Presentation of PhD-project: Computational modeling of non-conventional, lean premixed gas turbine combustors

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Lean premixed combustion - reduction of pollutants

Strategies for gas-turbines with CO_2-capture are based on three principles:

- “Post-combustion”
- “Pre-combustion”
- “Oxy-fuel-combustion”

A main challenge will be to minimize the levels of NO_x. This may be achieved by lean premixed combustion.

Combustion instabilities

Burning a lean mixture in a confined space leads to combustion instabilities

- Instabilities are recognized as large amplitude pressure and velocity oscillations, which lead to [1]:
  - Thrust oscillations
  - Severe vibrations that interfere with control-system operation
  - Enhanced heat transfer and thermal stresses to combustor walls
  - Oscillatory mechanical loads that result in low or high cycle fatigue of system components
  - Flame blowoff or flashback

These phenomena may result in premature component wear that could lead to costly shutdown or catastrophic component failure

Instability-driving mechanisms

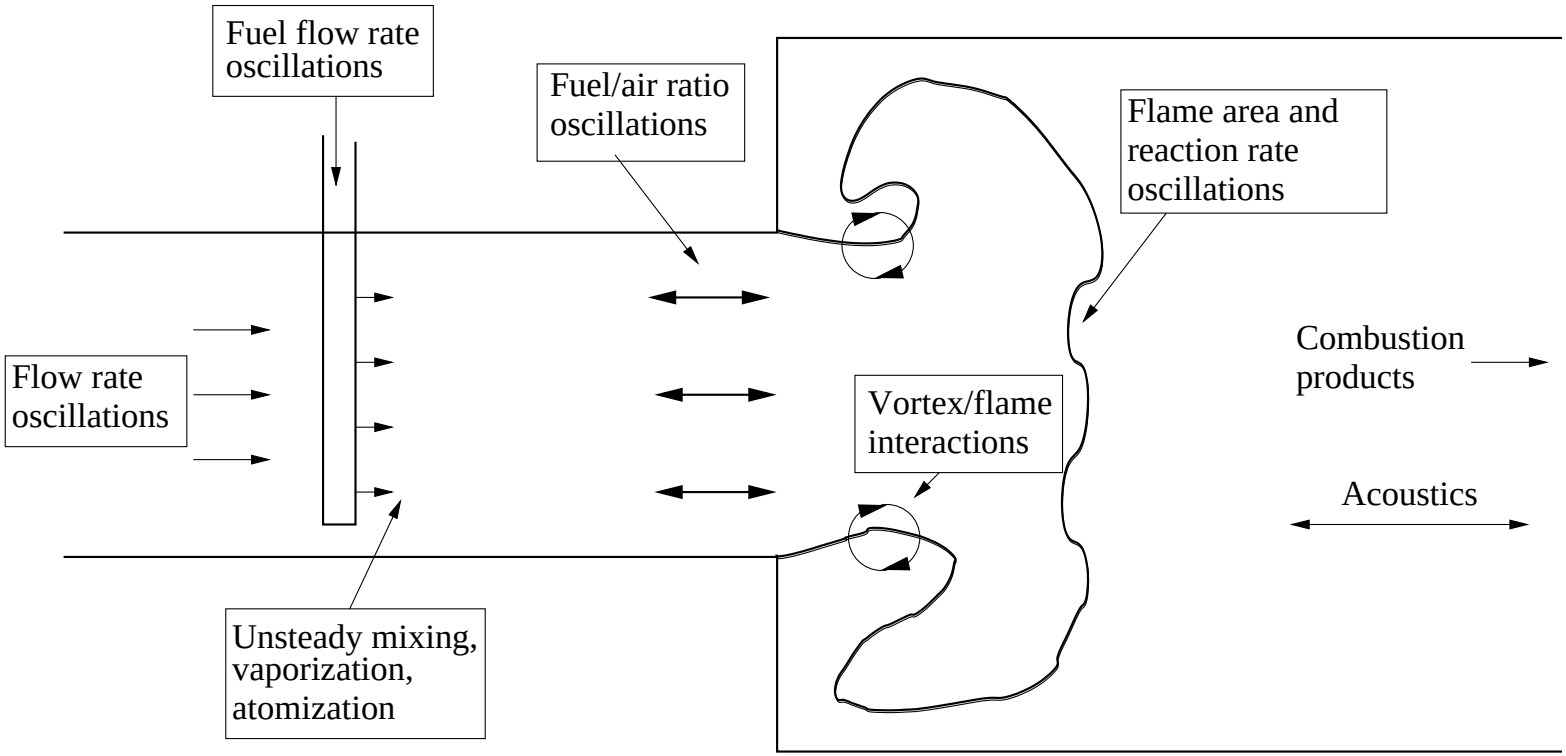


Figure: Processes that can cause combustion instabilities in gas turbines [1].

Identification and control of combustor instabilities

Extensive experimental and theoretical work has been done to adress three relevant issues:

- Setup of active controllers able to stabilize the combustor
- Identification of the physicochemical mechanisms responsible for the instability of the gas turbine combustors at lean conditions
- Definition of the combustor stability map to predict the critical operating conditions

Modeling

The processes shown in the previous figure have an role in determining the combustors dynamic behavior. It is difficult to understand the role played by each contribution, system dynamics as a function of the operating conditions. Modeling combustion instabilities can be done with:

- Sophisticated models: Fully coupled energy, mass and momentum balance equations
- Simple models: For example perfectly stirred reactor

Perfectly stirred reactor (PSR)

The perfectly stirred reactor (PSR) model can be used to model the combustion zone, studying for instance the role of chemical kinetics in driving oscillations.

$$\frac{dY_i}{dt} = \frac{1}{\tau}(Y_{i,\text{in}} - Y_i) + \frac{R_i}{\rho} \qquad i = 1, \ldots, \text{number of species}$$

$$\frac{dh}{dt} = \frac{1}{\tau}(h_{\text{in}} - h) + Q \qquad \text{adiabatic reactor, } Q = 0$$

$$\frac{dp}{dt} = 0 \qquad \text{isobaric reactor, } p = 1 \text{ atm}$$

$$\frac{1}{\tau} = \frac{\dot{m}_{\text{in}}}{\rho \cdot V_{\text{R}}} \qquad \tau = \text{reactor residence time}$$

R_i is the species volumetric reaction rate.

Chemical mechanisms

Global single-step chemical mechanism for methane and propane [2, 3]

$$R_{CH_4} = 1.4704 \cdot 10^{12} \cdot \rho^2 \cdot Y_{CH_4} \cdot Y_{O_2} \cdot \exp(-17404.0/T)$$
$$R_{C_3H_8} = 4.773 \cdot 10^{8} \cdot \rho^{1.75} \cdot Y_{C_3H_8}^{0.1} \cdot Y_{O_2}^{1.65} \cdot \exp(-15098.0/T)$$

For the detailed chemistry calculations, GRI-Mech 3.0 [4] was used for the methane-air combustion and the San-Diego mechanism [5] was used for the propane-air combustion.

Simulations

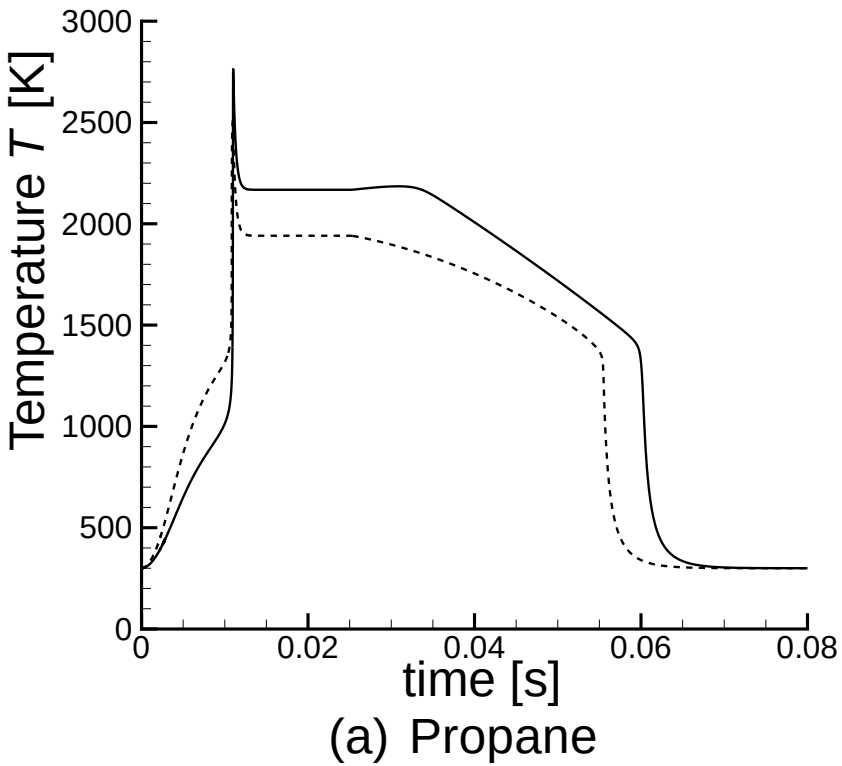
Variations of:

- Fuel composition
- Inflowing equivalence ratio:
  $\phi_{\text{in}} = \bar{\phi}_{\text{in}} \cdot (1.0 + 0.025 \cos(200 \cdot \pi \cdot t))$
  $\phi_{\text{in}} = \bar{\phi}_{\text{in}} \cdot (1.0 + 0.05 \cos(200 \cdot \pi \cdot t))$
- Inflowing temperature:
  $T_{\text{in}} = 300.0 \cdot (1.0 + 0.05 \cos(200 \cdot \pi \cdot t))$ K
- Inlet flow rate (residence time):
  $\dot{m}_{\text{in}}/V_{\text{R}} = 500.0 \cdot (1.0 + 0.05 \cos(200 \cdot \pi \cdot t))$ kg/(m^{3}s)

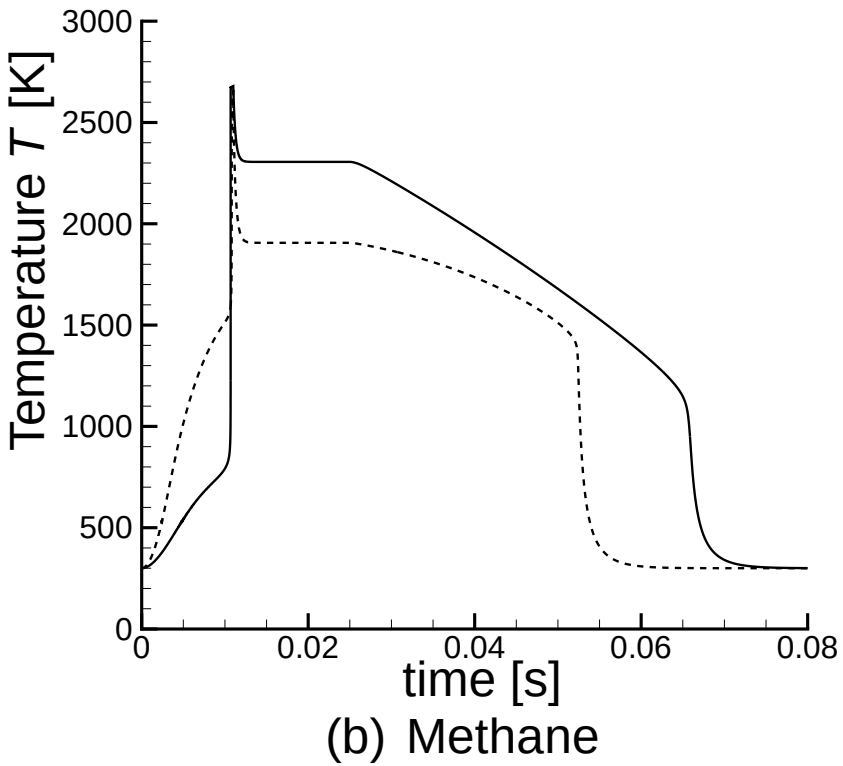
The resulting reaction-rate oscillations can be studied.

Results

These results will also be presented at the MekIT-conference in May 2007

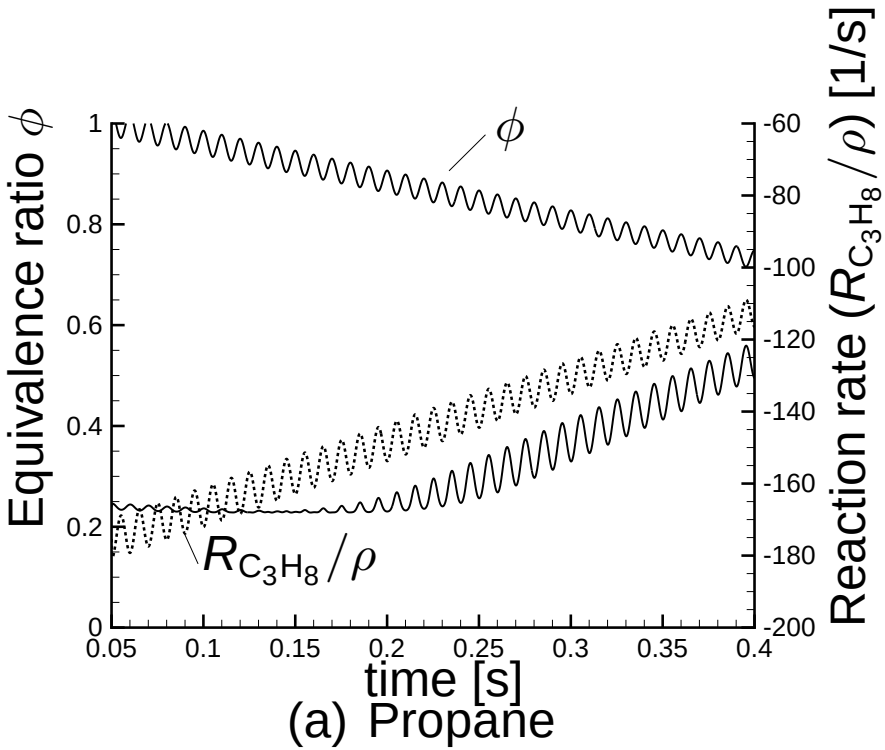


(a) Propane



(b) Methane

Figure: Ignition and extinction of propane and methane, full line: single step global mechanism, dotted line: detailed mechanism



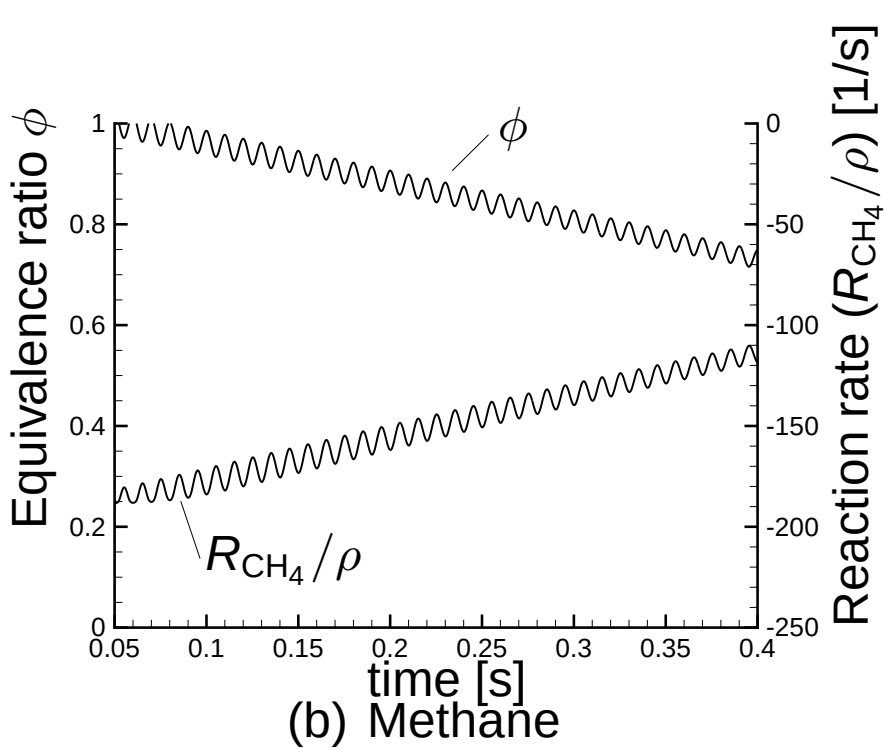
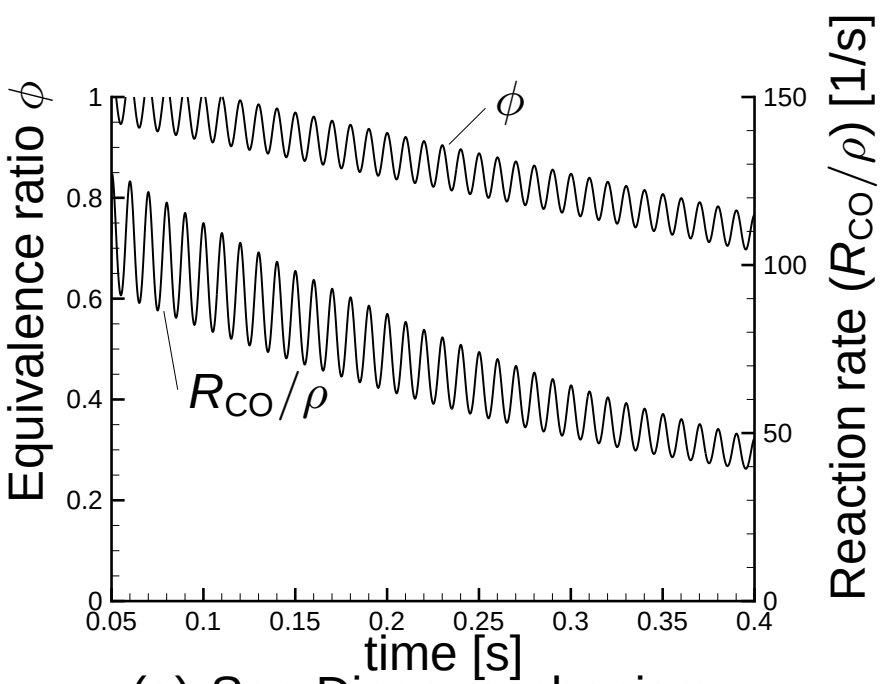
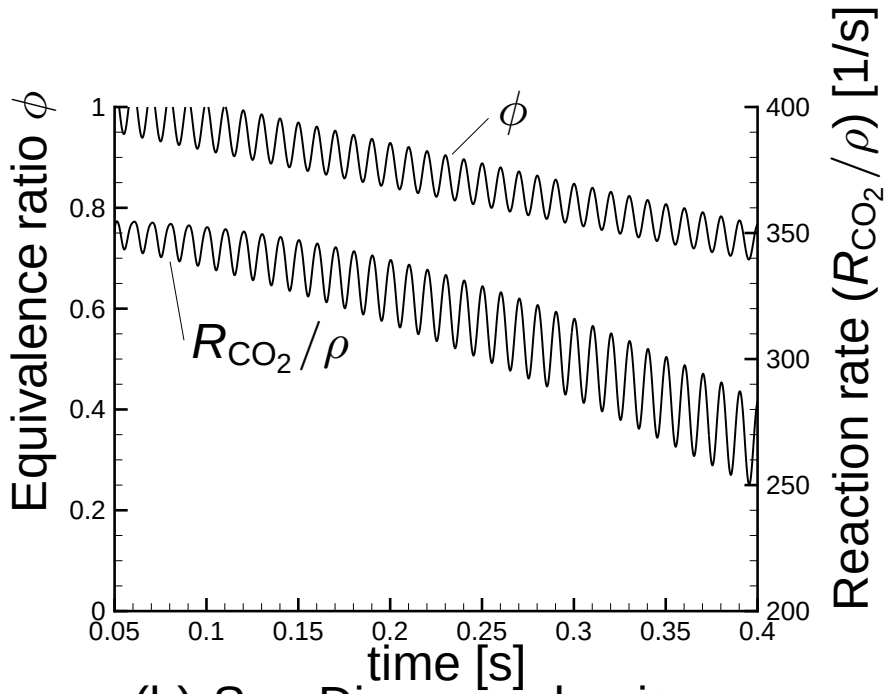


Figure: Reaction-rate response to 2.5% variation in $\bar{\phi}_{in}$, full line: single step global mechanism, dotted line: detailed mechanism

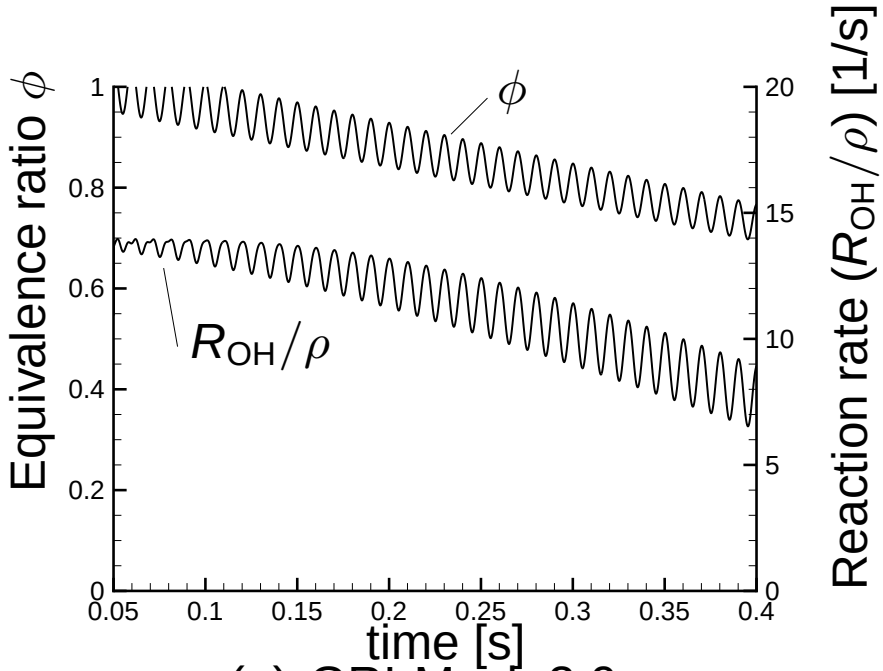


(a) San-Diego mechanism

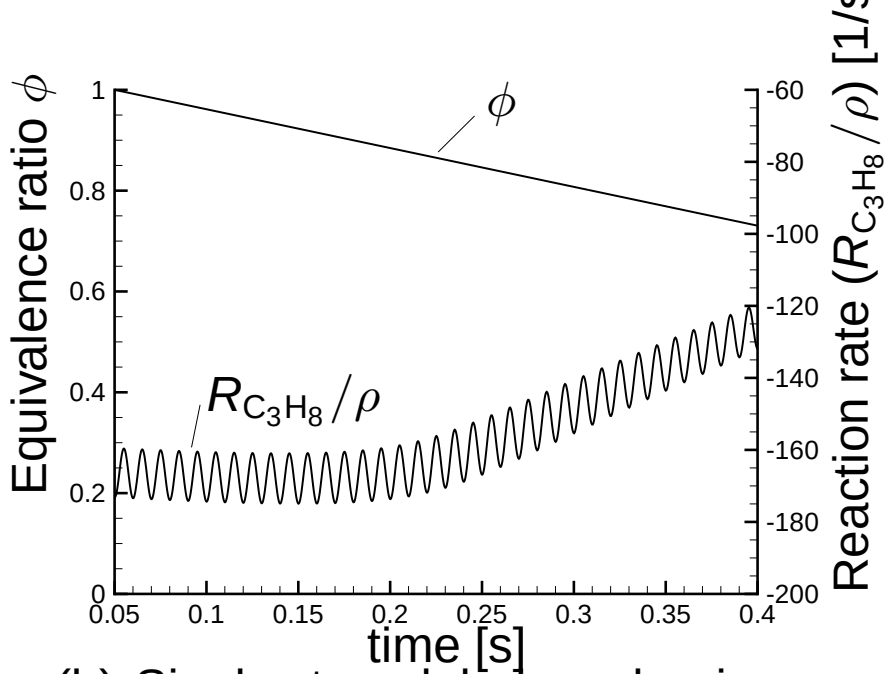


(b) San-Diego mechanism

Figure: Reaction-rate response to 5% variation in $\bar{\phi}_{in}$



(a) GRI-Mech 3.0



(b) Single step global mechanism

Figure: (a): Reaction-rate response to 5% variation in $\bar{\phi}_{in}$, (b): reaction-rate response to 5% variation in $\dot{m}_{in}/V_R$

Conclusions

- The use of global single-step mechanisms can lead to erroneous conclusions.
- Variations of the reactor temperature inlet predict small oscillations of the reaction rates.
- Similar oscillations imposed on the inlet mass flow rate gives larger, but nearly constant, amplitude for all equivalence ratios.
- Simulations indicates that varying equivalence ratios play a role in the driving of combustion instabilities at lean conditions.

References



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