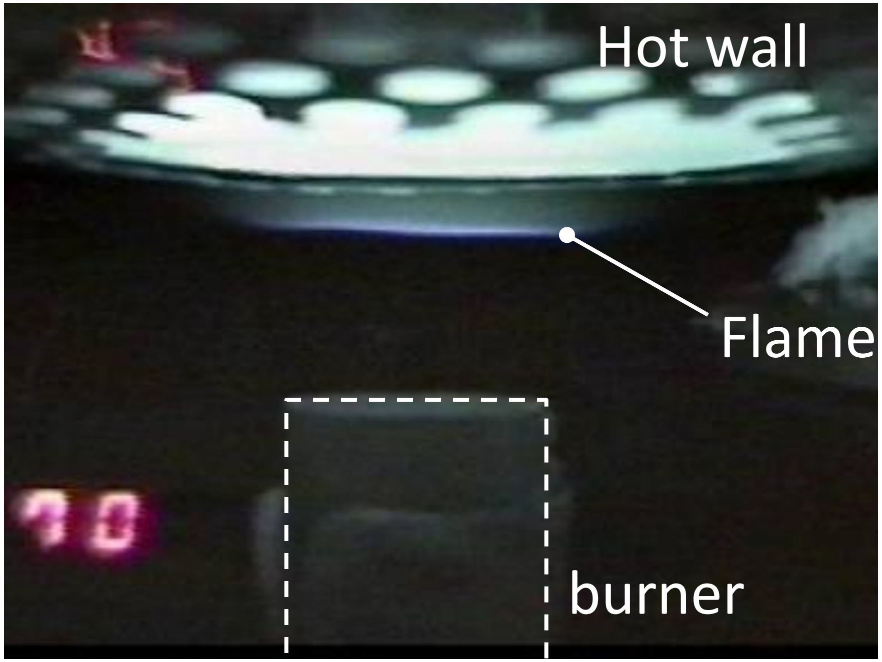
10^{-5} g for 10 seconds



Experimental rack

Experimental setup





$\varepsilon = 8\ s^{-1}$

Wall temperature:

Tw = 973 K

Distance between wall and burner exit:

L = 2.5 cm

Burner inner diameter:

D = 2.0 cm

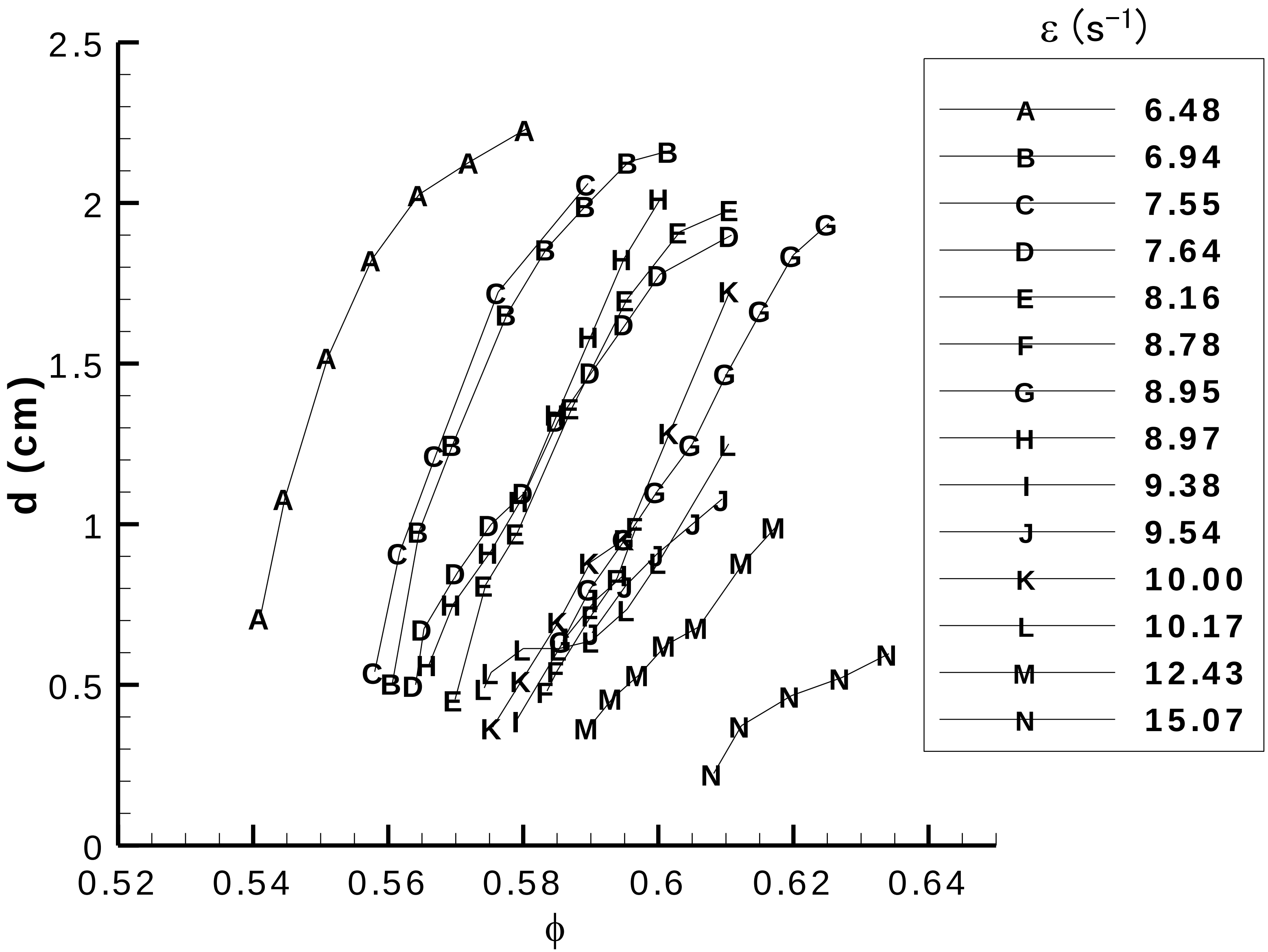
Stretch rate:

$\varepsilon = U/D$

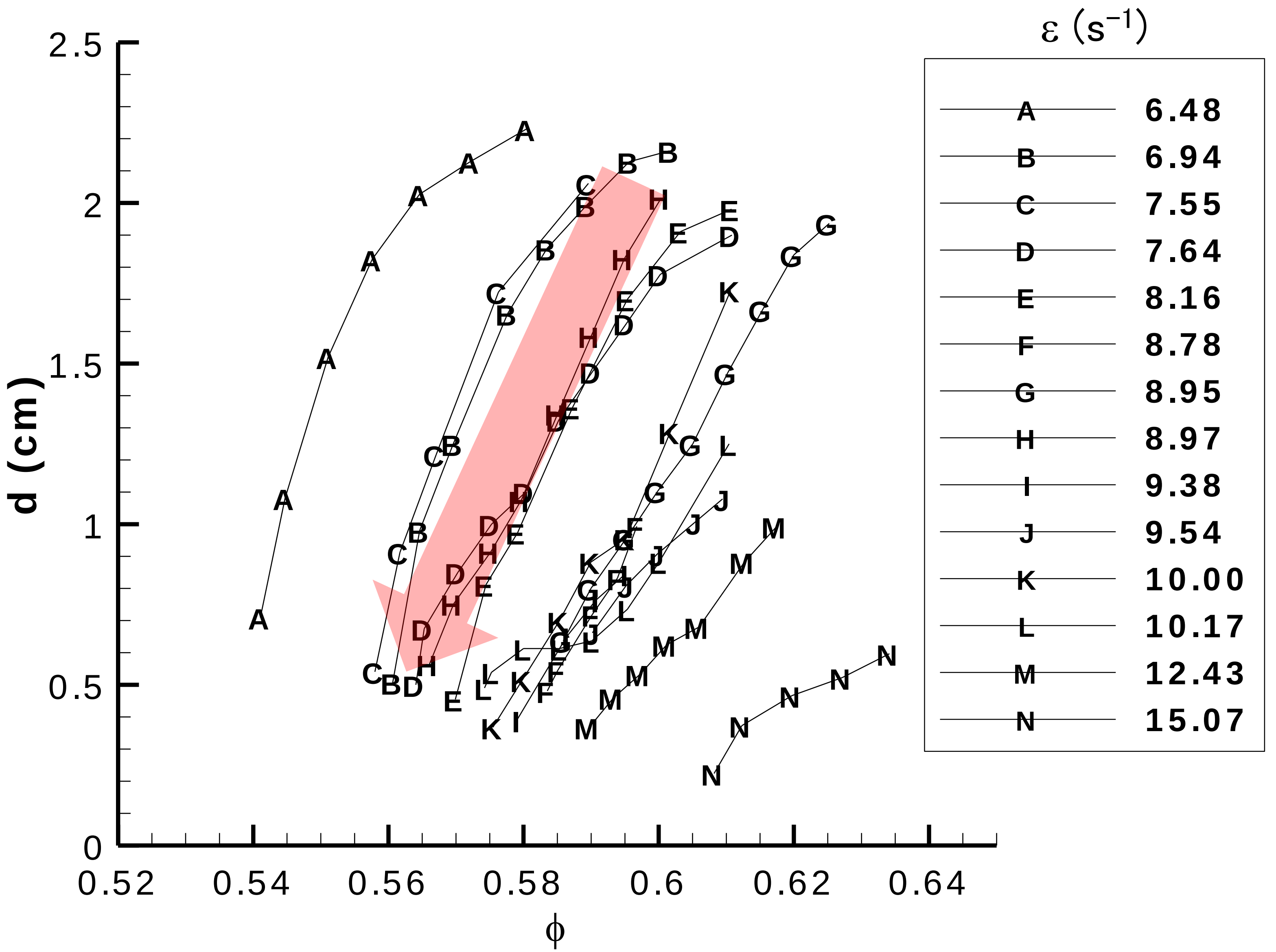
Experimental procedures

1. Changing ϕ at constant ε
2. Changing ε at constant ϕ

Exp. results (1. changing ϕ at constant ε)

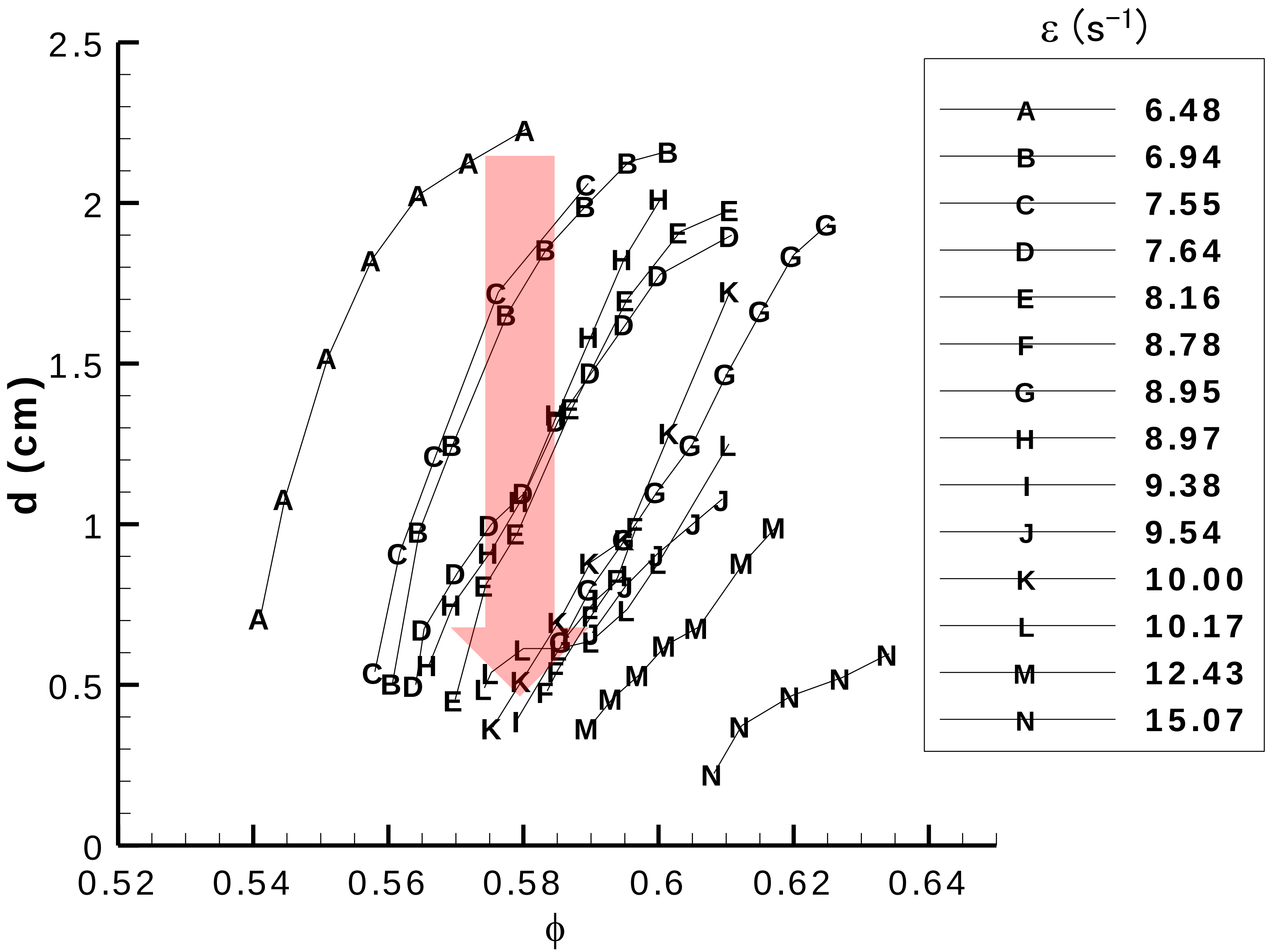


Exp. results (1. changing ϕ at constant ε)



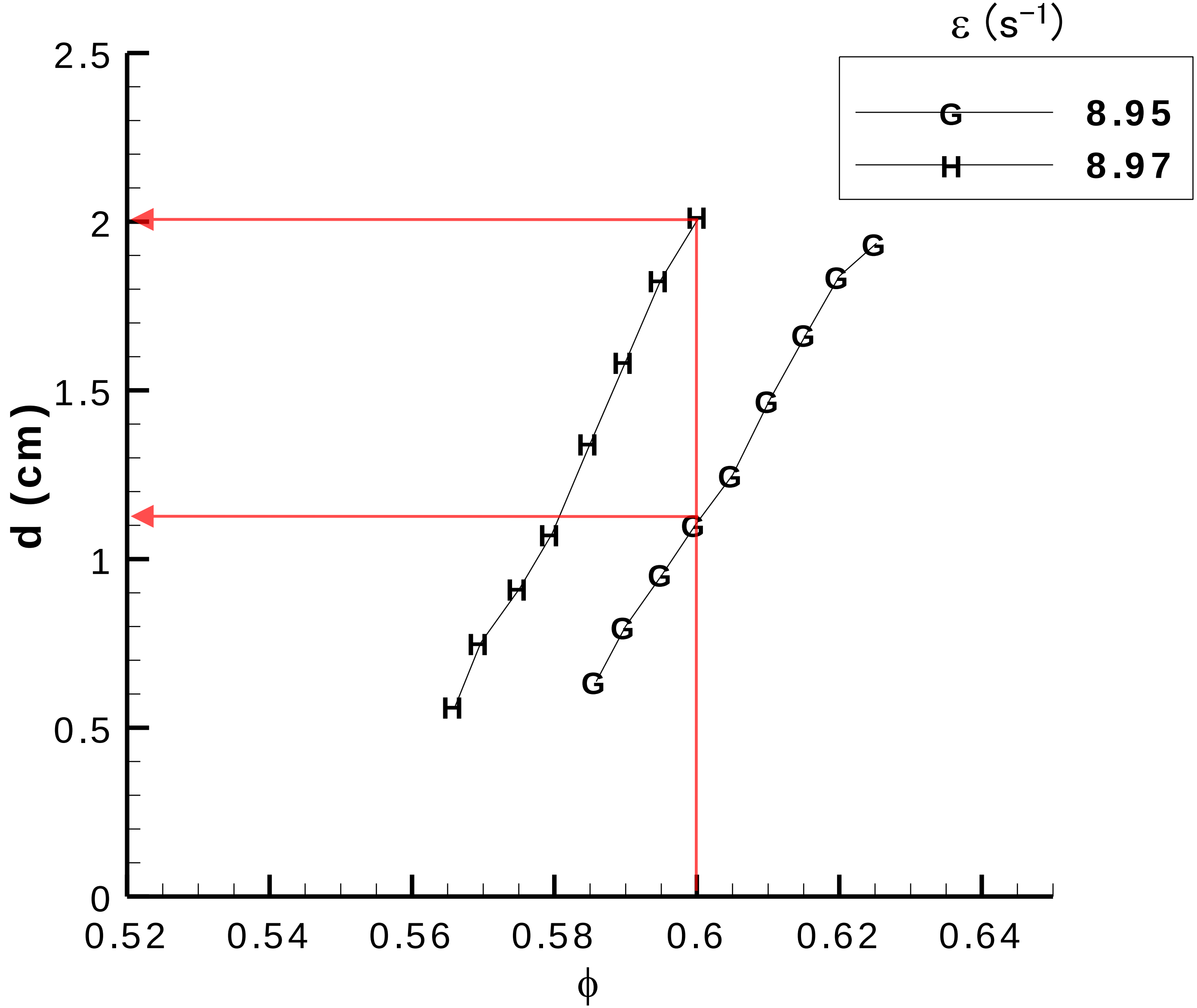
d gets close to the hot wall as ϕ decreases at constant ε

Exp. results (1. changing ϕ at constant ε)



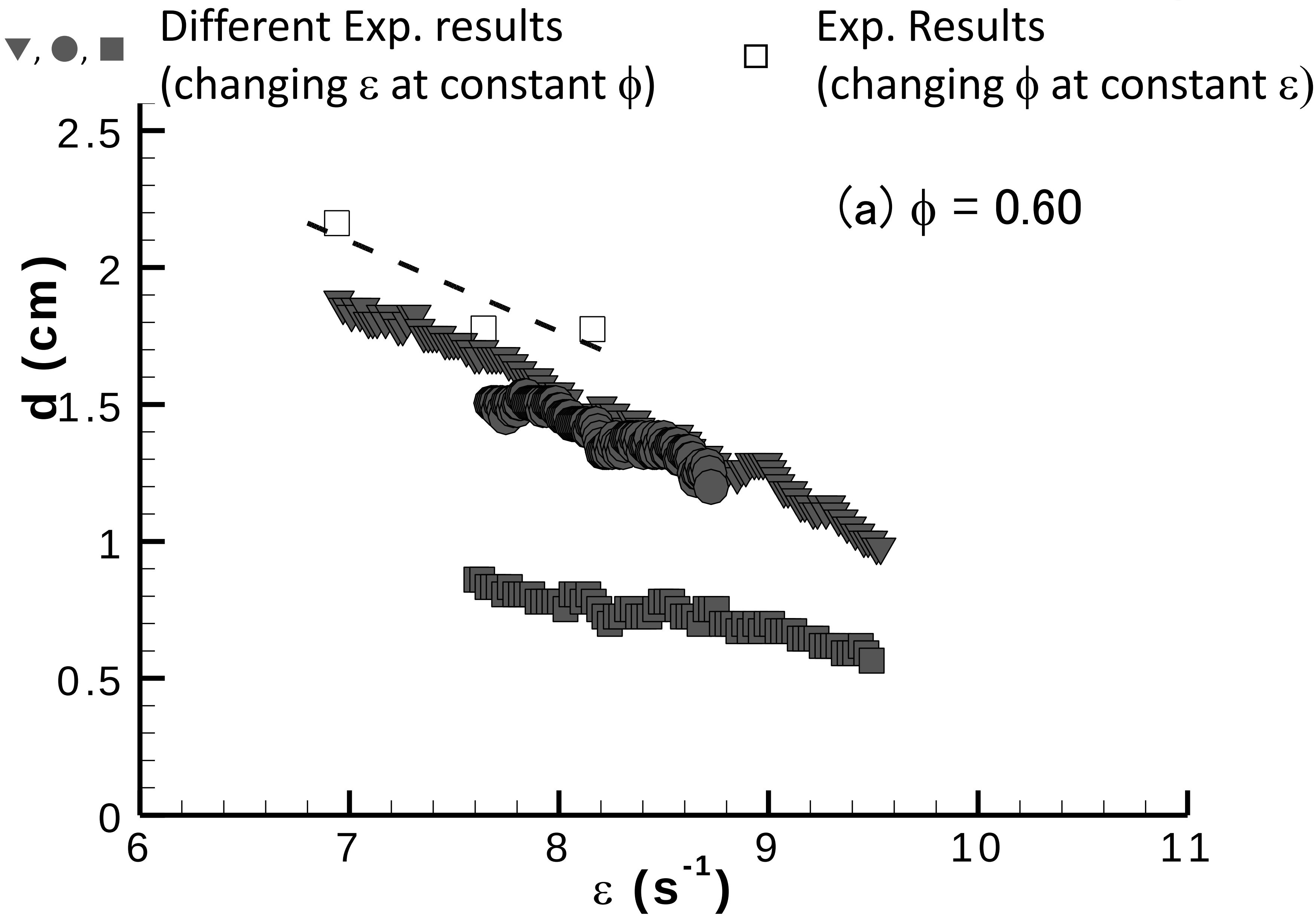
d gets close to the hot wall in case of higher ε at the same ϕ

Exp. results (1. changing ϕ at constant ε)

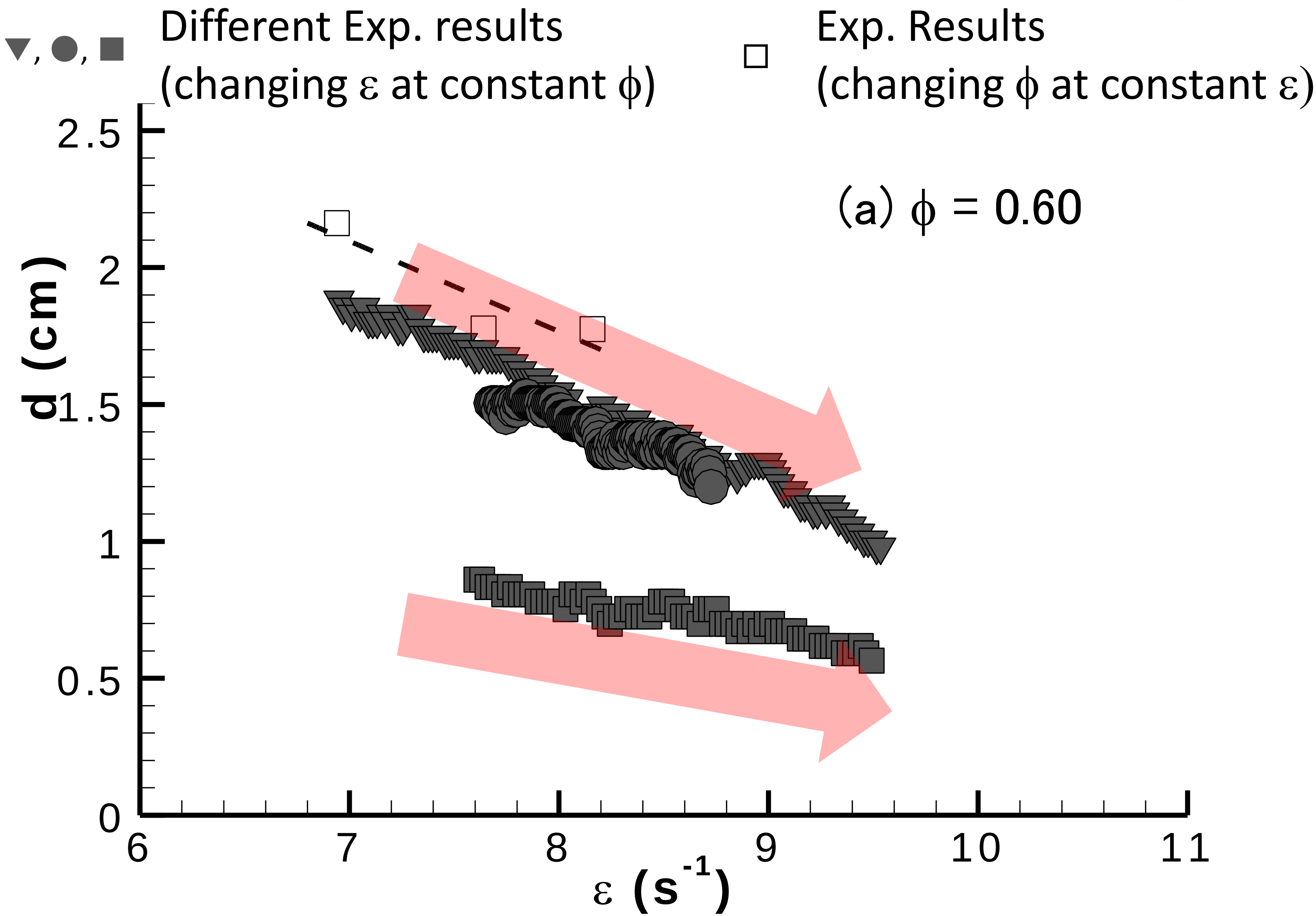


Two groups of flame locations in the identical conditions

Exp. results (2. changing ε at constant ϕ)

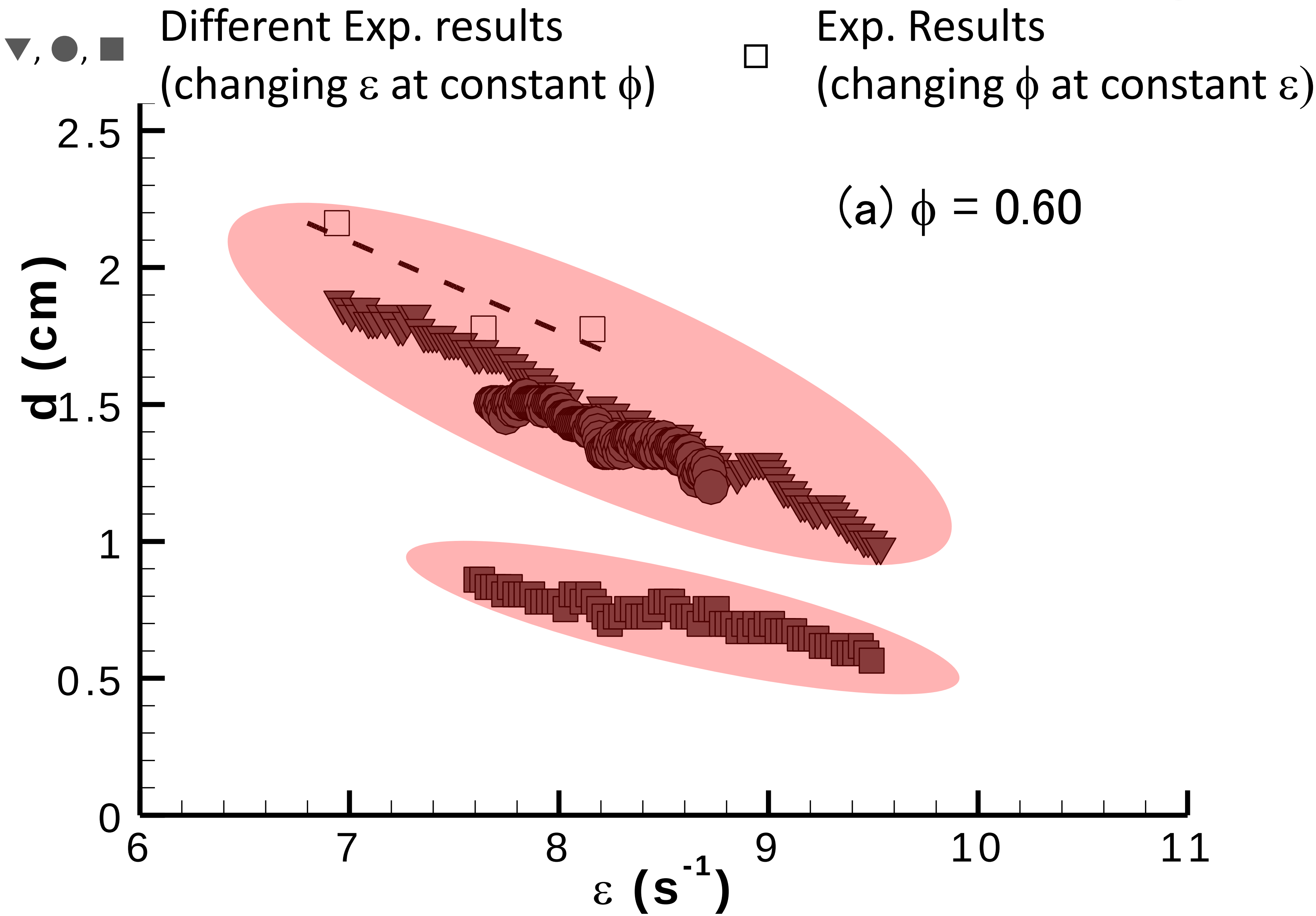


Exp. results (2. changing ε at constant ϕ)



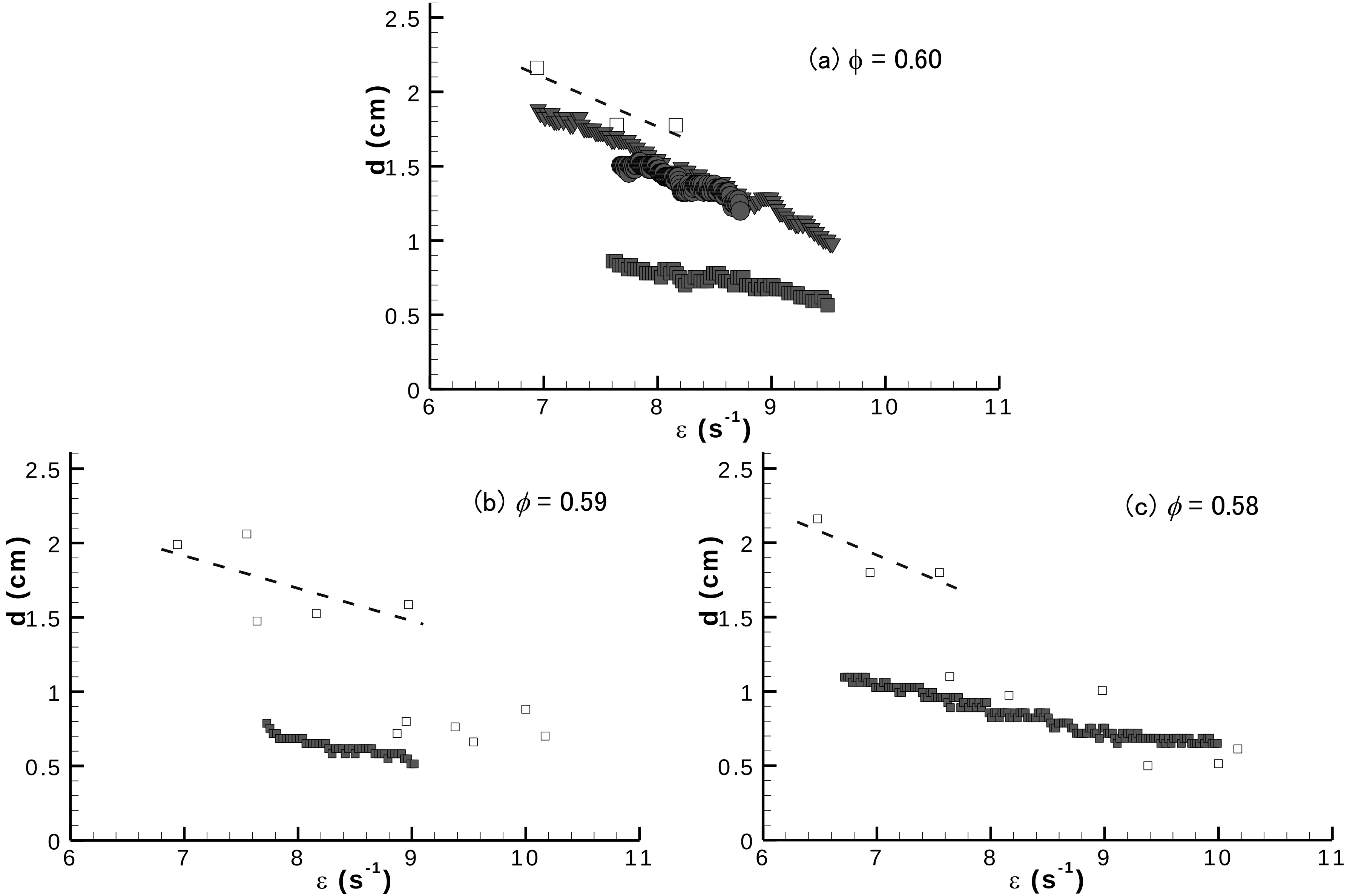
d gets close to the hot wall as ε increases

Exp. results (2. changing ε at constant ϕ)

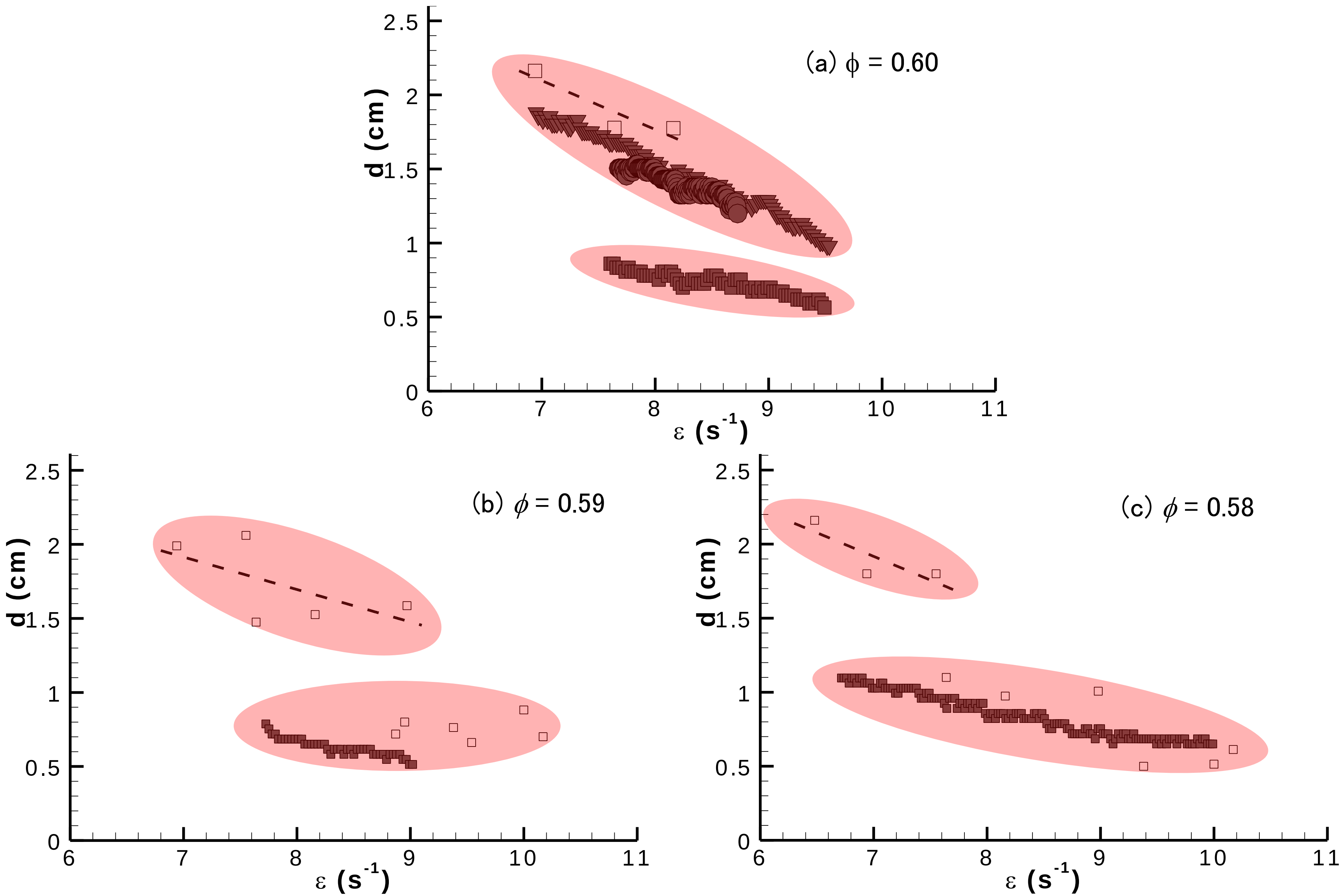


Two groups of flame locations in the identical conditions

Flame bifurcations



Flame bifurcations



Flame bifurcations were confirmed experimentally

Computational methods

- Flame code with arc-length continuation method for stretched premixed flames in stagnation flow

$$\frac{\partial \rho}{\partial \mathrm{t}} + \frac{\partial \mathrm{U}}{\partial X} = -2\rho G$$

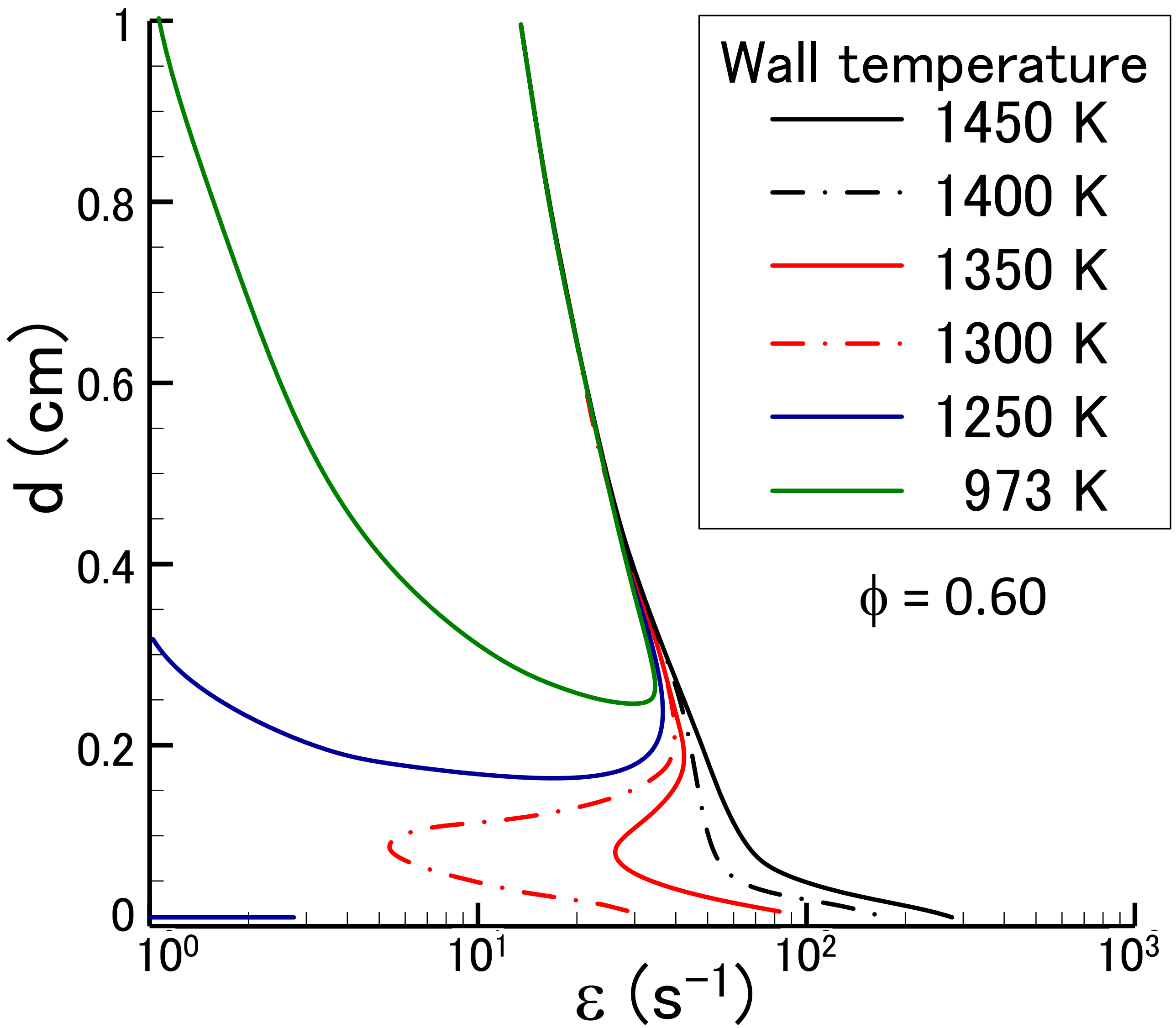
$$L(G) = \frac{\partial}{\partial X}\left(\mu \frac{\partial G}{\partial X}\right) - \rho G^2 + \rho\left(\frac{da}{dt} + a^2\right)$$

$$C_p L(T) = \frac{\partial}{\partial X}\left(\lambda \frac{\partial T}{\partial X}\right) - \sum_{k=l}^{n} \rho Y_k V_k C_{pk} \frac{\partial T}{\partial X} - \sum_{k=l}^{n} h_k \omega \mathrm{M}_k + q_r$$

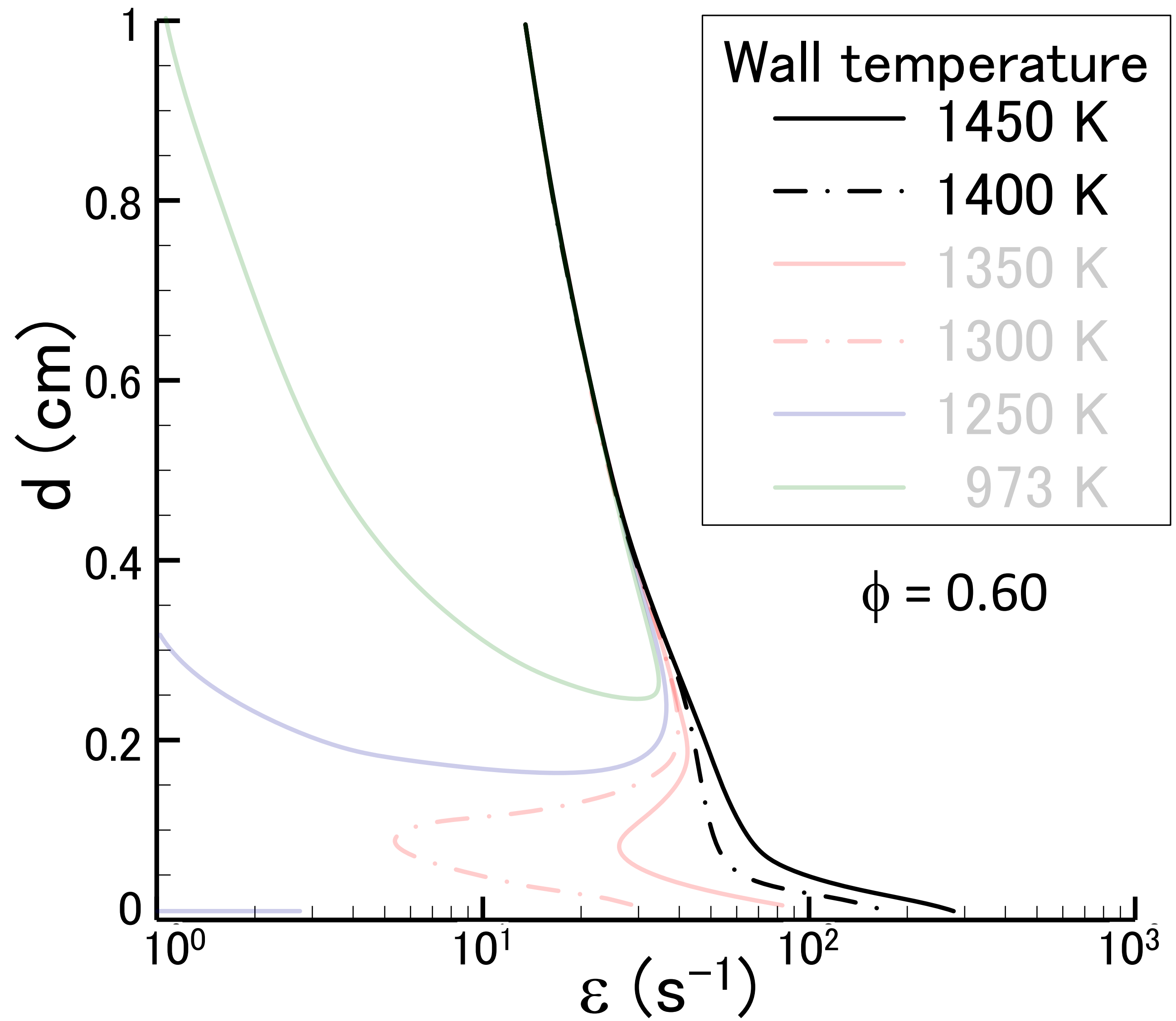
$$L(Y_k) = -\frac{\partial}{\partial X}(\rho Y_k V_k) + \sum_{k=l}^{n} \omega M_k$$

- Chemical kinetics mechanism
  C1 chemistry (18 species and 58 reactions)
- Radiative heat loss
  Optically thin model for CO_2, H_2O, CH_4 and CO species
  (Adiabatic condition and Statistical narrow band model)
- Equivalence ratio: 0.60
- Flame location: the location of the maximum CH mole fraction

Calc. results – flame locations

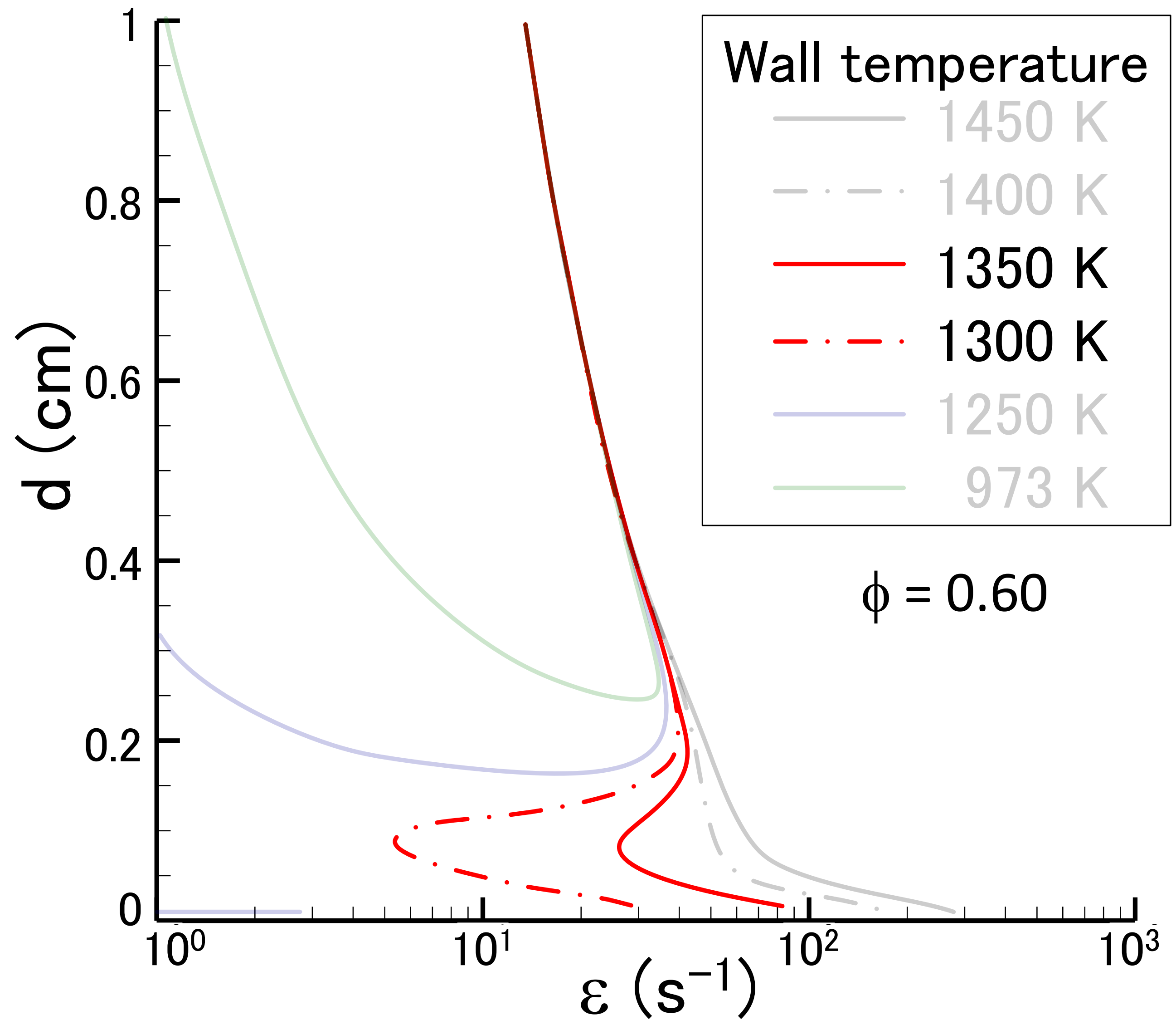


Calc. results – flame locations



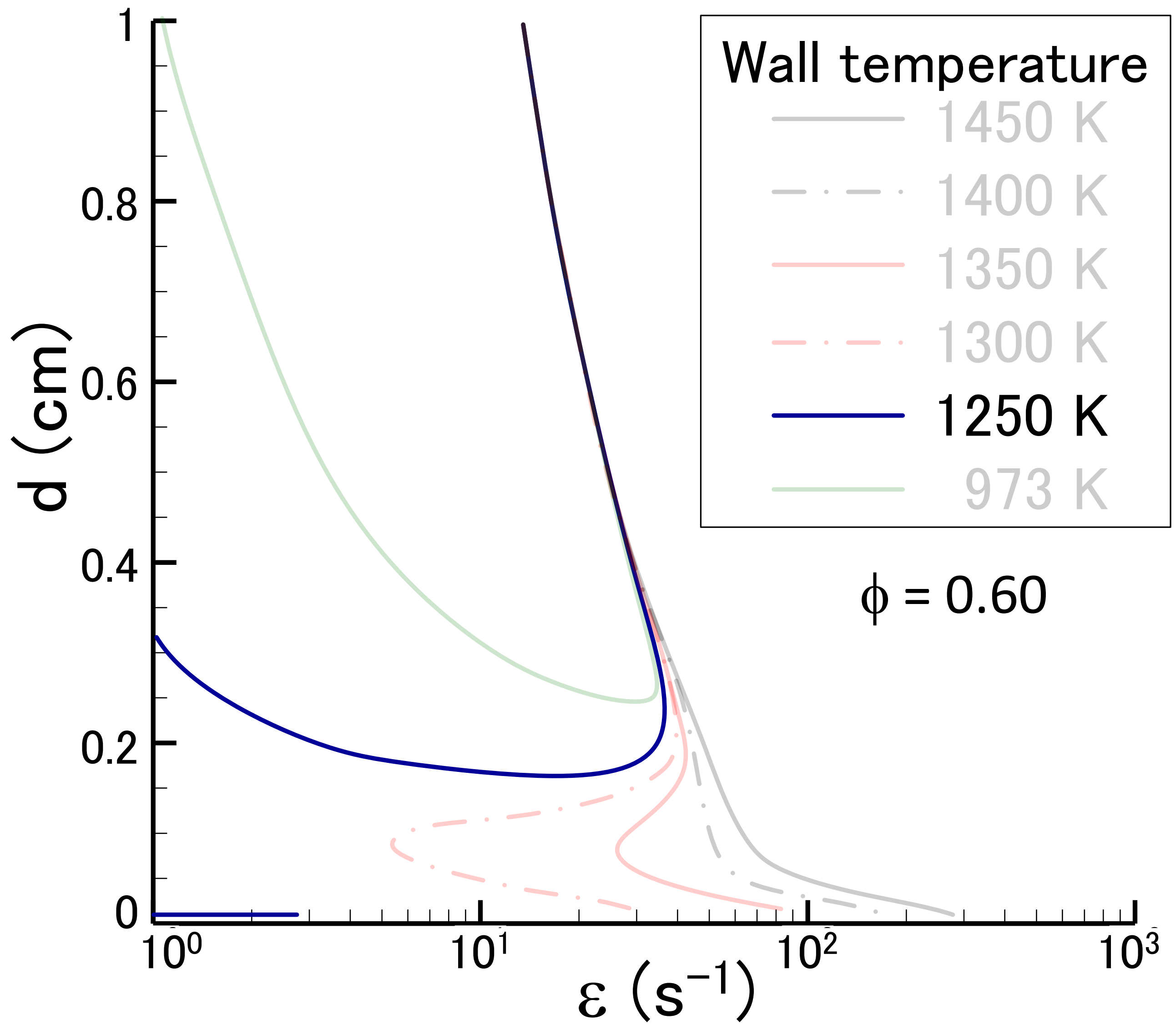
Flame locations get close to the hot wall monotonously

Calc. results – flame locations



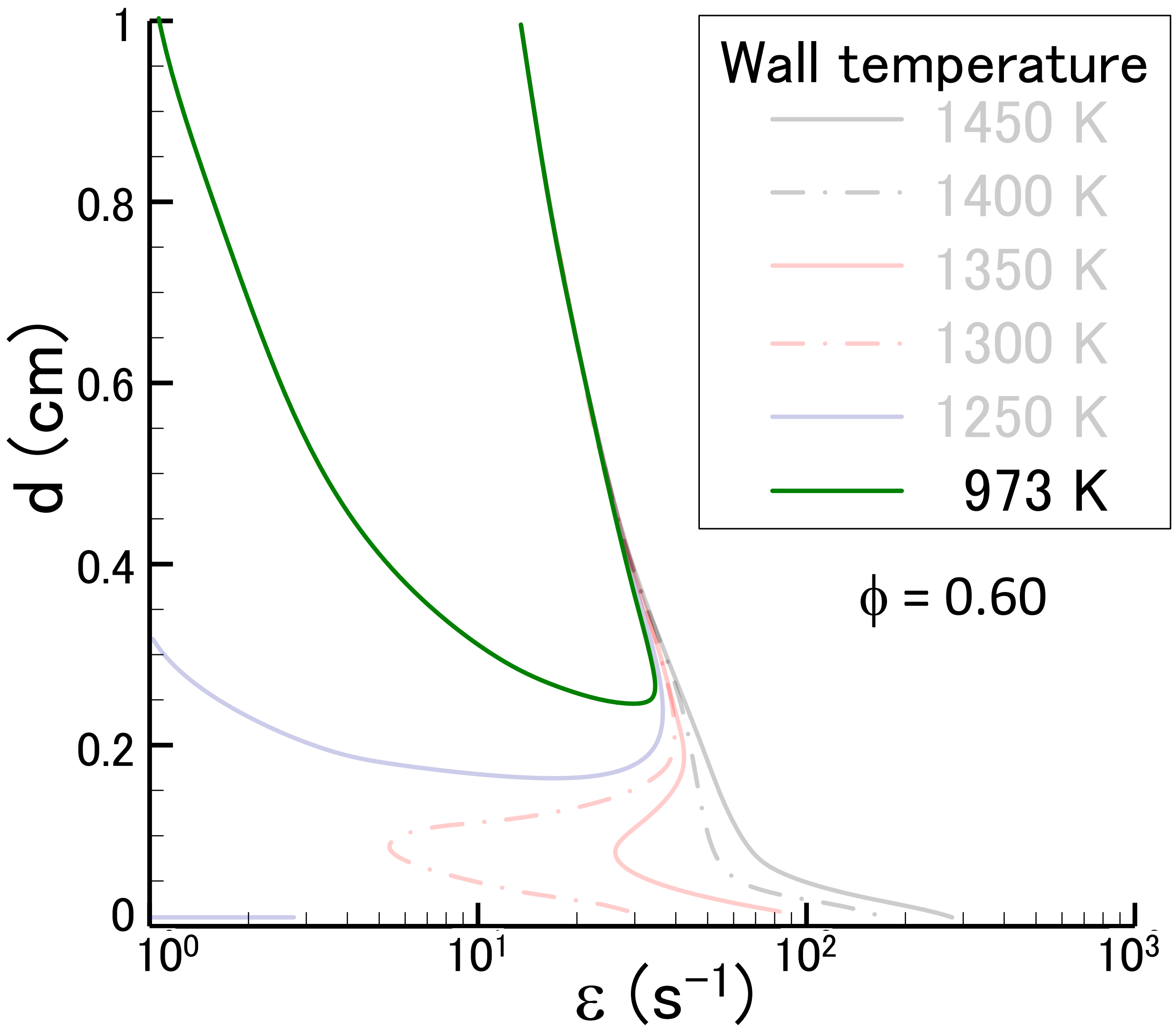
S-shape solutions appear

Calc. results – flame locations



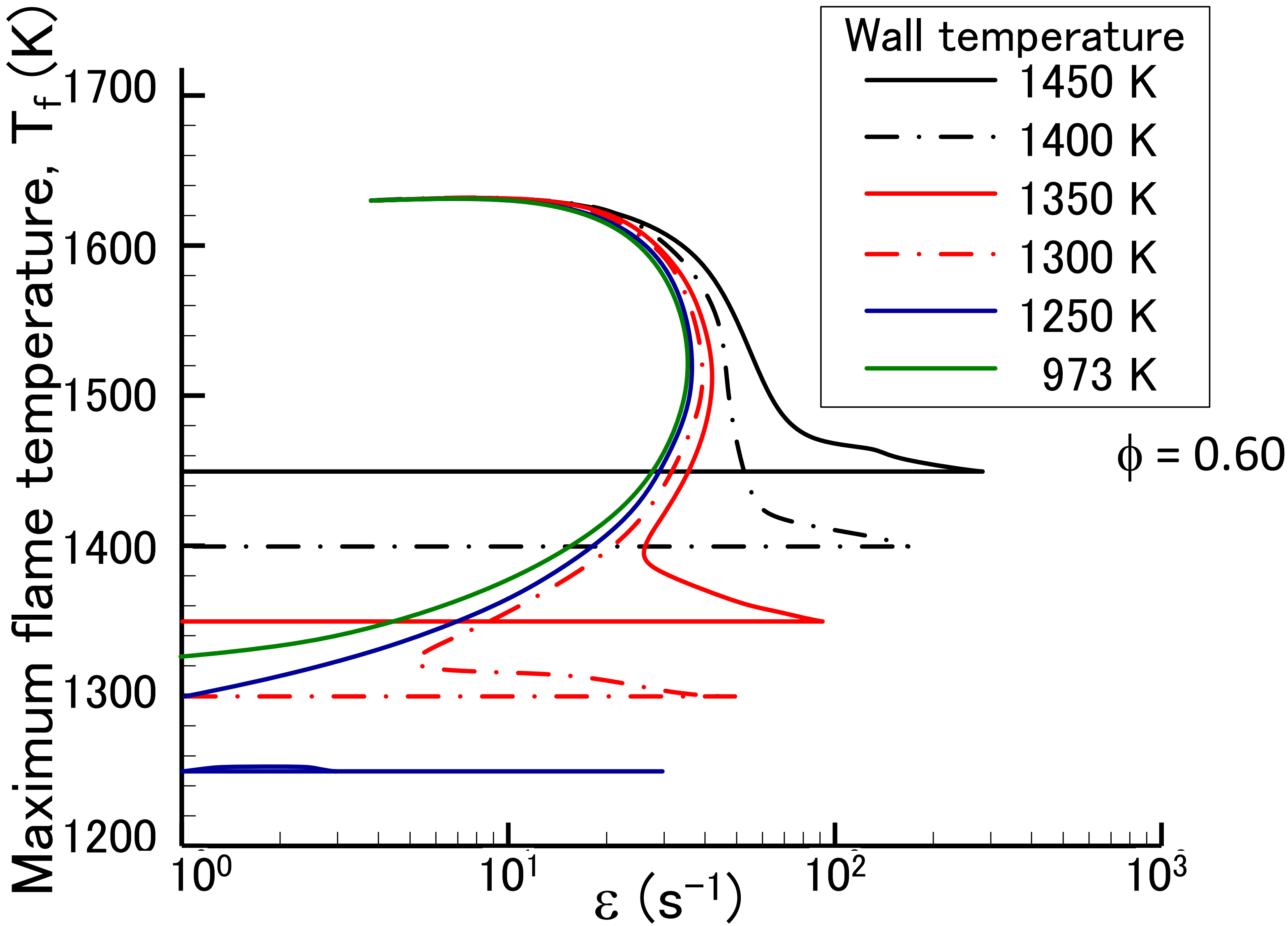
Solution is separated

Calc. results – flame locations

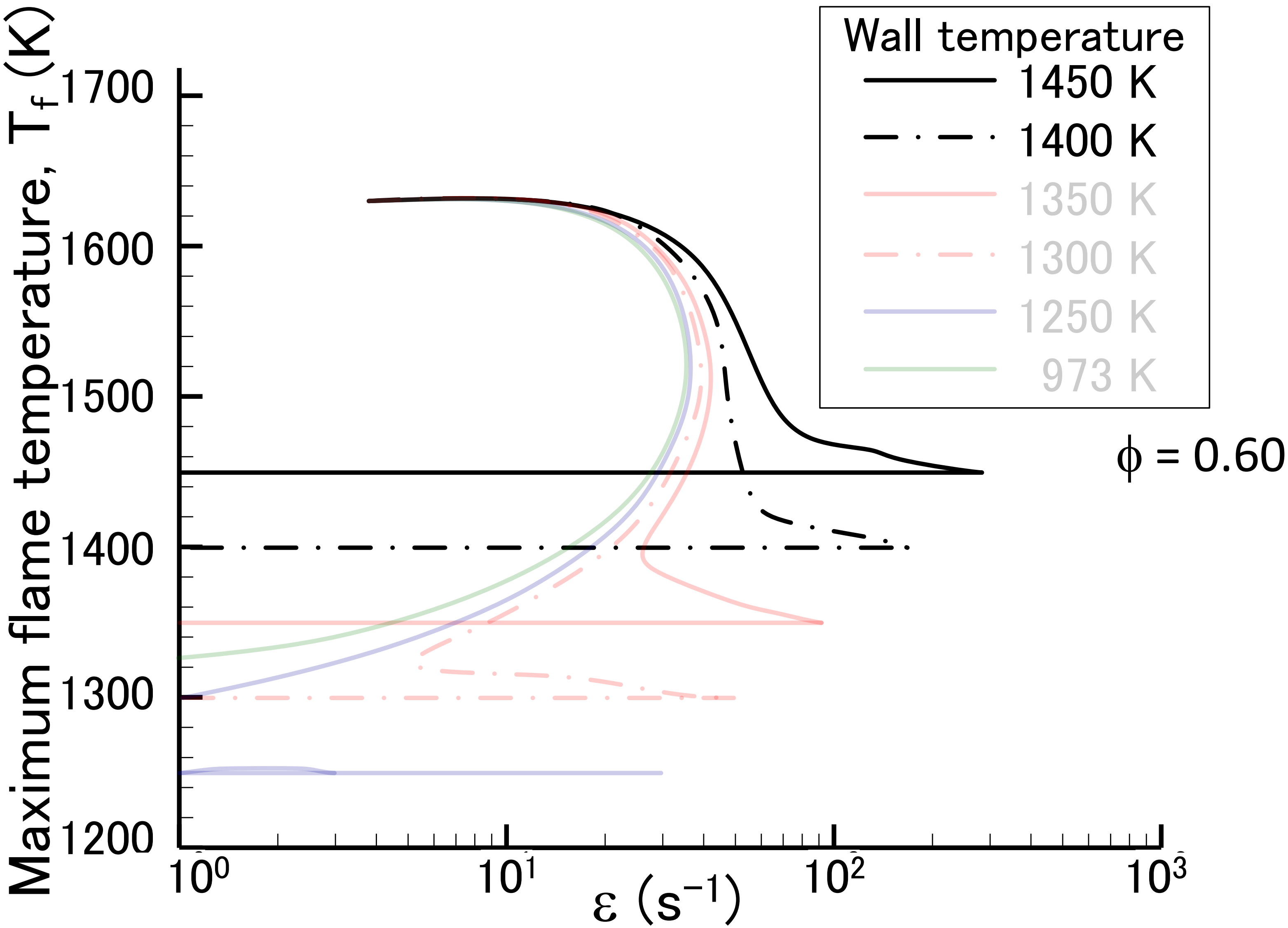


U-shape solution appears

Calc. results – flame temperature

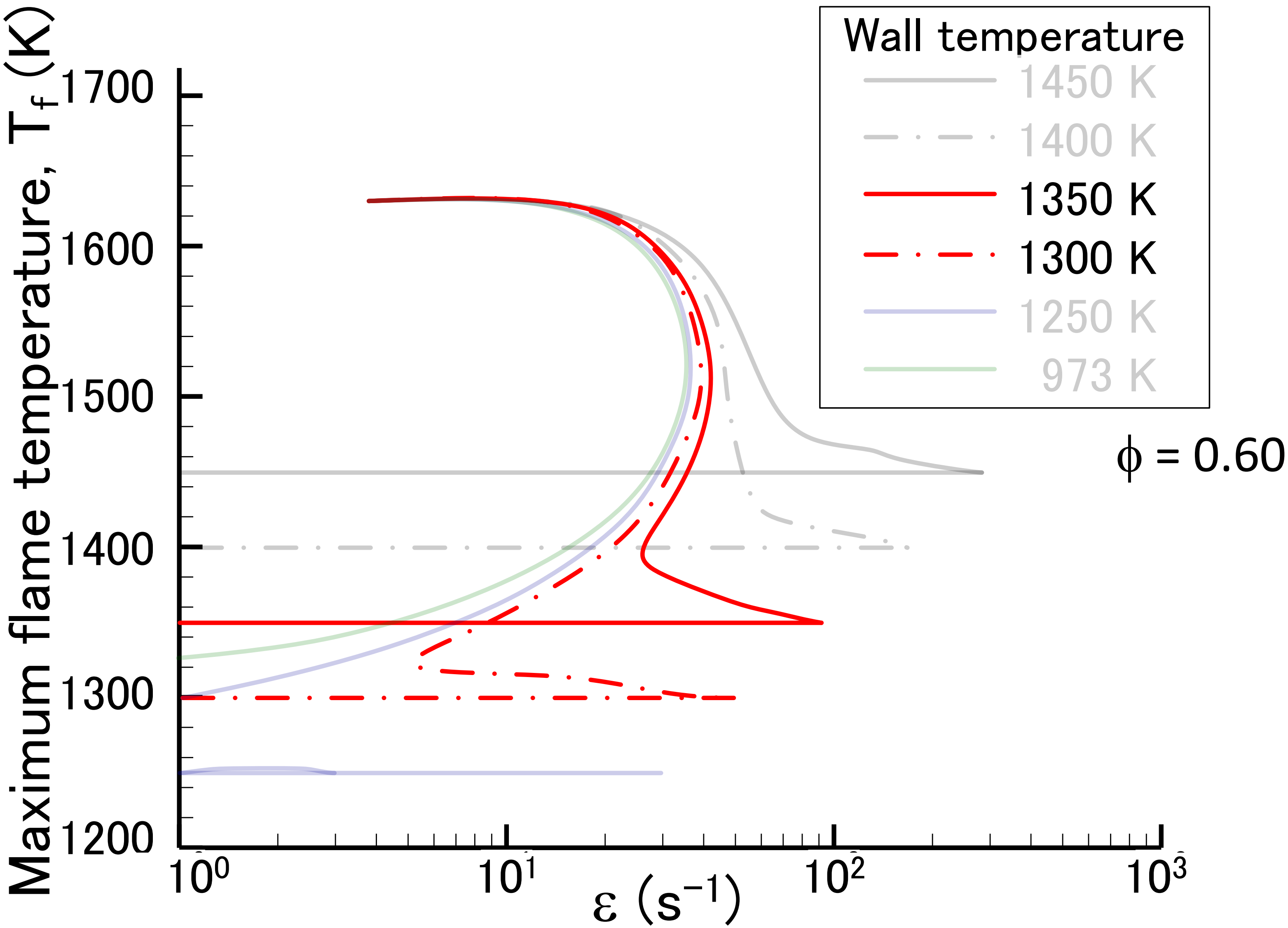


Calc. results – flame temperature



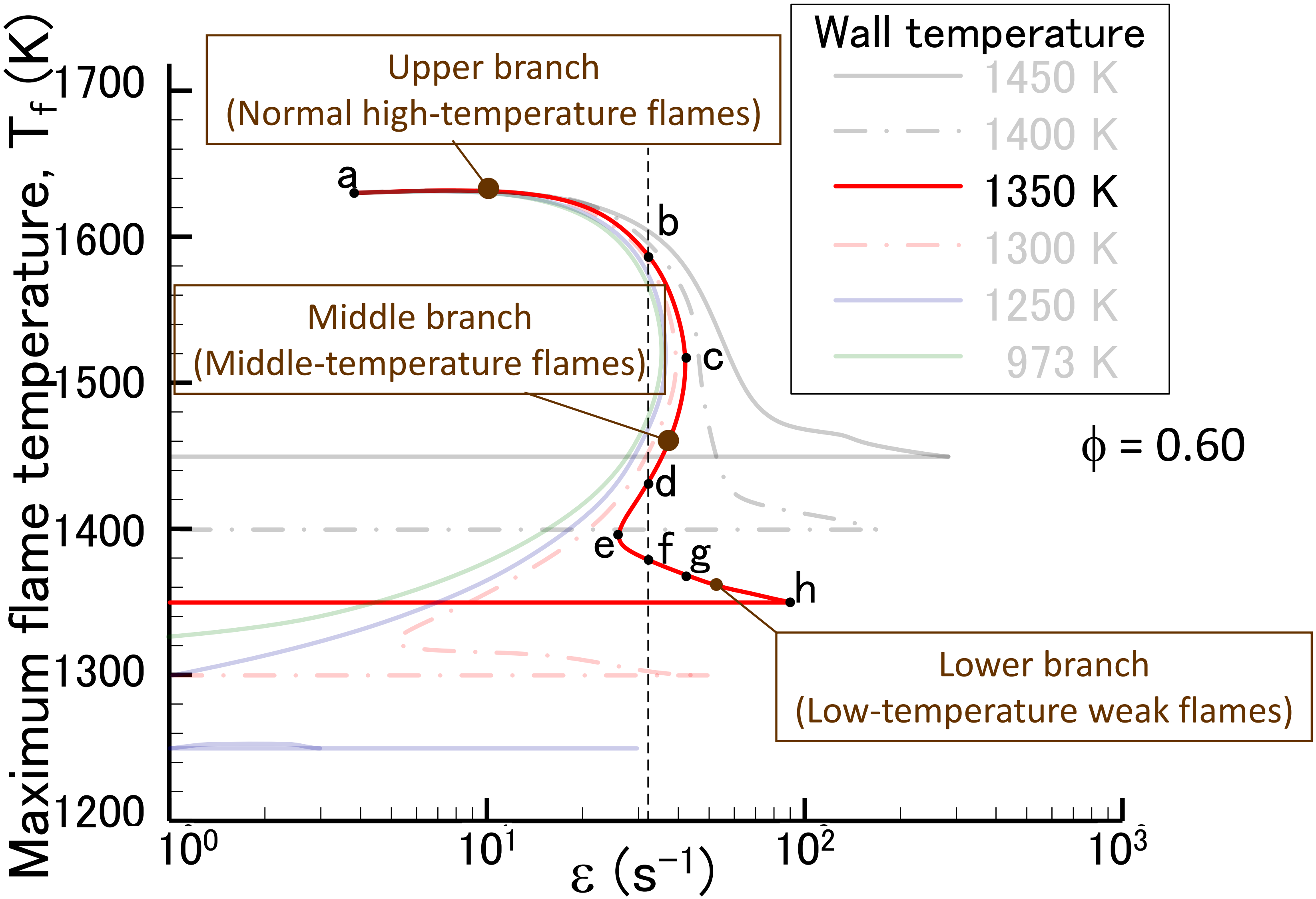
Flame temperatures decrease to wall temperature monotonously

Calc. results – flame temperature

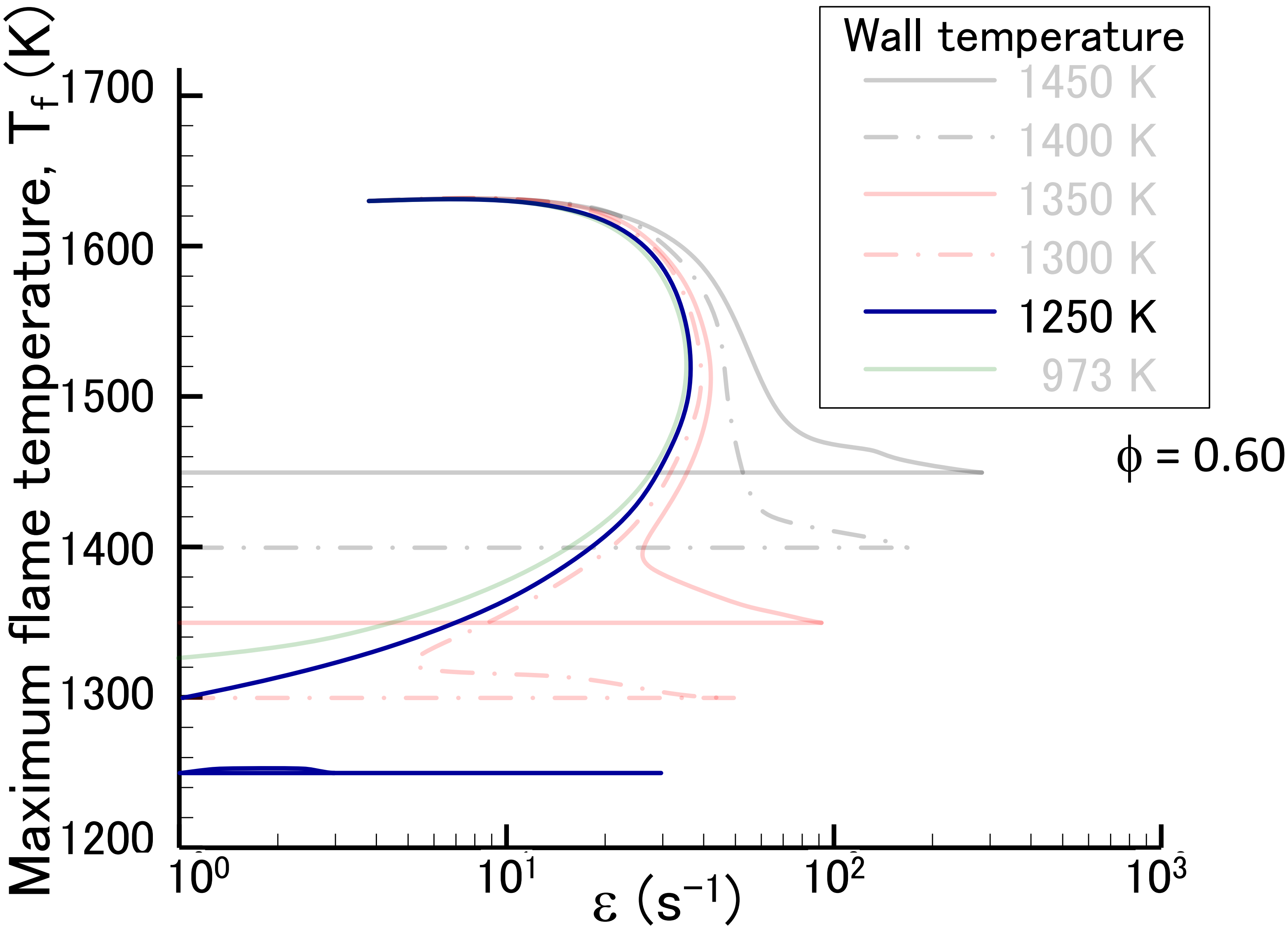


Computational results also showed flame bifurcations

Calc. results – flame temperature

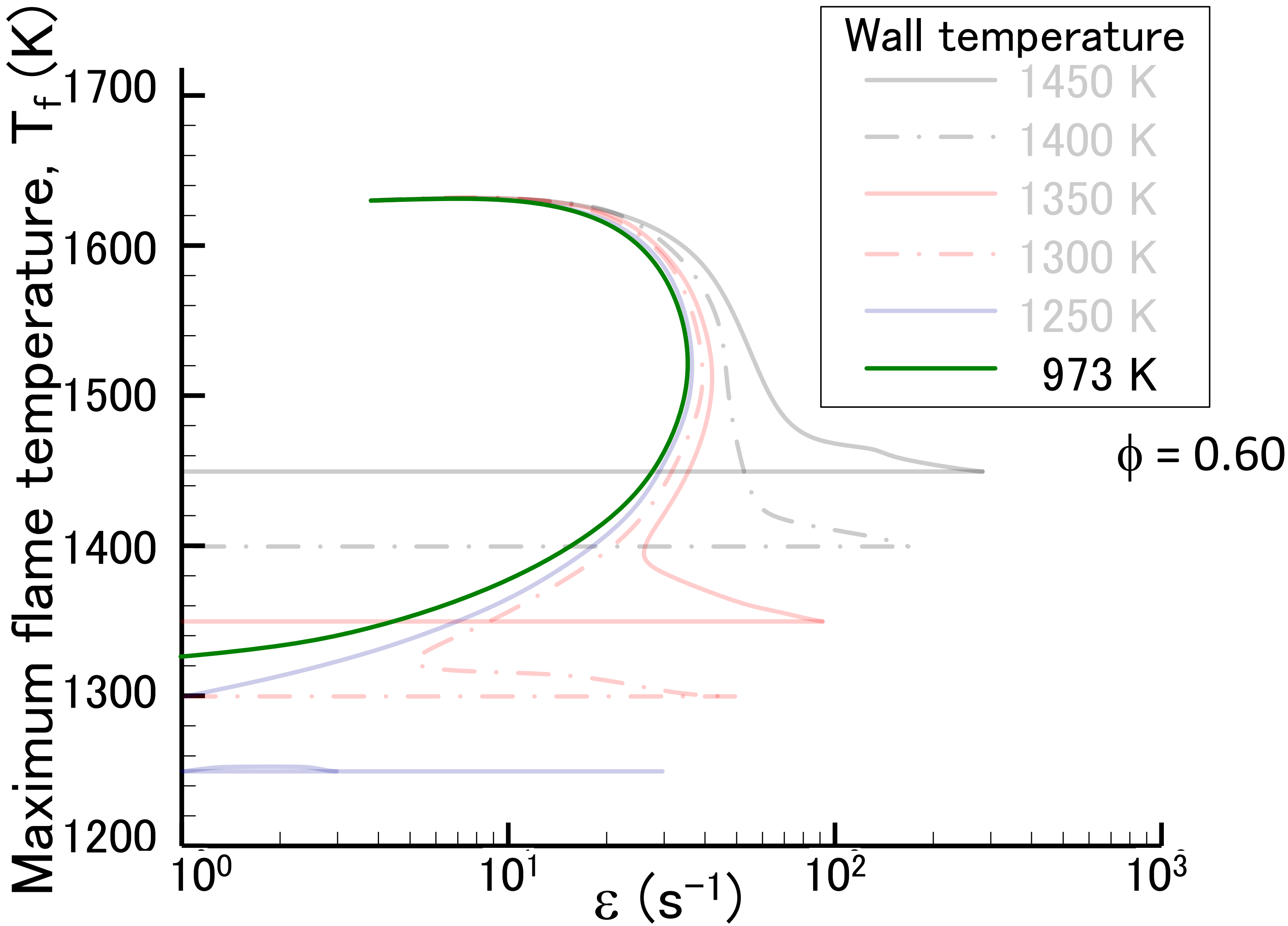


Calc. results – flame temperature



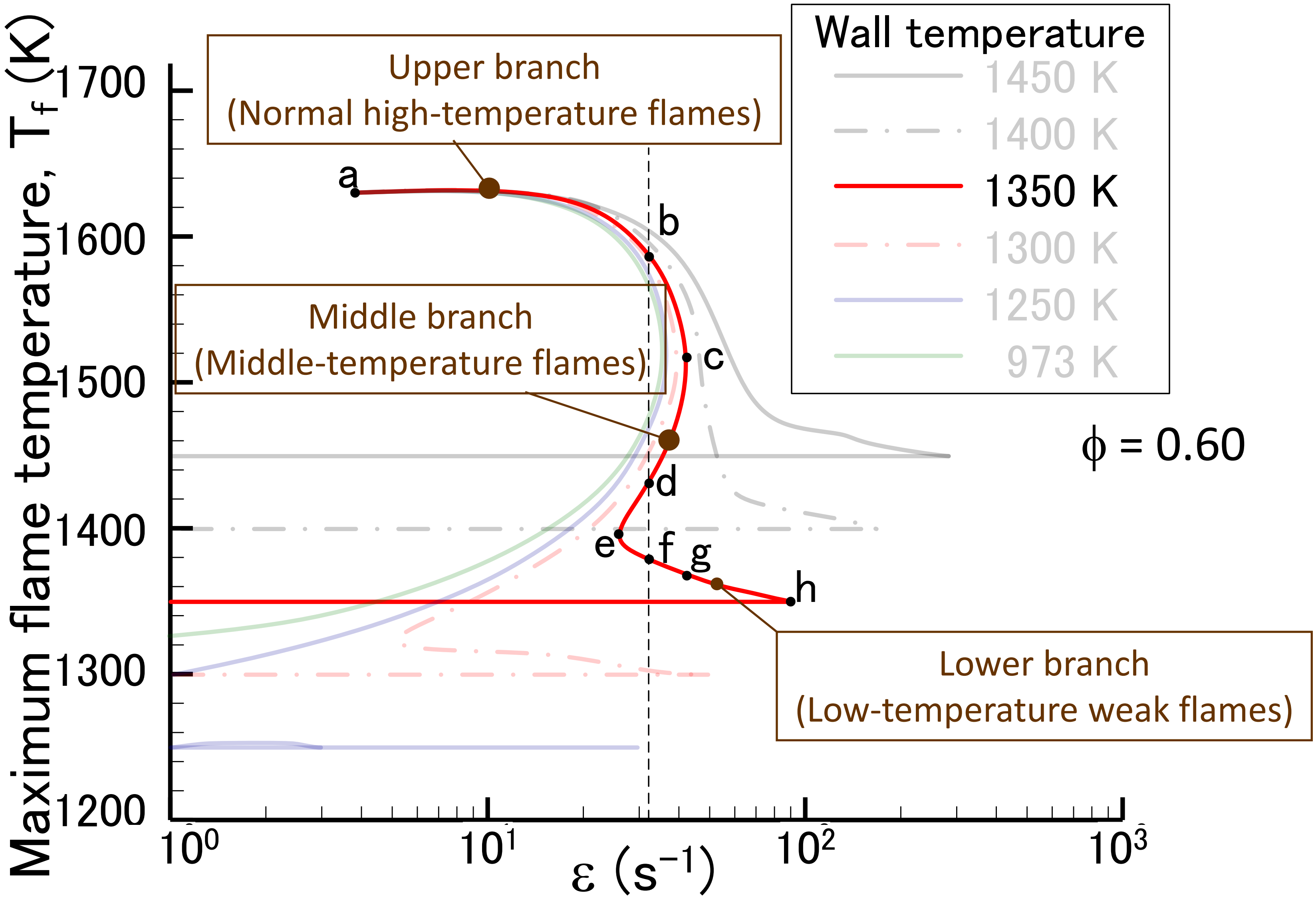
The lower branch is separated from the middle branch

Calc. results – flame temperature



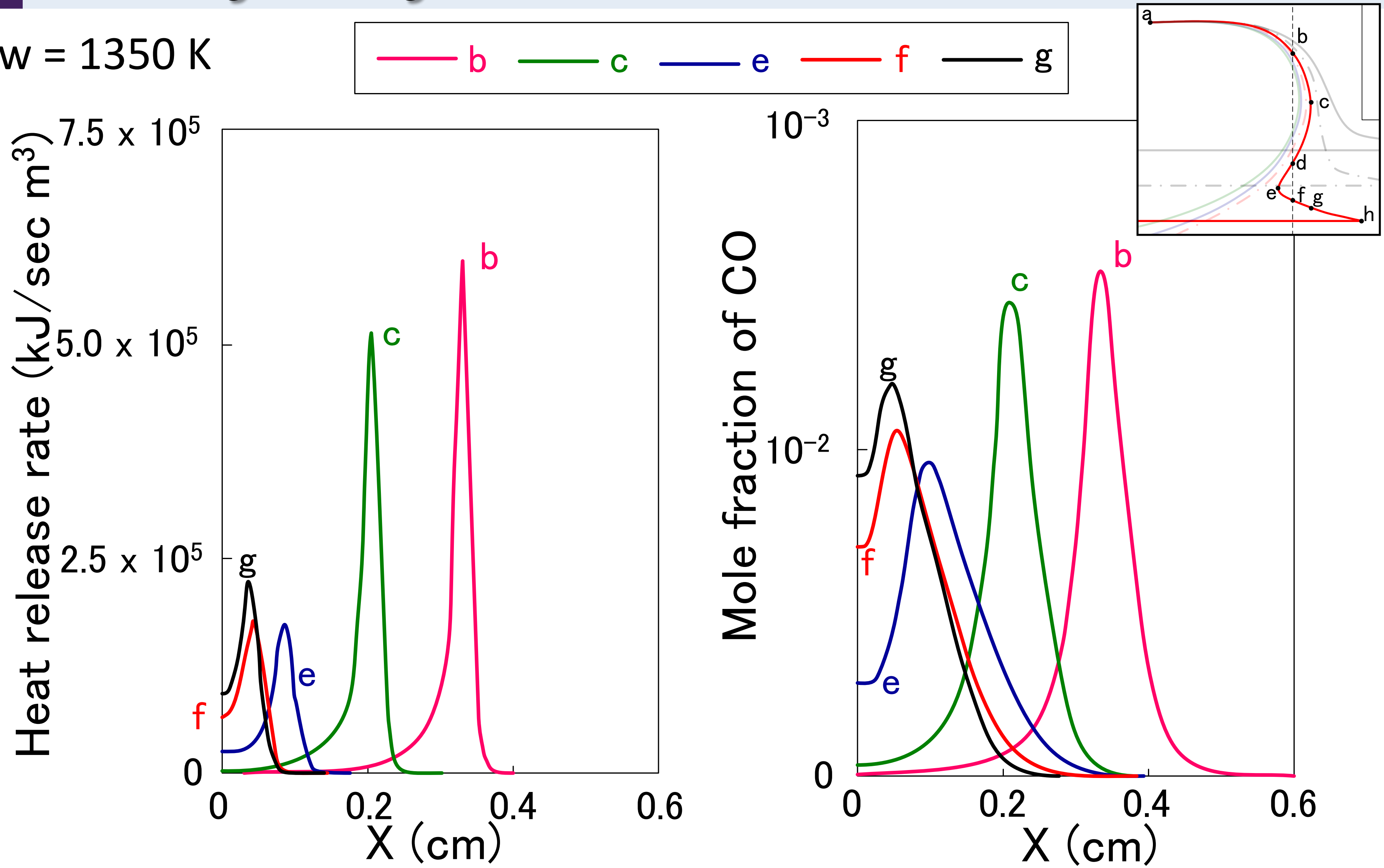
The lower branch is disappeared

Calc. results – flame temperature



Profiles of heat release rate and CO

Tw = 1350 K



Profiles of heat release rate and CO

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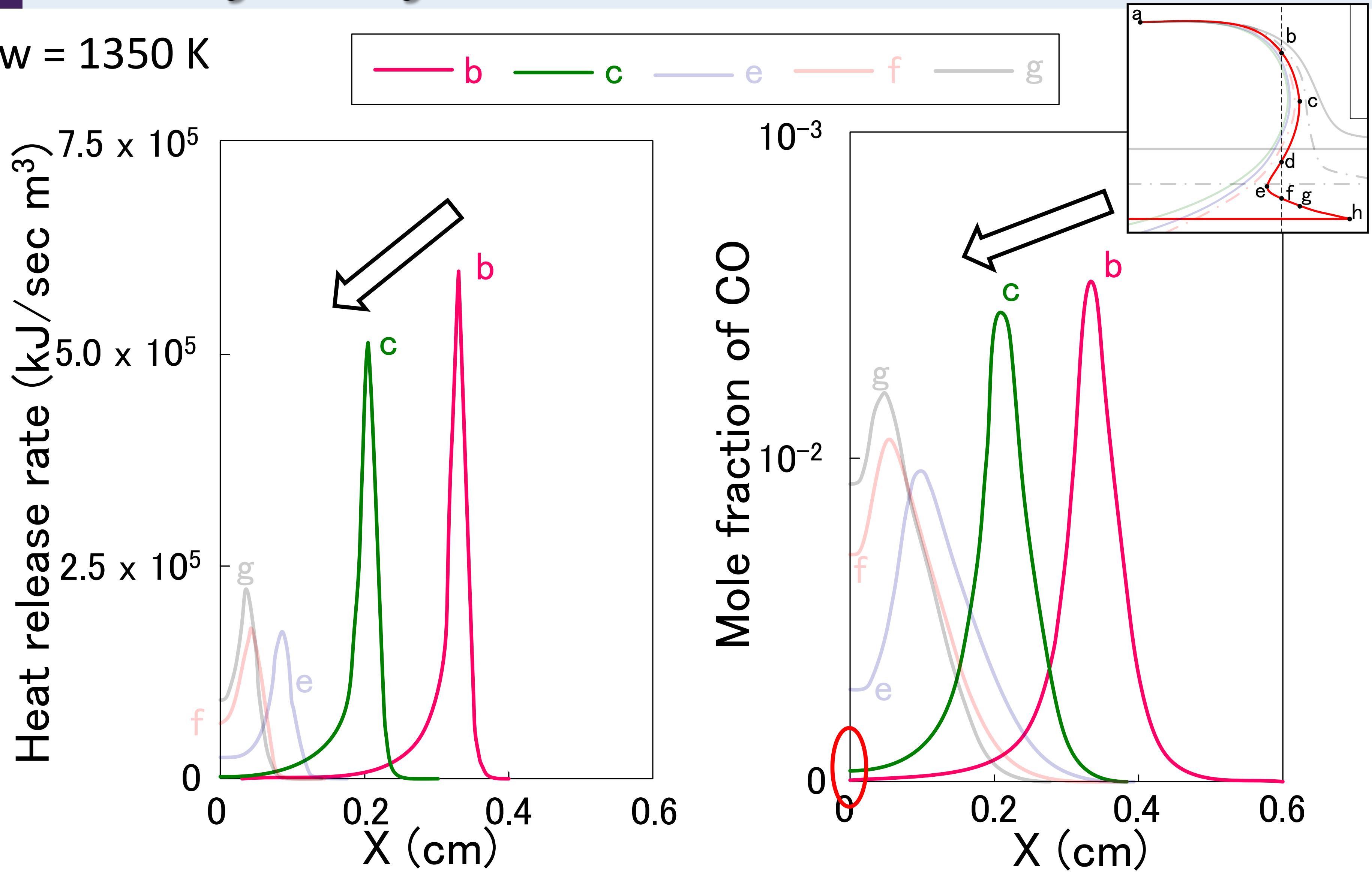
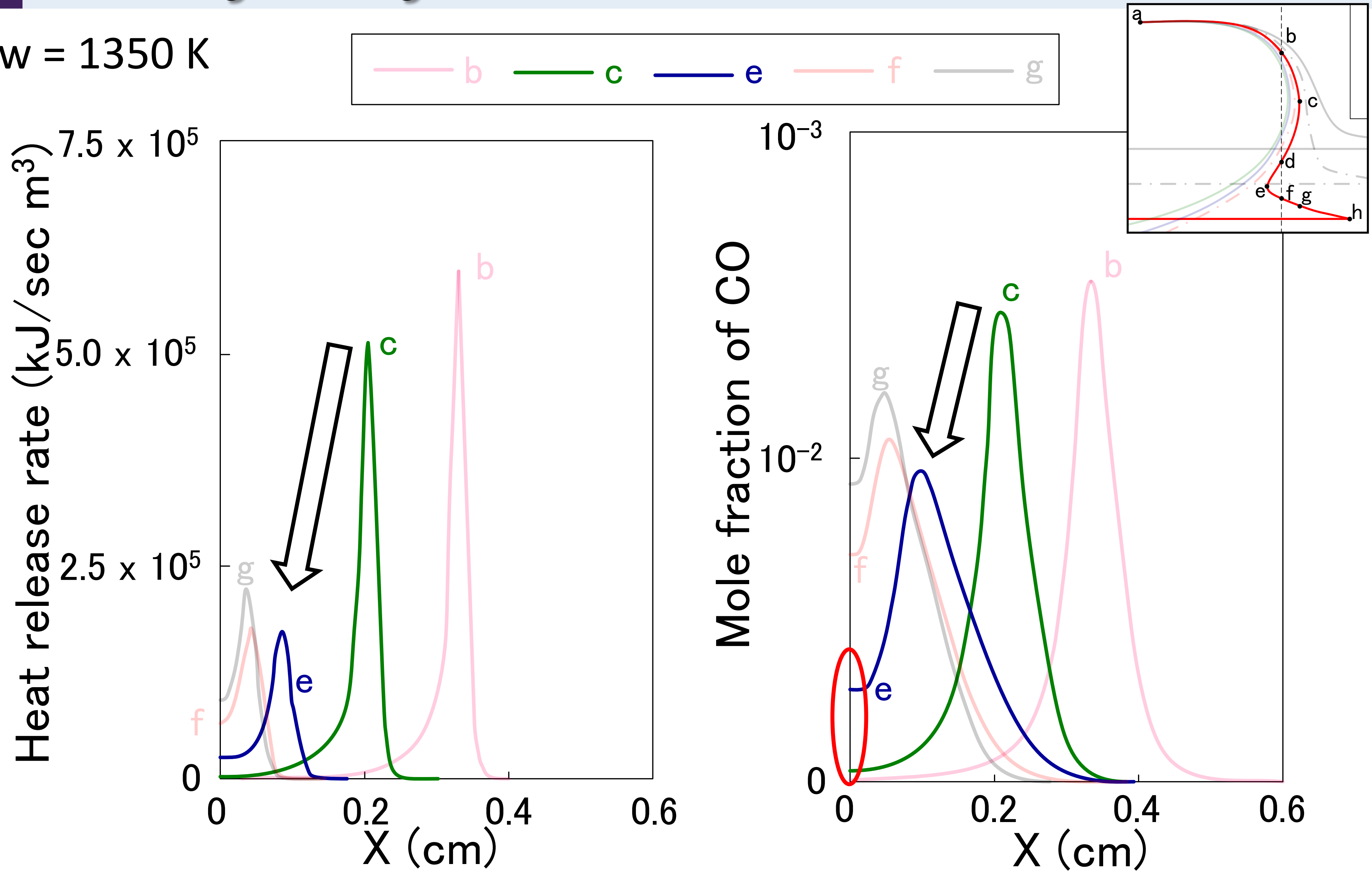


Upper branch: A Complete combustion is attained.

Profiles of heat release rate and CO

Tw = 1350 K

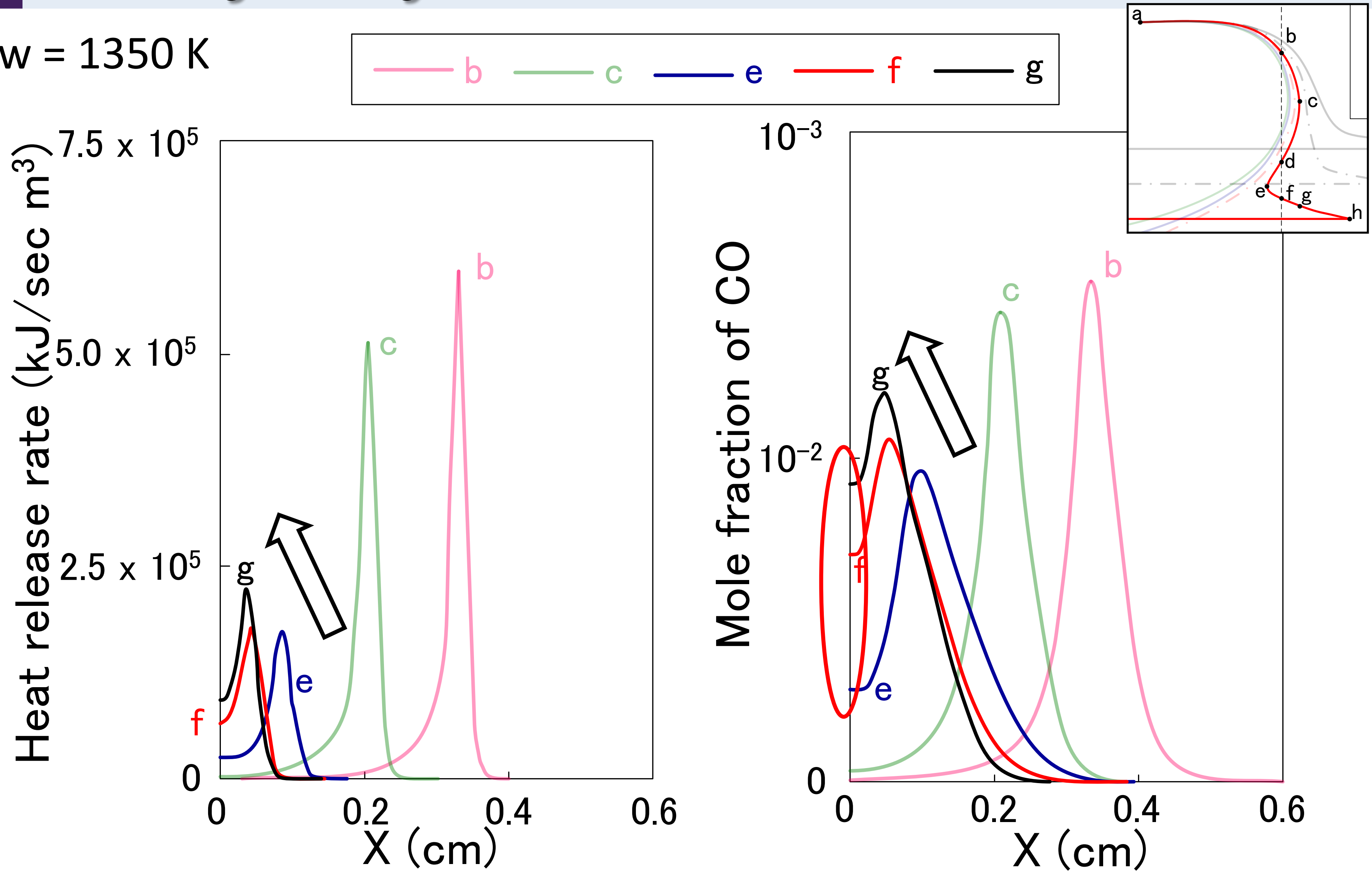


Middle branch:

HRR decreases as ε decreases. As a result, T_f decreases.

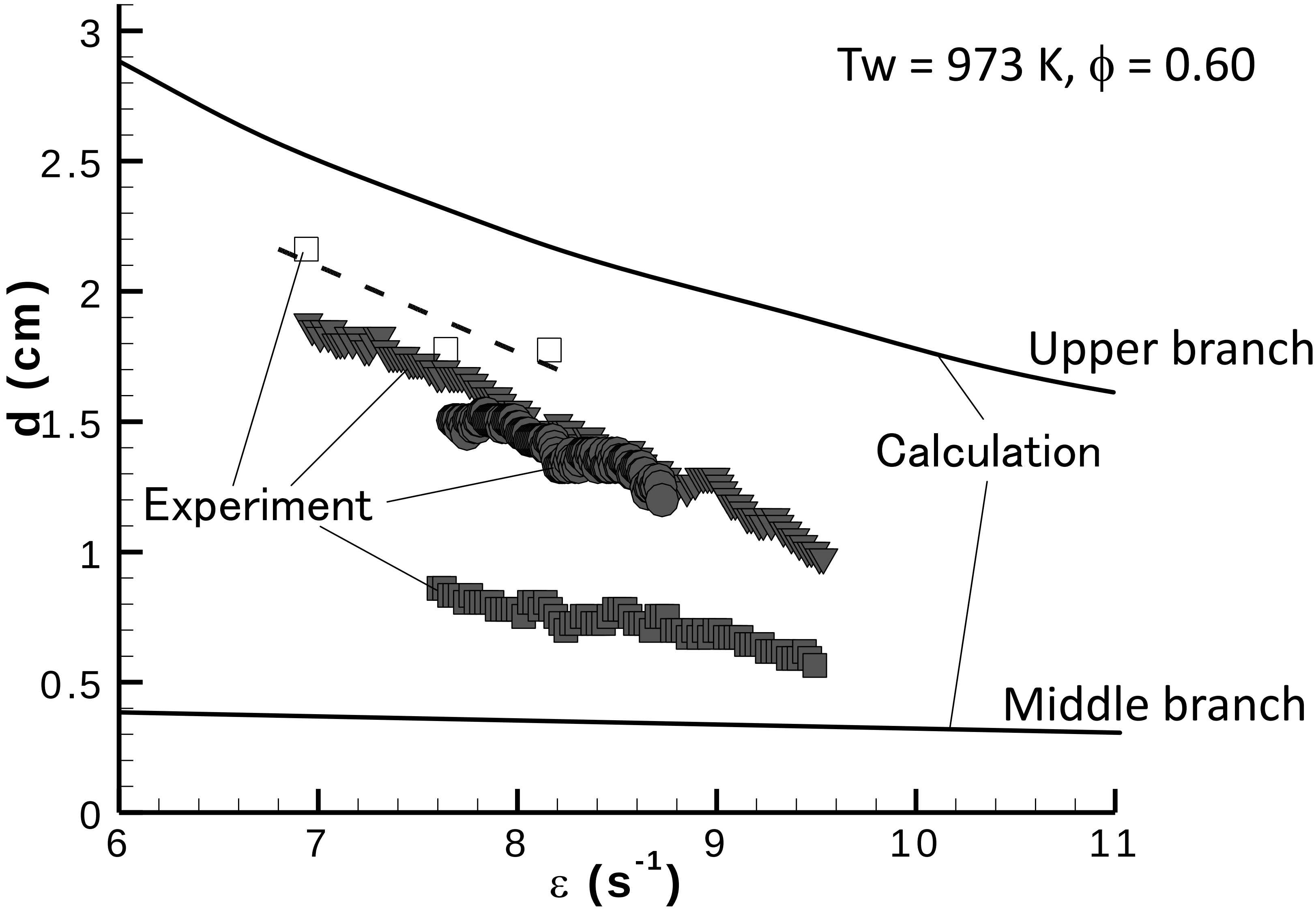
Profiles of heat release rate and CO

Tw = 1350 K

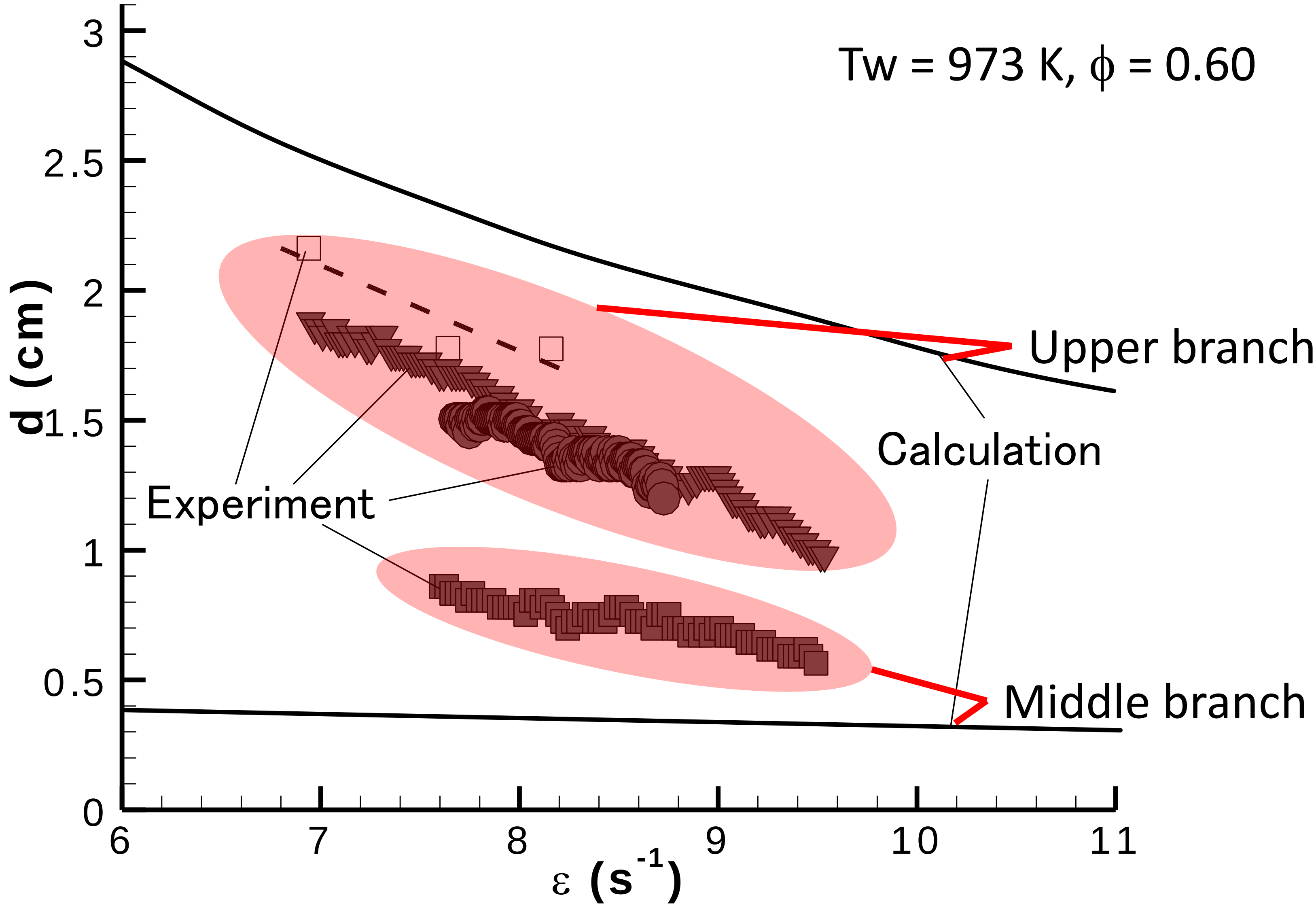


Lower branch: HRR increases as ε increases. However, an incomplete combustion is suggested. As a result, T_f decreases.

Comparison between Exp. and Calc. results



Comparison between Exp. and Calc. results



Flame bifurcations of experiments were upper and middle branch

Conclusions (1)

Microgravity experiments and computations were conducted on characteristics of stretched premixed methane-air flames in front of an inert hot wall. Special attention was paid to flame structures and flame bifurcations.

1. Two groups of flame locations were successfully measured by microgravity experiments at the identical conditions of the stretch rate, equivalence ratio and wall temperature.

2. A complete combustion is attained in high-temperature flames and an incomplete combustion in low-temperature flames.

Conclusions (2)

3. For two groups of the flame locations obtained by the microgravity experiments, although the exact stability boundary on middle branch is still open question, it was suggested that the flames far from the hot wall correspond to the normal high-temperature flames and the flames near the hot wall to middle-temperature flames.

Thank you for your attention