

# Hydrogen Realities:

# Hydrogen Basics, Challenges, Opportunities

Jacqueline O'Connor, Ph.D.

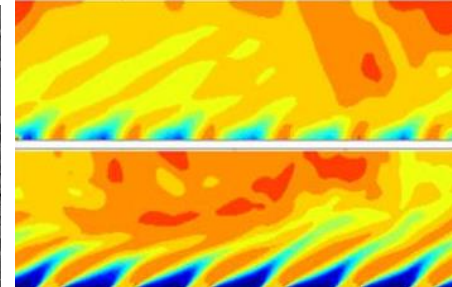
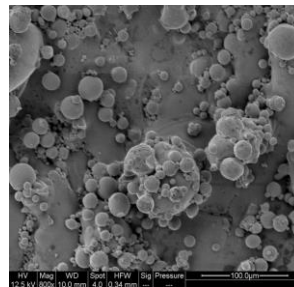
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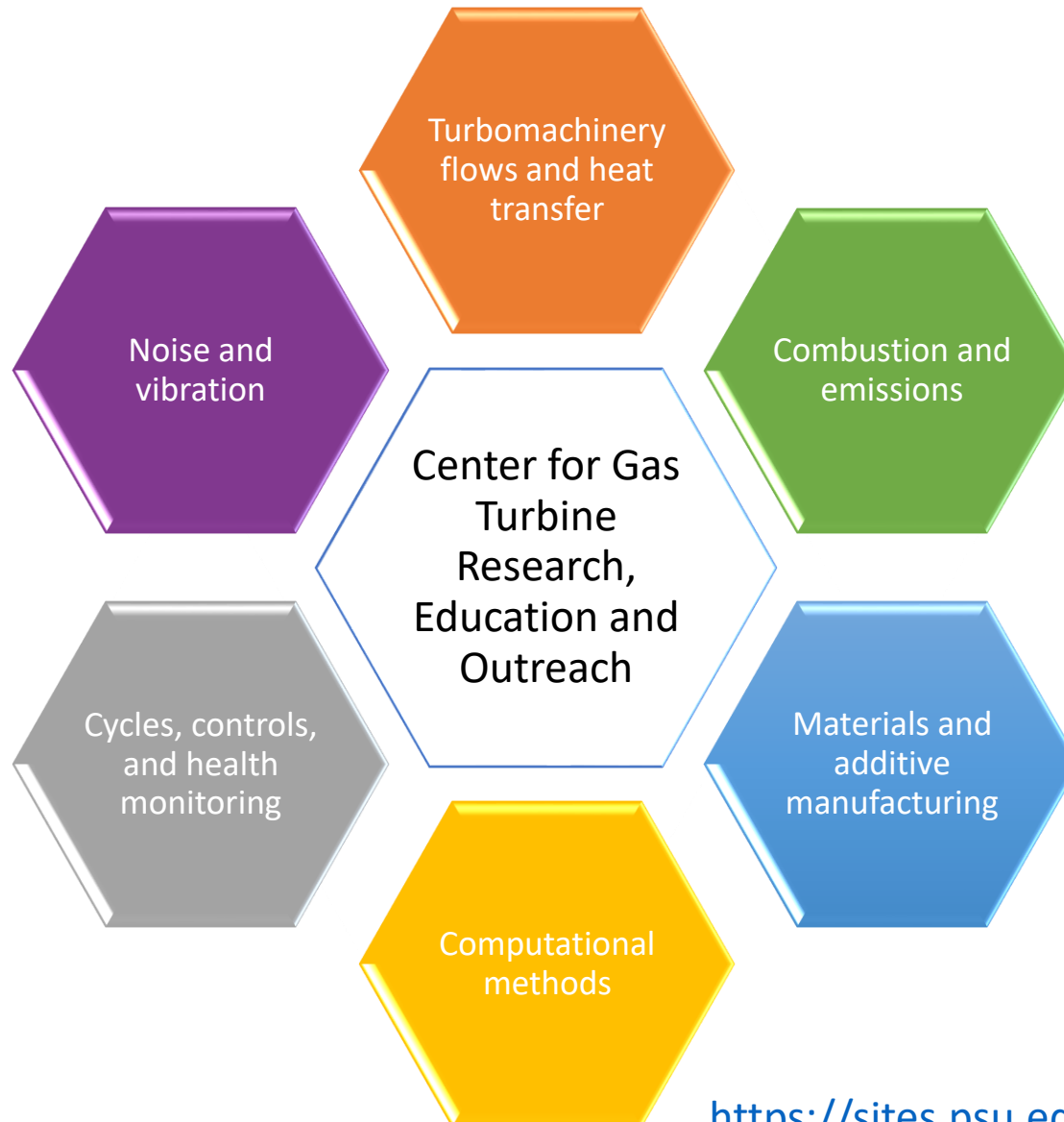
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**PennState**

# GTREO research addresses every part of the engine and industry, educating the future gas turbine workforce

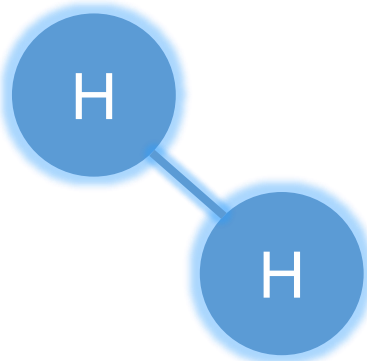


# Overview of presentation

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- Hydrogen: “a sneaky little molecule”
- Hydrogen combustion basics
- Hydrogen challenges and opportunities

# Hydrogen is the lightest element on Earth, but packs a big punch as a fuel, particularly for ground-based applications



## Key chemical properties:

- Mass-specific energy density: 120 MJ/kg
- Volume-specific energy density: 0.01005 MJ/L at STP
- Flammability limits: 4-74% in air at STP

## Key physical properties:

- MW = 2.061 g/mol
- MP = -259.16 °C
- BP = -252.879 °C
- Density at STP = 0.08988 g/L
- Diffusivity in air at STP = 0.756 cm<sup>2</sup>/s
  - (compare to 0.21 for CH<sub>4</sub>)

1										2									
H Hydrogen 1.008										He Helium 4.003									
3										4									
Li Lithium 6.941										Be Beryllium 9.012									
5										6									
Na Sodium 22.990										Mg Magnesium 24.305									
7										8									
K Potassium 39.098										Ca Calcium 40.078									
9										10									
Rb Rubidium 85.468										Sr Strontium 87.62									
11										12									
Cs Cesium 132.905										Ba Barium 137.328									
13										14									
Fr Francium 223.020										Ra Radium 226.025									
Sc Scandium 44.956										Ti Titanium 47.867									
V Vanadium 50.942										Cr Chromium 51.996									
Mn Manganese 54.938										Fe Iron 55.845									
Co Cobalt 58.933										Ni Nickel 58.693									
Cu Copper 63.546										Zn Zinc 65.38									
Ga Gallium 69.723										Ge Germanium 72.631									
As Arsenic 74.922										Se Selenium 78.972									
Br Bromine 79.904										Kr Krypton 83.798									
Y Yttrium 88.906										Zr Zirconium 91.224									
Nb Niobium 92.906										Mo Molybdenum 95.95									
Tc Technetium 98.907										Ru Ruthenium 101.07									
Rh Rhodium 102.906										Pd Palladium 106.42									
Ag Silver 107.868										Cd Cadmium 112.411									
In Indium 114.818										Sn Tin 118.711									
Sb Antimony 121.760										Te Tellurium 127.6									
I Iodine 126.904										Xe Xenon 131.294									
Hf Hafnium 178.49										Ta Tantalum 180.948									
W Tungsten 183.84										Re Rhenium 186.207									
Os Osmium 190.23										Ir Iridium 192.217									
Pt Platinum 195.085										Au Gold 196.967									
Hg Mercury 200.592										Tl Thallium 204.383									
Pb Lead 207.2										Bi Bismuth 208.980									
Po Polonium [208.982]										At Astatine 209.987									
Rn Radon 222.018										Ac Actinium 227.028									
Th Thorium 232.038										Pa Protactinium 231.036									
U Uranium 238.029										Np Neptunium 237.048									
Pu Plutonium 244.064										Am Americium 243.061									
Cm Curium 247.070										Bk Berkelium 247.070									
Cf Californium 251.080										Es Einsteinium [254]									
Fm Fermium 257.095										Md Mendelevium 288.1									
No Nobelium 259.101										Lr Lawrencium [262]									

Atomic Number
<b>Symbol</b>
Name
Atomic Mass

Hydrogen is a reasonable replacement fuel by some metrics, but others cause some challenges in combustion technologies

	H <sub>2</sub>	CH <sub>4</sub>	Gasoline	Diesel
Mass-specific energy density (MJ/kg)	120	55	44	46
Volume-specific energy density (MJ/L at STP)	0.01005	0.0364	32	34
Mass diffusivity in air (cm <sup>2</sup> /s)	0.756	0.21	n/a	n/a
Adiabatic flame temperature (°C)	2254	1963	2138	2102
Flame speed (cm/s at STP)	300	40	~35	~35

Adiabatic flame temperature is the maximum temperature of a combustion reaction, indicative of potential thermal loads

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Combustion reaction: Fuel + Air  $\rightarrow$  Products (+ Heat)

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Combustion reaction: Fuel + Air  $\rightarrow$  Products  $T_{ad}$

# Adiabatic flame temperature is the maximum temperature of a combustion reaction, indicative of potential thermal loads

Combustion reaction: Fuel + Air → Products  $T_{ad}$

### Opportunities

The diagram shows a gas turbine cycle with four states: 1 (inlet), 2 (after compression), 3 (after combustion), and 4 (after expansion). The temperatures at these states are labeled  $T_1$ ,  $T_2$ ,  $T_3$ , and  $T_4$ . Below the schematic is a P-V diagram showing the cycle path: 1-2 (compression), 2-3 (constant pressure combustion), 3-4 (expansion), and 4-1 (constant pressure cooling).

$$\eta_{th,max} = 1 - \frac{T_1}{T_3} = 1 - \frac{T_1}{T_{ad}}$$

### Challenges

The top diagram illustrates three cooling methods for turbine components: 1. Film cooling, 2. Internal passage cooling, and 3. Impingement cooling. The text next to it is: Han, Dutta, Ekkad, "Gas Turbine Cooling".

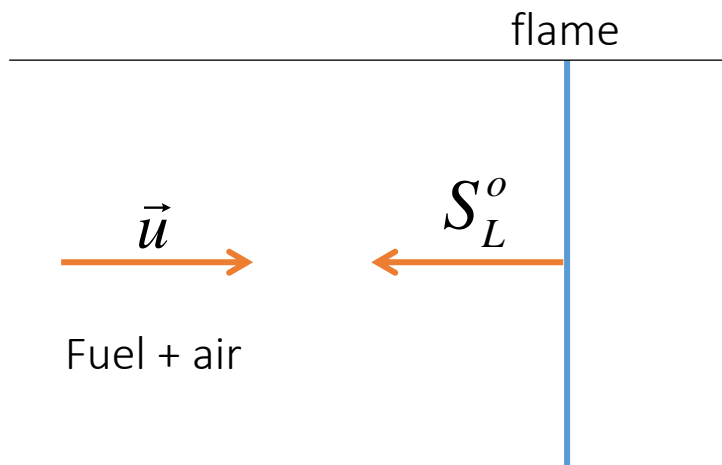
The bottom graph shows the 100-hour rupture stress (in MPa) versus temperature (in °C) for various materials. The y-axis ranges from 0 to 100 MPa, and the x-axis ranges from 600 to 1200 °C. The materials shown are:

- Medium-strength cast nickel alloys (713°C)
- High-strength cast nickel alloys (in 100 MAR M 200, B 1900)
- Unidirectionally solidified nickel alloys
- Chromium alloys
- Niobium alloys
- Molybdenum alloys
- Ceramics ( $Si_3N_4$ )
- Wrought nickel alloys (Nimonic 105, U700)
- Cobalt alloys (MAR M 509)

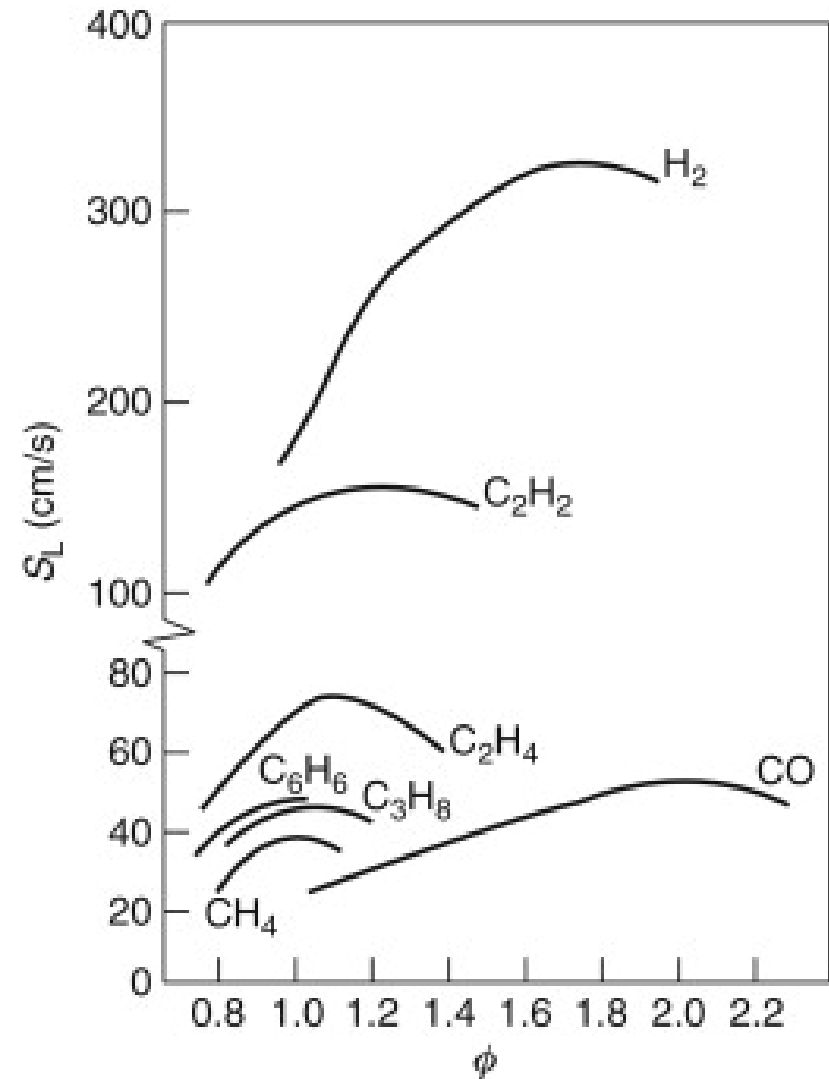
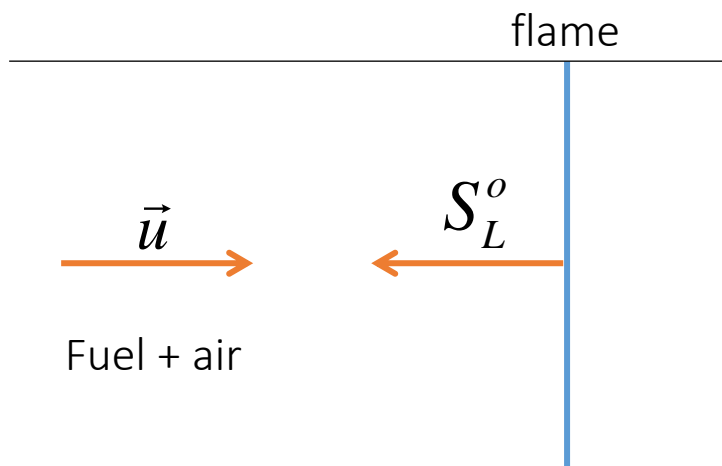
Hill & Peterson, Mechanics & Thermodynamics of Propulsion



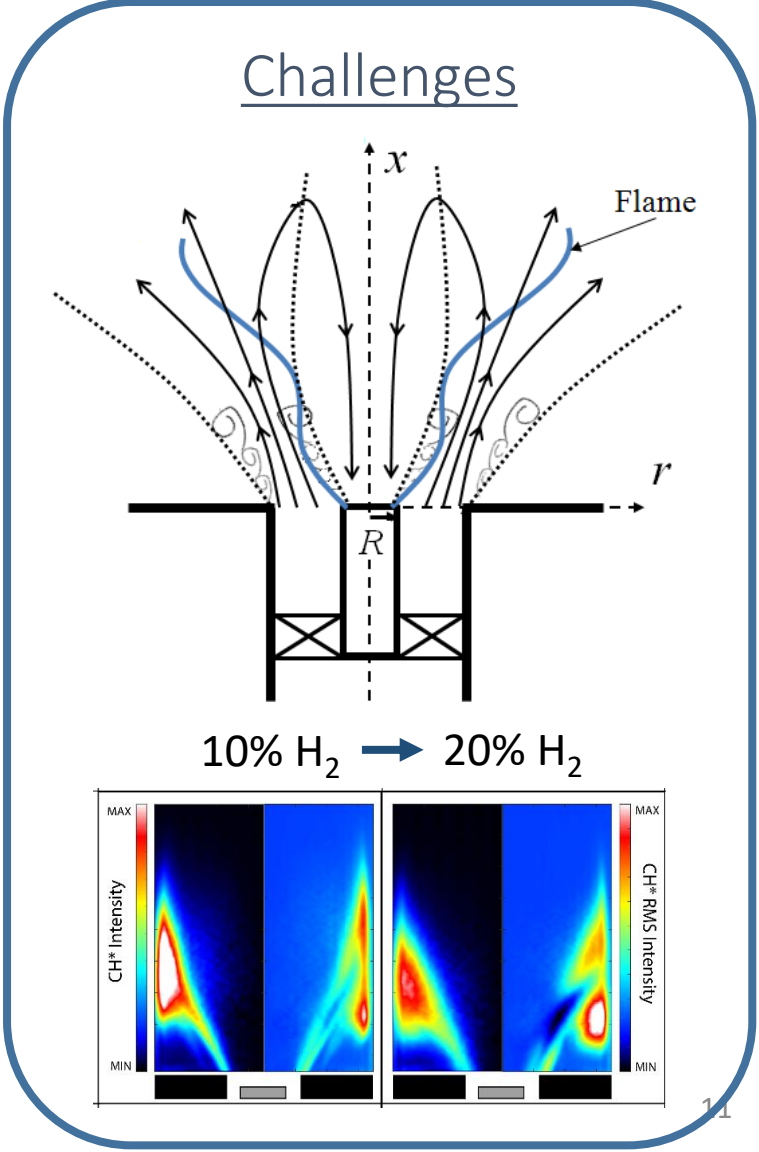
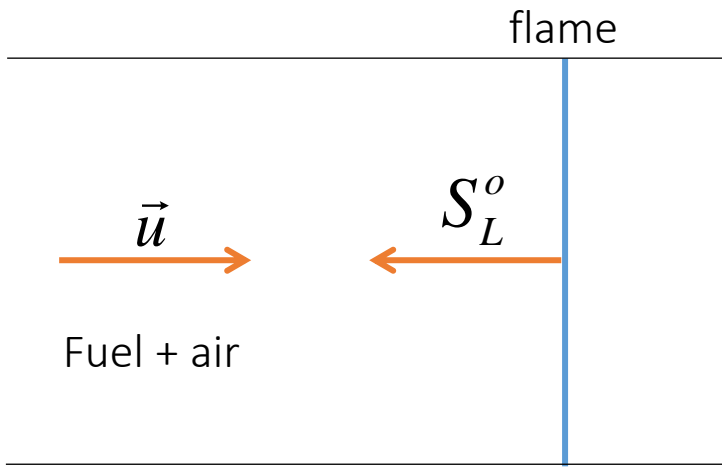
Flame stabilization in premixed combustion systems is driven by the flame speed of the mixture



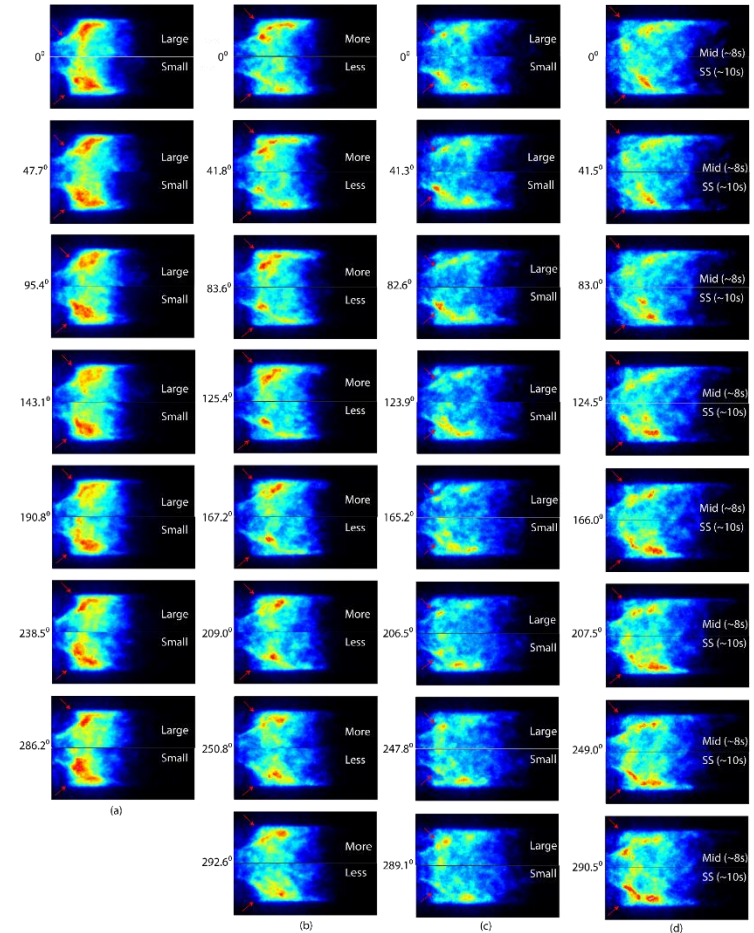
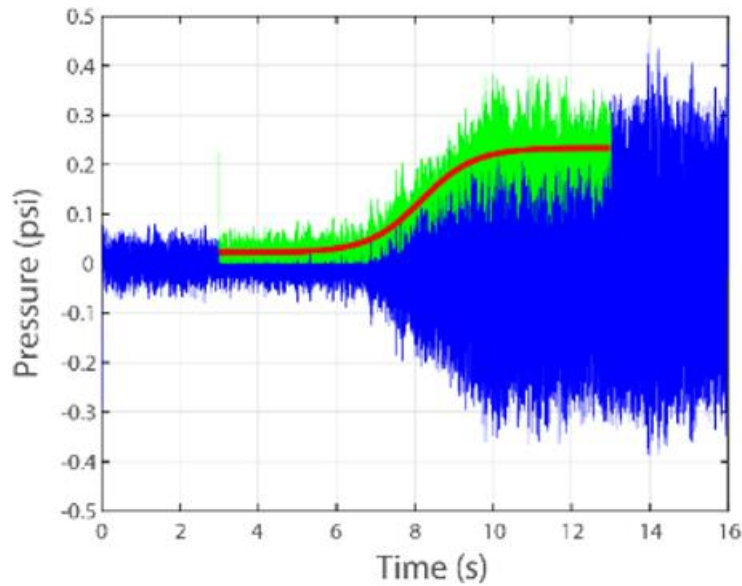
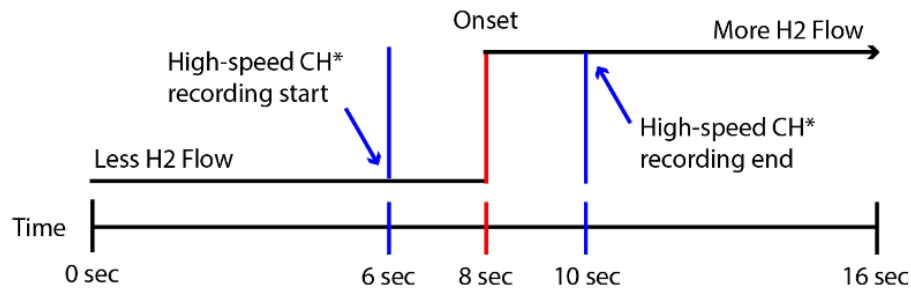
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# Hydrogen fuel may significantly change the operability of engines, including challenges like flame holding and instability



Strollo, J., Peluso, S., & O'Connor, J. (2020). "Effect of hydrogen on steady-state and transient combustion instability characteristics." *Journal of Engineering for Gas Turbines and Power*. In press

# Acknowledgements

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Questions?

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