Thermoacoustic Instabilities in LH2 Storage Systems and Novel Cryocooling Concepts Using Hydrogen as a Working Fluid

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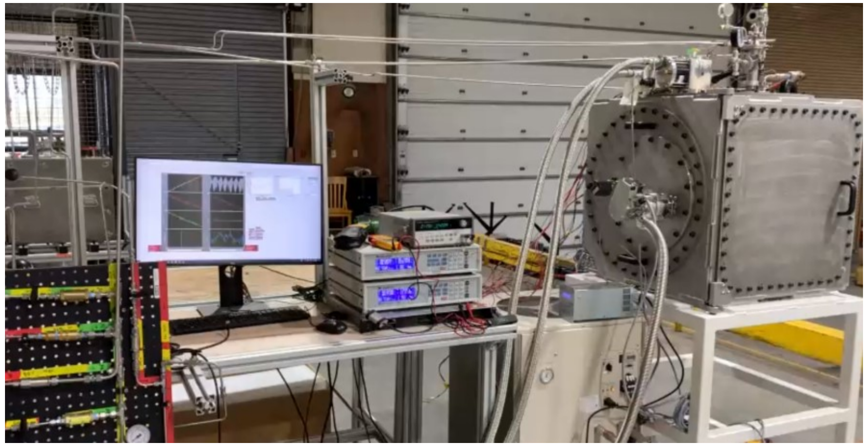
WASHINGTON STATE UNIVERSITY
Voiland College of
Engineering and Architecture

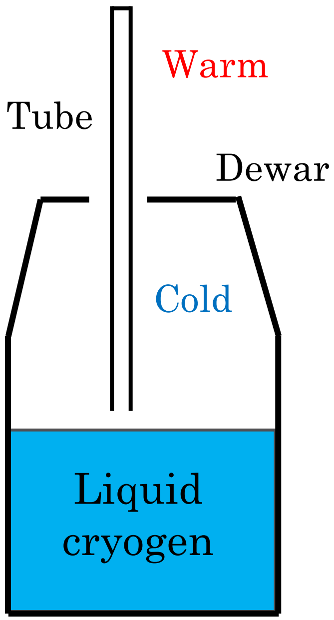
HYPER Center at WSU

- Liquid hydrogen research center at Washington State University
- Research, development, and testing of LH2 storage/transfer and cryogenic systems
- Producing own liquid hydrogen for laboratory experiments
- Working with industry (leading energy, aerospace, and high-tech companies) and government (DOE, NSF, NASA, etc.)
- Recently started reduced-order modeling (ROM) and high-fidelity computational fluid dynamics (CFD) for simulating complex LH2 phenomena

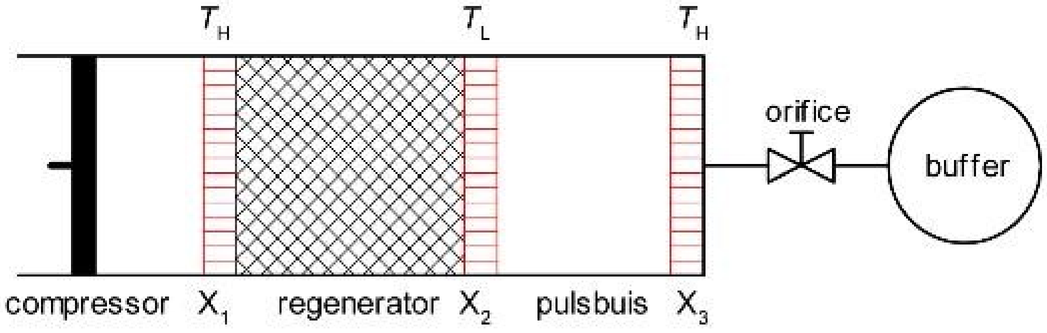


Thermoacoustic Phenomena: Overview

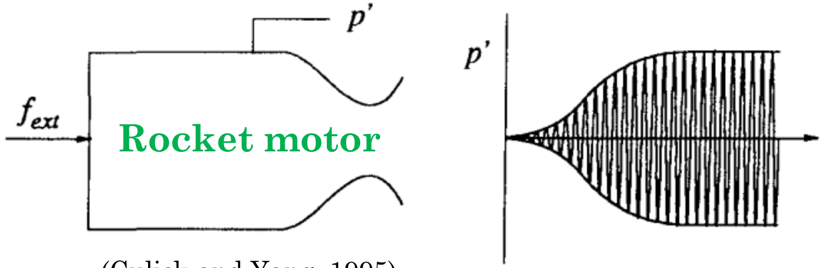
- Spontaneous thermoacoustic oscillations are the sound waves that appear inside resonators (e.g., tubes) due to instability of acoustic modes in the presence of large temperature gradients
- Often observed in narrow tubes used for sensors/venting/etc. in dewars with cryogenic fluids (Taconis oscillations) and may lead to large heat leaks, increasing boil-off rates, and vibrations undesirable for sensing instruments
- On the other hand, when supplied externally, sounds waves can be used to pump heat from cold to warm place, e.g., in pulse-tube cryocoolers
- Physical principles of Taconis oscillations and thermoacoustic coolers are similar to instabilities often observed in rocket motors



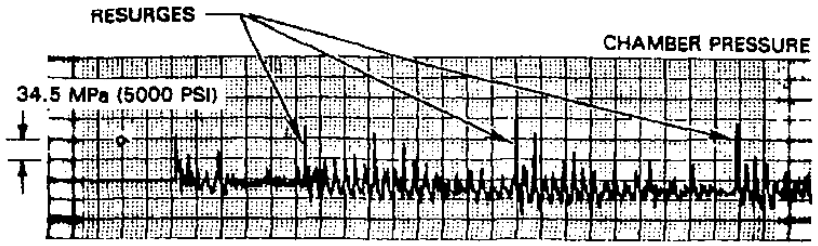
Pulse-tube cryocooler



https://en.wikipedia.org/wiki/Pulse_tube_refrigerator

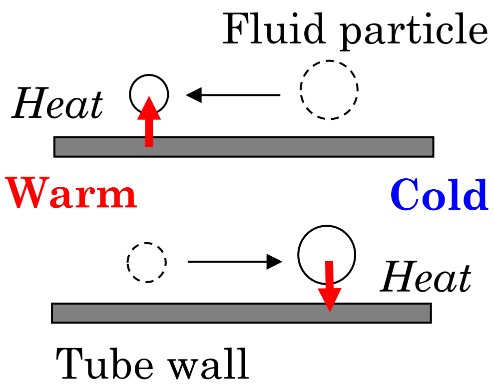


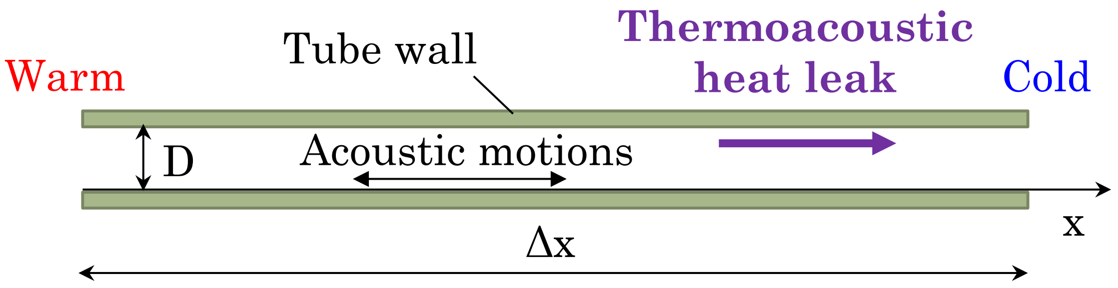
(Culick and Yang, 1995)



Thermoacoustic Oscillations: Origins

- Spontaneous thermoacoustic oscillations, including Taconis phenomena, appear when heat is periodically added to fluid particles when they are compressed and extracted when they are in rarefied state (which constitutes the **Rayleigh criterion**)
- Solid surface having large temperature gradient and aligned with acoustic motions provides opportunity for such thermal-to-acoustic energy transformation

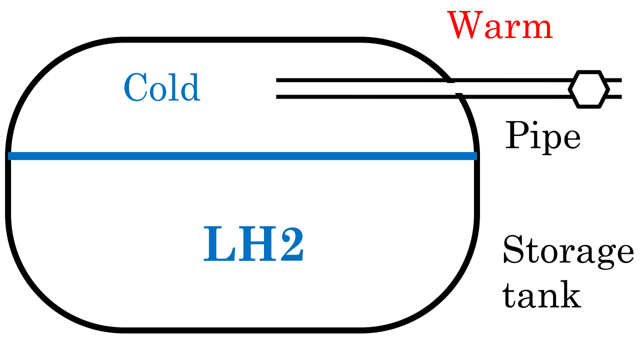




- If thermoacoustic power generation exceeds acoustic losses, Taconis oscillations appear
- Taconis oscillations usually correspond to lowest acoustic modes of resonators (e.g., tubes crossing walls of cryogenic vessels) and have their natural frequencies

Taconis Oscillations in LH2 Storage Systems

- Taconis oscillations can appear in storage tanks and transfer systems for liquid hydrogen



- Our objectives at HYPER:
  - investigate Taconis effects in cryogenic hydrogen systems
  - develop models for predicting onset of Taconis oscillations
  - demonstrate Taconis oscillation in H2 setups
  - validate modeling approach
  - explore novel techniques to regulate Taconis phenomena

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Taconis Oscillations: Modeling Approach

- In low-amplitude quasi-1D approximation, unsteady components of pressure and velocity (averaged over cross-section) can be presented as

$$p'(x,t) = Re\left[p(x)e^{i\omega t}\right] \quad u'(x,t) = Re\left[u(x)e^{i\omega t}\right]$$

- Governing fluid mechanics equations are transformed into thermoacoustic momentum and mass equations (Rott 1969, Swift 2002)

$$\frac{dp}{dx} = -\frac{i\rho\omega}{1-f_v}u \qquad \frac{du}{dx} = -\frac{i\omega\rho_m}{\gamma p_m}\left[1+(\gamma-1)f_k\right]p + \frac{f_k - f_v}{(1-f_v)(1-\sigma)}\frac{dT_m}{dx}\frac{u}{T_m}$$

Acoustic inertance, compliance and damping

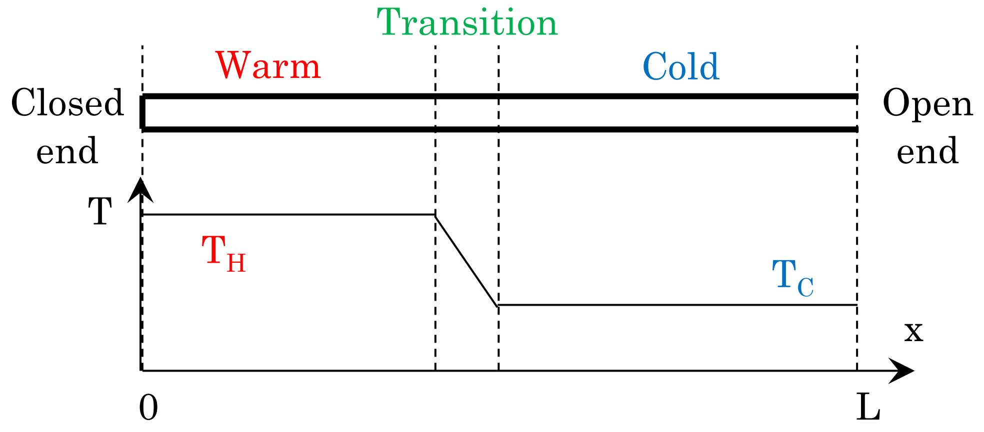
Thermoacoustic excitation (or extra dissipation)

- Thermoacoustic functions for circular pipe

$$f_{k,v} = 2\frac{J_1(y_{k,v})}{y_{k,v}J_0(y_{k,v})} \qquad y_{k,v} = \frac{(i-1)R}{\delta_{k,v}}$$

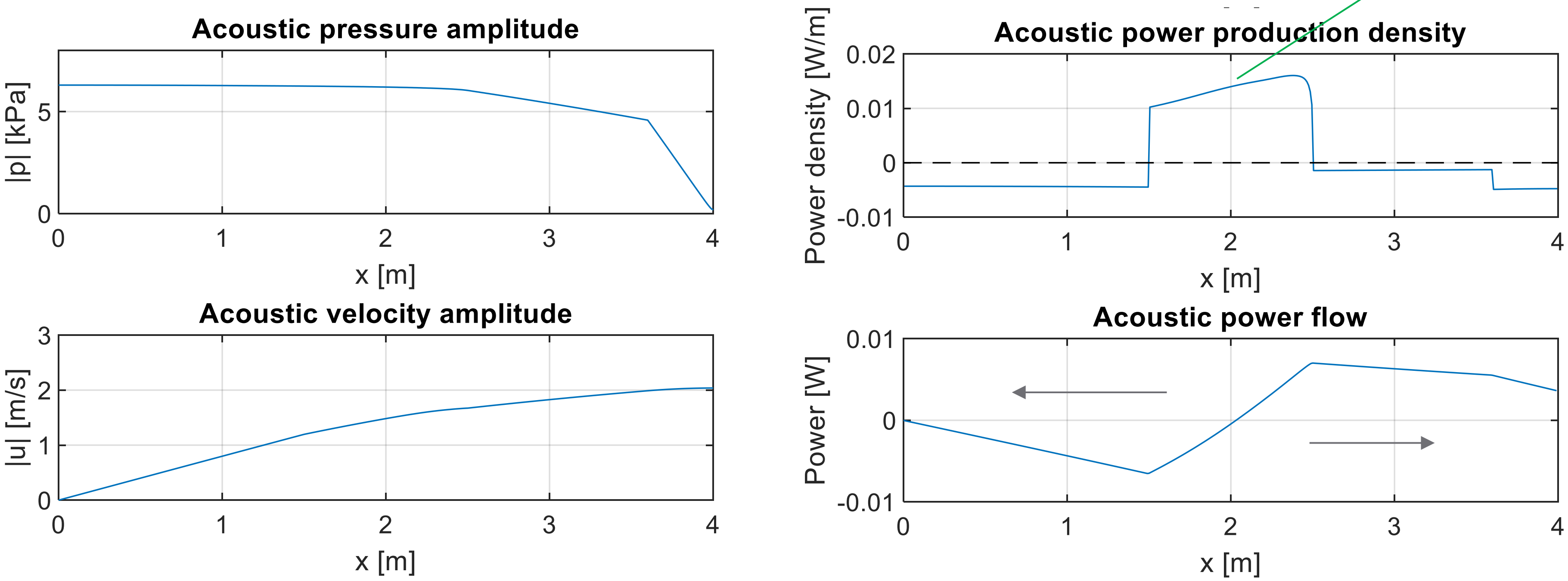
- Viscous and thermal penetration depths

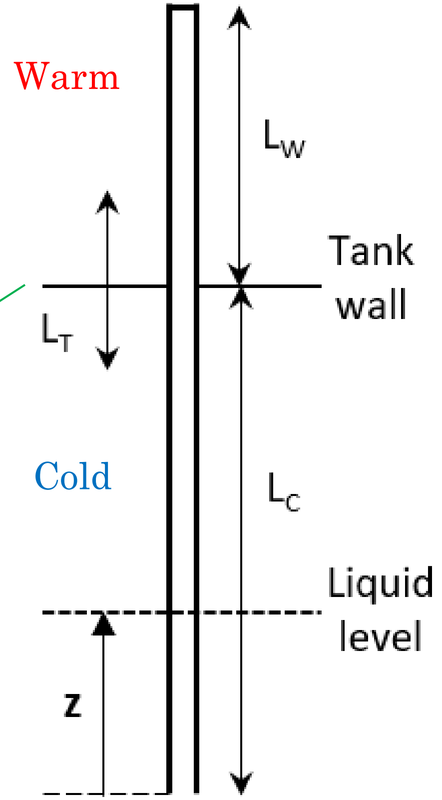
$$\delta_v = \sqrt{\frac{2\mu}{\rho\omega}} \qquad \delta_k = \sqrt{\frac{2k}{\rho\omega c_p}}$$



Acoustic Amplitudes and Power Production

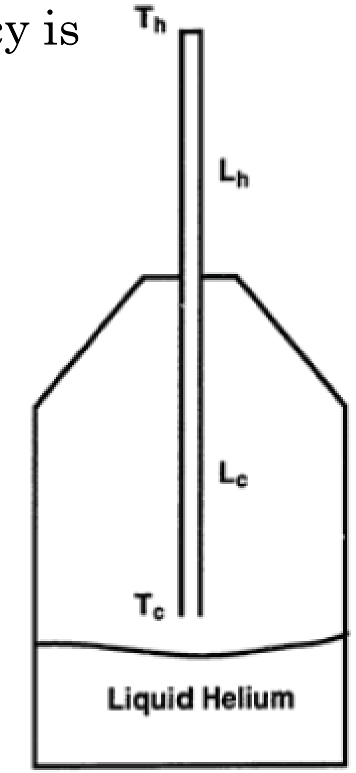
- Example of computed distributions of amplitudes and acoustic power
- LH2 tank, mean pressure 6 bar, tube length 4 m, radius 2.5 mm, submergence 0.4 m
- Acoustic power produced in the transition zone, 1.5 m < x < 2.5 m, and dissipated elsewhere, with power leaving at the open end





Taconis Oscillations: Initial Validation

- Thermoacoustic equations can be integrated along tube; initially unknown frequency is found by satisfying boundary conditions (so solutions are found iteratively)
- To find the onset of Taconis oscillations (i.e., critical hot-cold temperature ratio), temperature can be varied in the model till the frequency becomes a real number
- Model validation using test results by Gu (1993) for 1.5-m tube in helium dewar:



Input system parameters			Output results			
			Experiment		Modeling	
Radius	Lh/Lc	Th	**Tc,crit**	**Frequency**	**Tc,crit**	**Frequency**
5.84 mm	0.29	296.1 K	**9.61-10.6 K**	**31.4 Hz**	**9.5-10 K**	**30.2 Hz**
5.84 mm	0.67	296.2 K	**15.7-17.4 K**	**41.9 Hz**	**14-14.5 K**	**38.5 Hz**
2.48 mm	0.88	292.5 K	**27.9-29.8 K**	**52.3 Hz**	**28.5-29 K**	**55.3 Hz**
2.48 mm	1.4	294.5 K	**26.5-27.6 K**	**56.5 Hz**	**27-27.5 K**	**58.5 Hz**

Cold temperature intervals for Taconis onset

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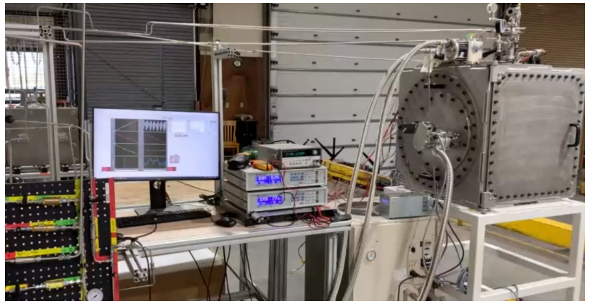
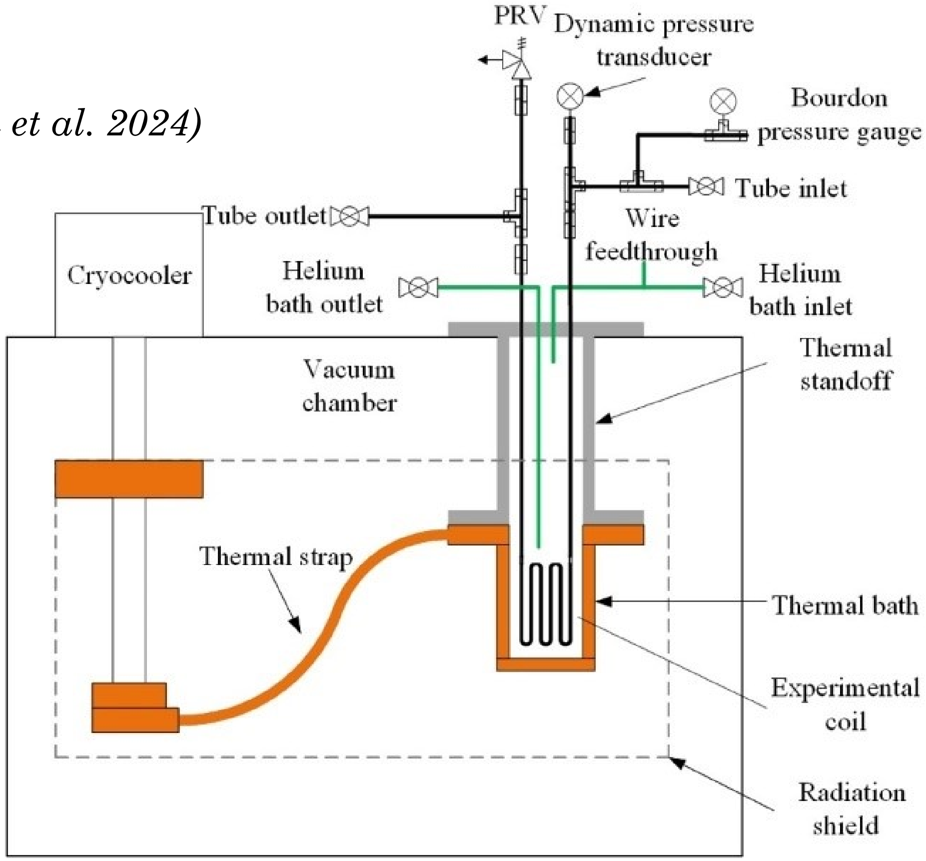
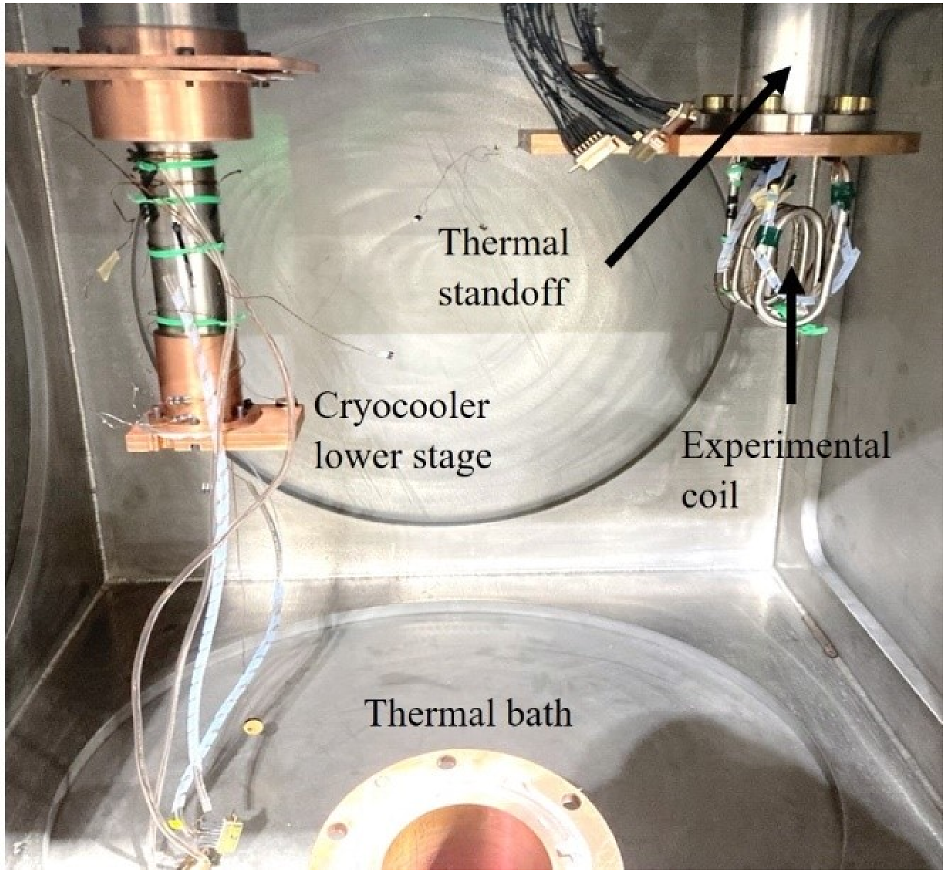
Experimental System at WSU



- U-shaped tube placed in cryostat
- Can vary system geometry, fluids, temperatures, mean pressure
- Record excitation and oscillation magnitudes in excited states

(Shenton et al. 2024)

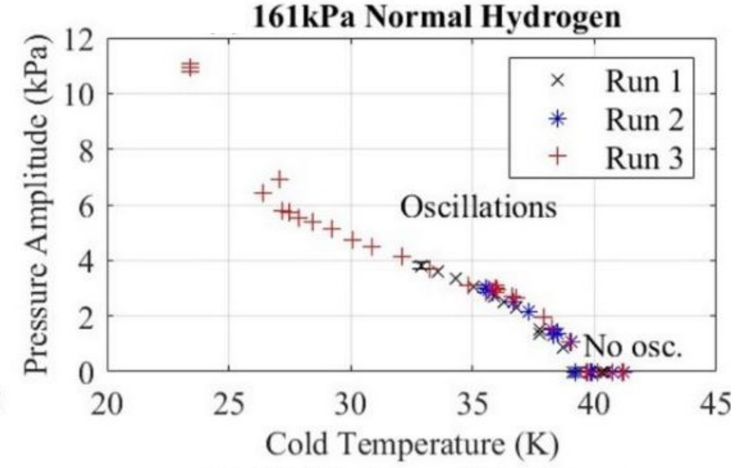


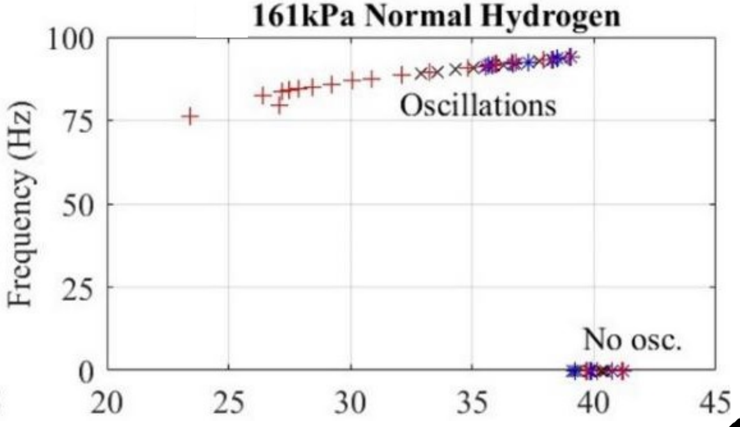


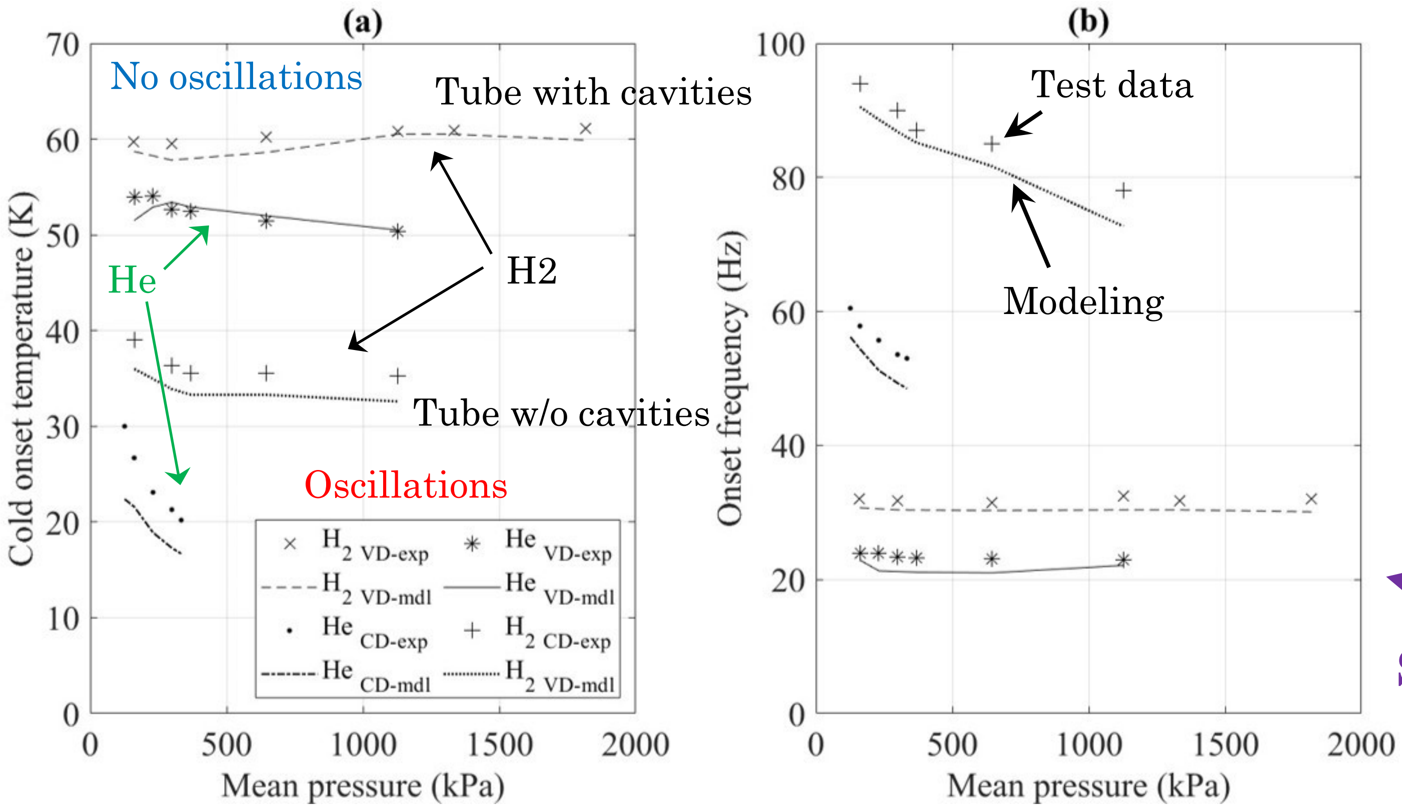
Results Obtained at WSU

- Hydrogen is easier to excite than helium
- Cavities in the warm section promote oscillations
- Oscillations were measured in gaseous, supercritical and two-phase hydrogen

Example of experimental run at fixed pressure and variable temperature





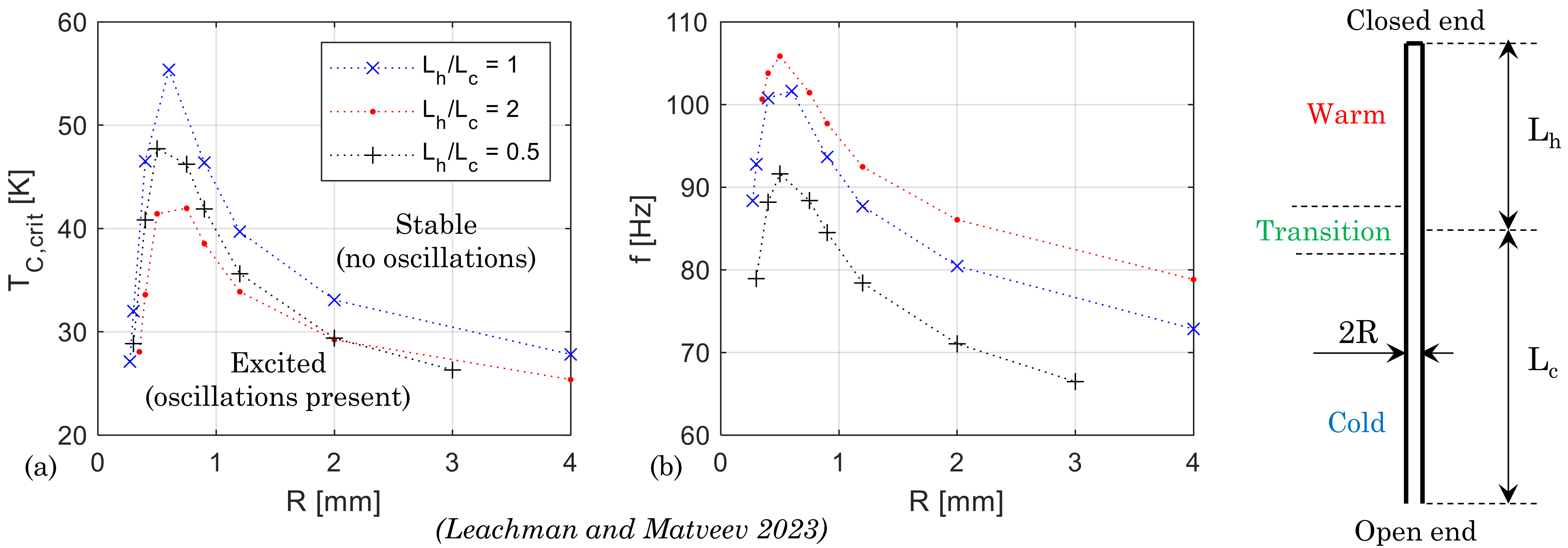


(Shenton et al. 2024)

Summary of stability boundary properties (onset conditions)

Parametric Modeling

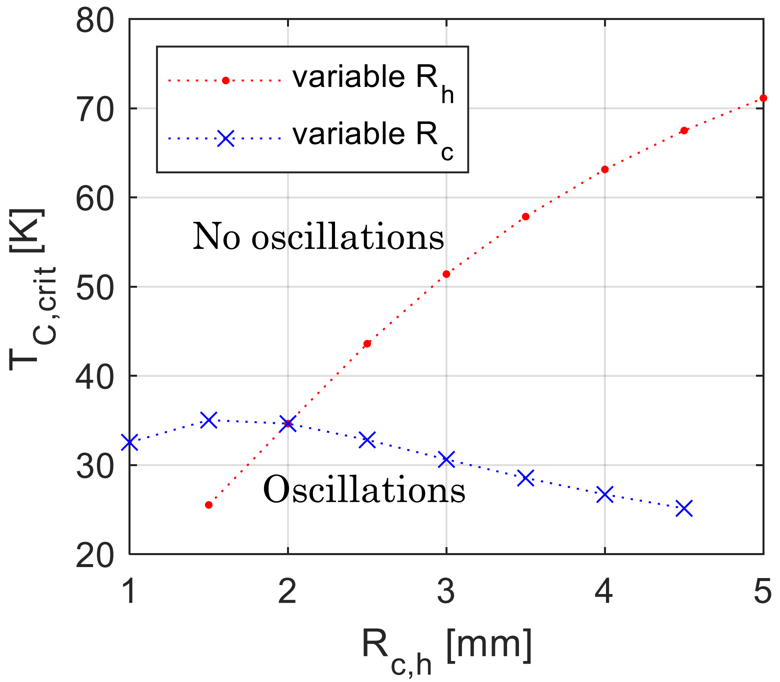
- Variable parameters: tube radius and hot-to-cold length ratio
- Fixed conditions: H_2 at 3 bar, tube length 1.5 m, warm temperature 300 K, transition 0.3 m
- Reported results: onset cold temperature and corresponding frequency of Taconis oscillations
- There is optimal excitation range of tube radii (~0.5-1.5 mm) and length ratio (L_h/L_c ~ 1)

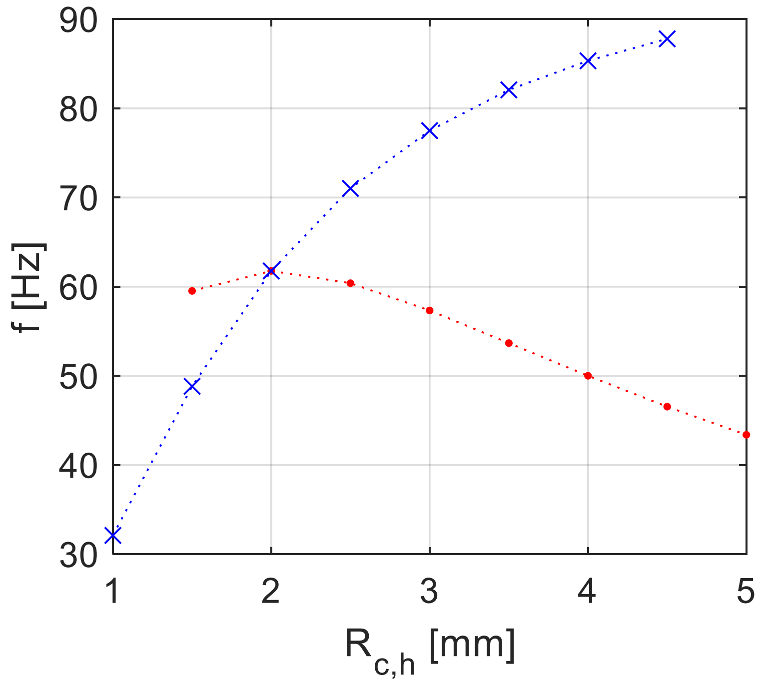


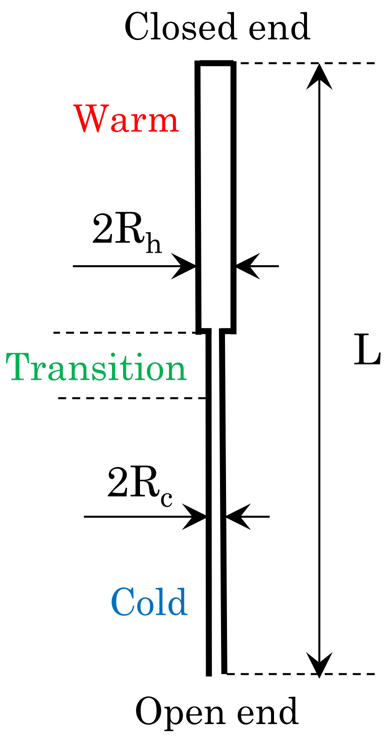
(Leachman and Matveev 2023)

Parametric Modeling

- Variable parameters: radius of warm and cold tube sections
- Fixed conditions: H2 at 3 bar, L = 1.5 m, L_h/L_c = 1, T_h = 300 K, default r = 2 mm
- Reported results: onset cold temperature and corresponding frequency of Taconis oscillations
- Wider radius of *warm section* strongly encourages oscillations and narrower suppresses





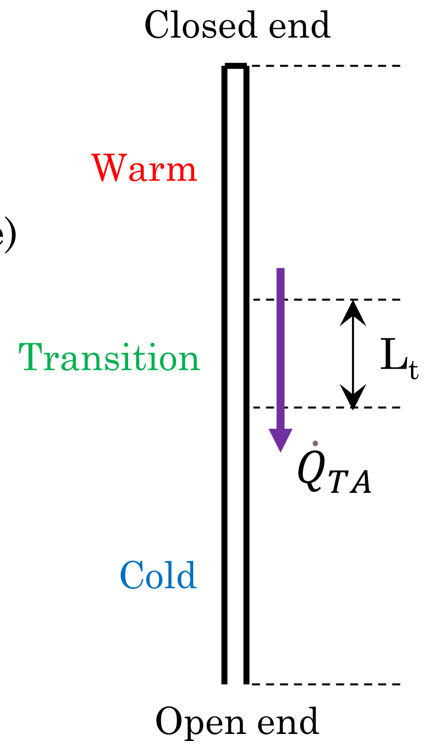


(Leachman and Matveev 2023)

Heat Leak

- Thermoacoustic heat transport (in addition to ordinary conduction) can be estimated given acoustic amplitudes

$$\dot{Q}_{TA} = \frac{1}{2} Re\left[p\tilde{u}\frac{\tilde{\tilde{f}}_v - f_k}{(1+\sigma)(1-\tilde{f}_v)}\right]A + \frac{\rho_m c_p |u|^2 A}{2\omega(1-\sigma^2)|1-f_v|^2} Im\left[f_k + \sigma\tilde{f}_v\right]\frac{dT_m}{dx}$$



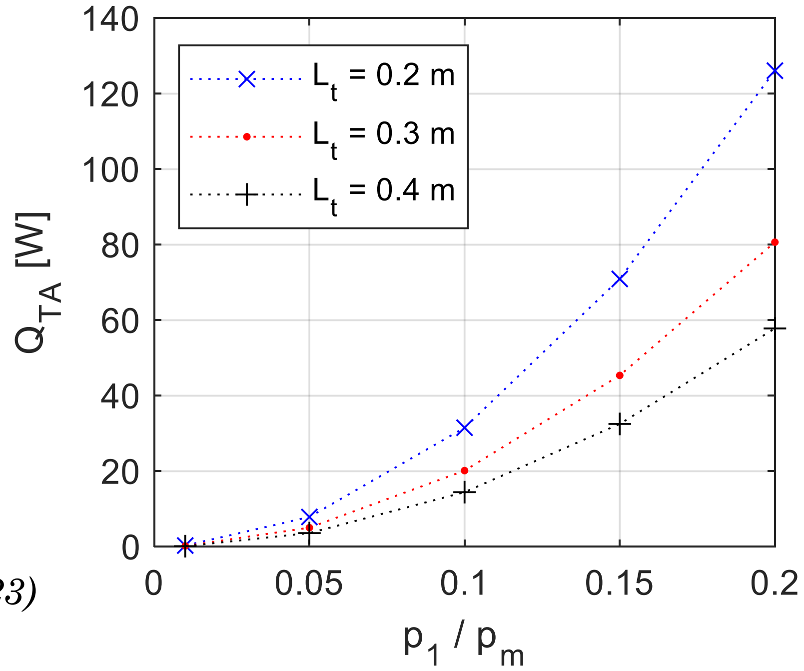
- Variable parameters: pressure amplitude and transition length

- pressure magnitude cannot be found by linear model (it is usually <20% of mean pressure)

- Fixed conditions: hydrogen at 3 bar, tube length 1.5 m, radius 2 mm, T_h = 300 K, T_c = 30 K

- Thermoacoustic heat increases with increasing acoustic amplitudes and steeper temperature gradients

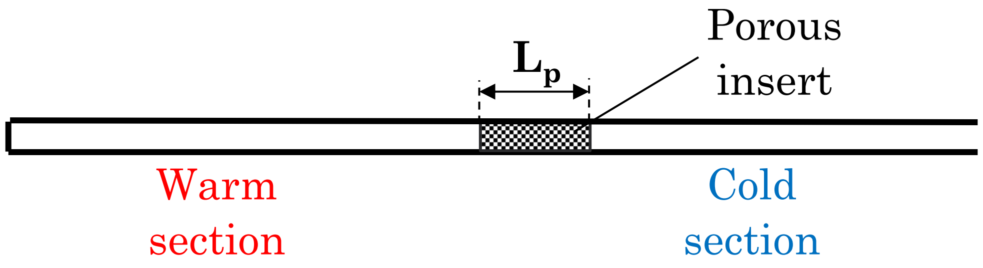
(Leachman and Matveev 2023)

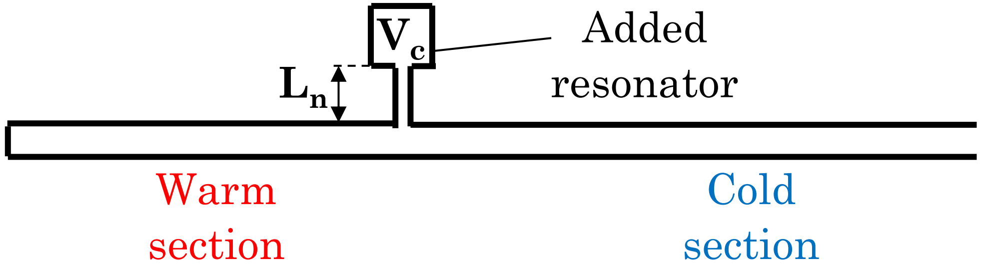


Taconis Oscillations: Prevention

- At the *design stage* of LH2 tanks, one can reduce chances of Taconis oscillations by
  - **avoiding wider warm sections**
  - **introducing asymmetry**
  - **increasing acoustic damping**
  - **making the overall tube length shorter**
  - **increasing length of temperature transition** (e.g., extending tube insulation)

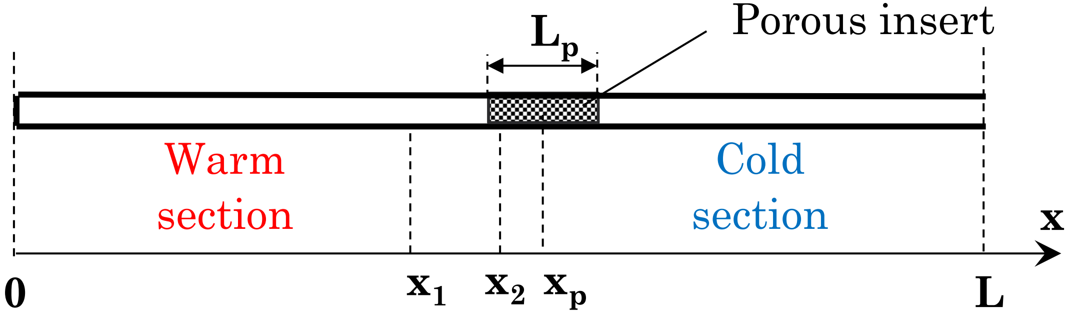
- In the *existing systems*, one can add resonators or porous inserts to help suppress oscillations (but incorrect application may encourage Taconis effects!)

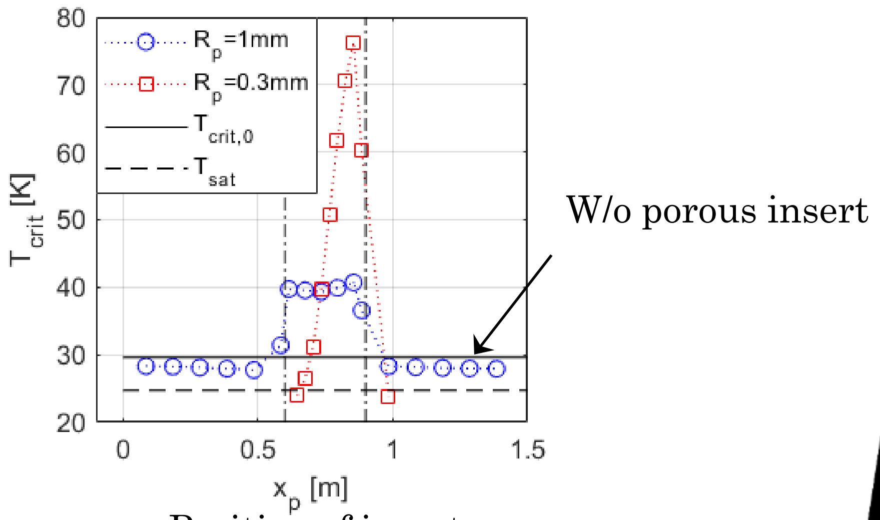




Taconis Oscillations: Prevention

- Porous insert outside temperature transition zone effectively damps oscillations, but when positioned inside temperature gradient zone, it can enhance oscillations (i.e., performing as an engine)

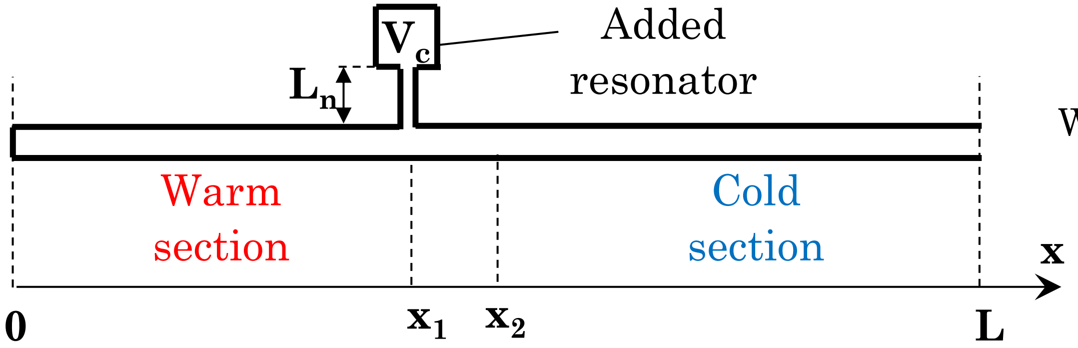


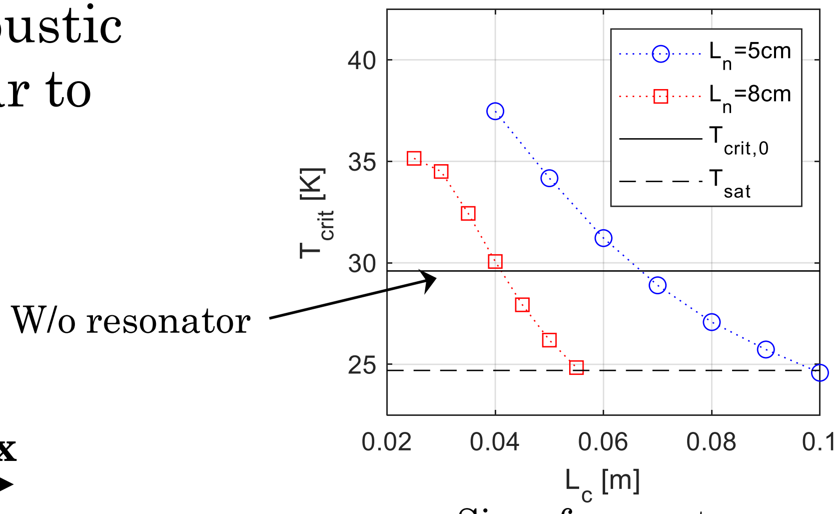


Position of insert

(Matveev 2024)

- Added resonator can absorb and dissipate acoustic energy, but it can also act as amplifier (similar to wider warm sections)

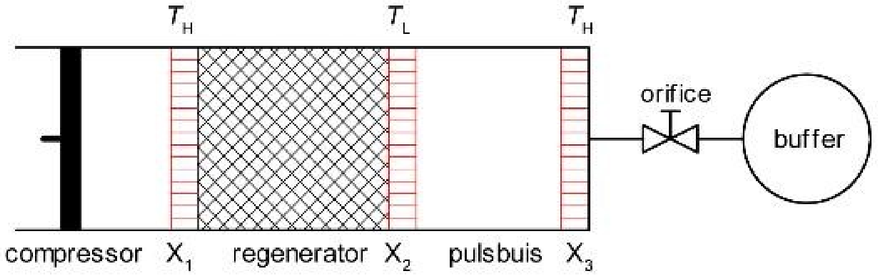




Size of resonator

Cryocooling: Hydrogen Opportunity

- Most cryocoolers employ helium, including pulse-tube refrigerators
- Their efficiencies are usually <20% of Carnot cycle
- Moreover, helium is not a renewable substance, and significant efforts are being undertaken to reduce helium consumption



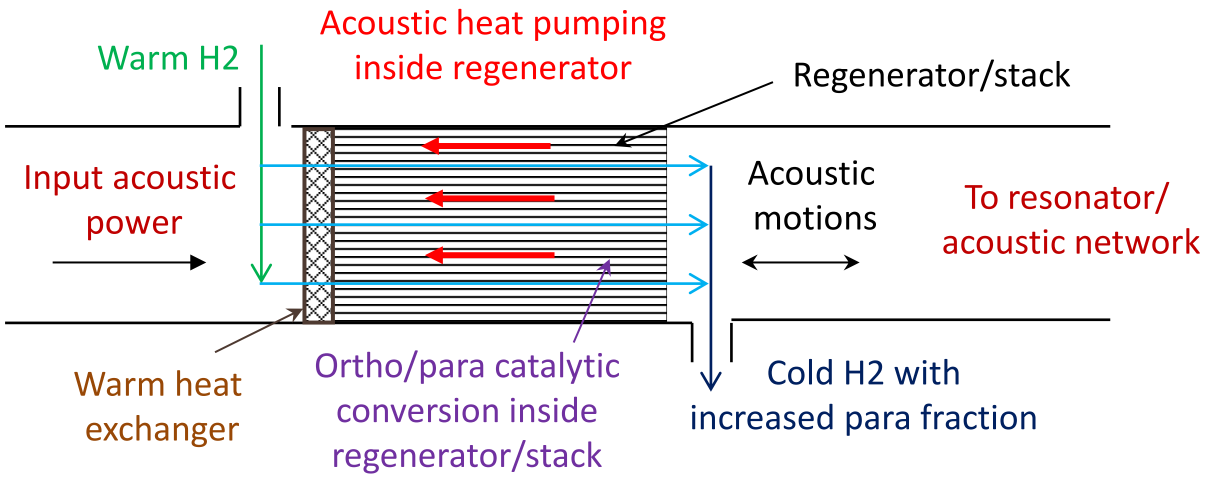
https://en.wikipedia.org/wiki/Pulse_tube_refrigerator

- In the 1970's, experiments with hydrogen cryocoolers showed advantages, but limited knowledge (at that time) of safe hydrogen handling and economic reasons prevented practical adaptation
- Easier excitation of Taconis oscillations in hydrogen demonstrate its potential promise for cryocooling
- Moreover, in the hydrogen liquefaction process, conversion from orthohydrogen to parahydrogen is required to minimize boil-off losses of LH2
- Porous regenerator can be catalyzed to cool down and convert flowing through hydrogen, this eliminating a need for cold heat exchanger and catalytic bed, which can potentially improve efficiency of hydrogen liquefaction

Cryocooling: Hydrogen Opportunity

- Catalyzed regenerator with flowing through hydrogen that is cooled down and transformed
- Catalytic reaction can be modeled with empirical correlation for evolution orthohydrogen fraction

$$\frac{dy_o}{dx} = \left(y_{o,eq} - y_o\right)\frac{k_v M A_s}{\dot{m}}$$



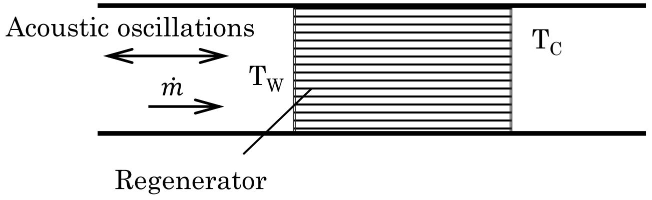
- To model thermoacoustic processes, the energy equation is introduced for enthalpy flow along the regenerator (in addition to momentum and mass equations)

$$\dot{H} = \dot{E} + \frac{1}{2} Re\left[p_1 \tilde{U}_1 \frac{(\tilde{\tilde{f}}_v - f_k)\beta T_m}{(1+\sigma)(1-\tilde{f}_v)(1+\theta)}\right] + \dot{m}h +$$

$$\left[\frac{\rho_m c_p |U_1|^2}{2\omega A_f (1-\sigma^2)|1-f_v|^2} Im\left(\tilde{f}_v + \frac{(f_k - \tilde{\tilde{f}}_v)(1+\theta f_v/f_k)}{(1+\sigma)(1+\theta)}\right) - (A_f k + A_s k_s)\right]\frac{dT_m}{dx}$$

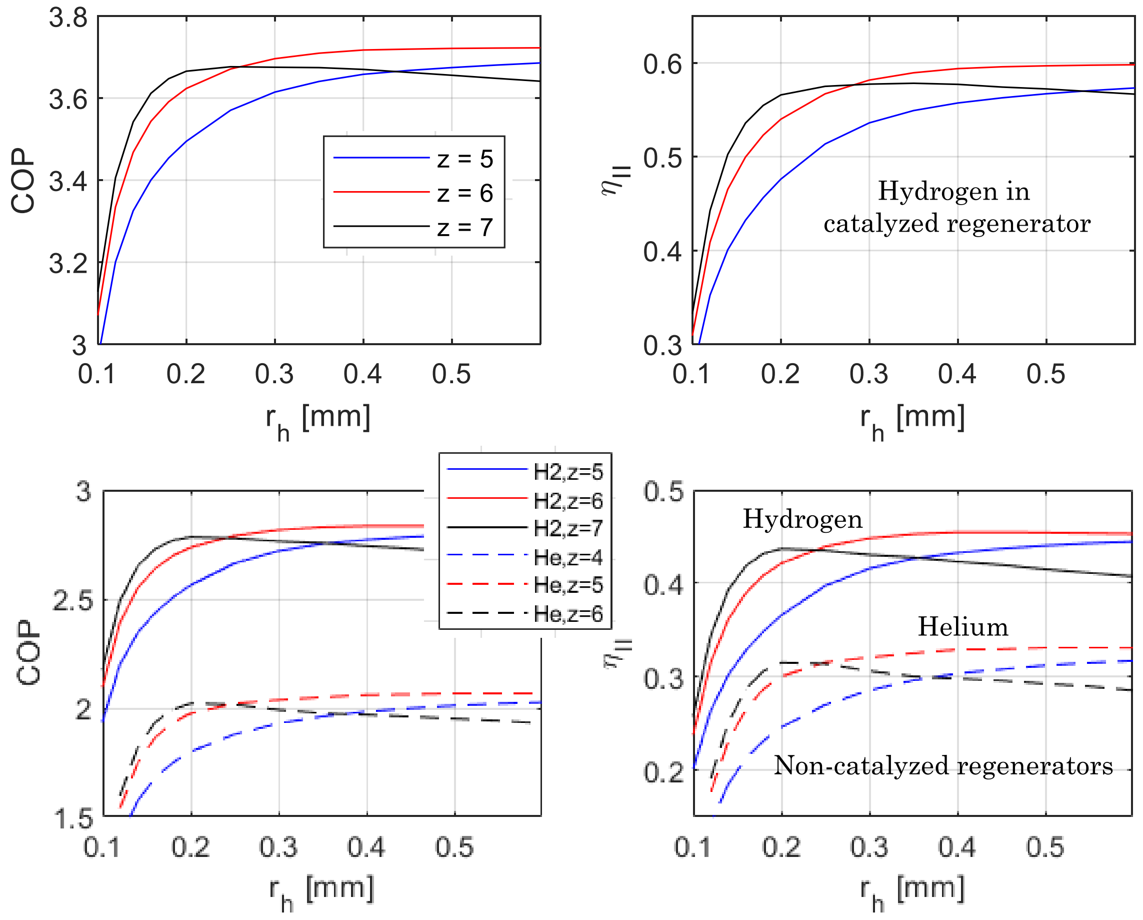
Cryocooling: Hydrogen Opportunity

- Performance metrics $COP = \frac{\dot{m}(h_w - h_c)}{\dot{E}_w - \dot{E}_c}$ $\eta_{II} = COP\,\frac{T_w - T_c}{T_c}$



- Case study with variable pore size and acoustic impedance

Stack length	20 cm
Stack porosity	0.5
Solid material	Stainless steel
Mean pressure	5 bar
Mean mass flux	0.15 kg/(s-m^2)
Acoustic frequency	100 Hz
Inlet temperature	80 K



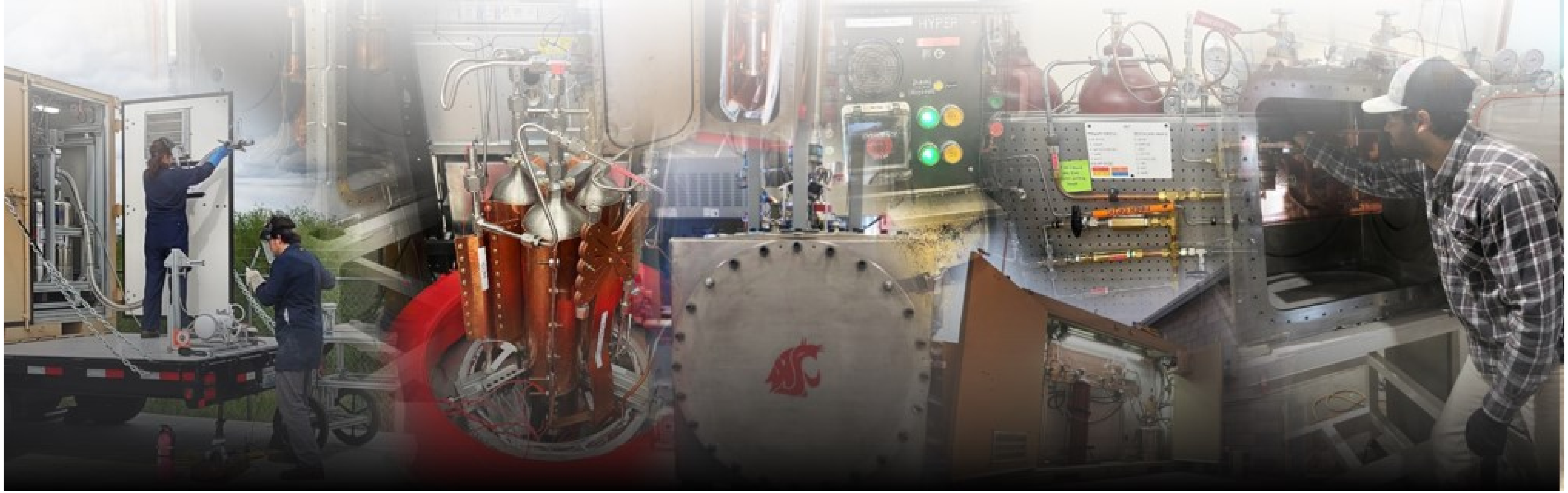
- Hydrogen shows significant advantage over helium in optimized configurations

- We are currently designing traveling-wave thermoacoustic engine-cryocooler

(Matveev and Leachman 2024)

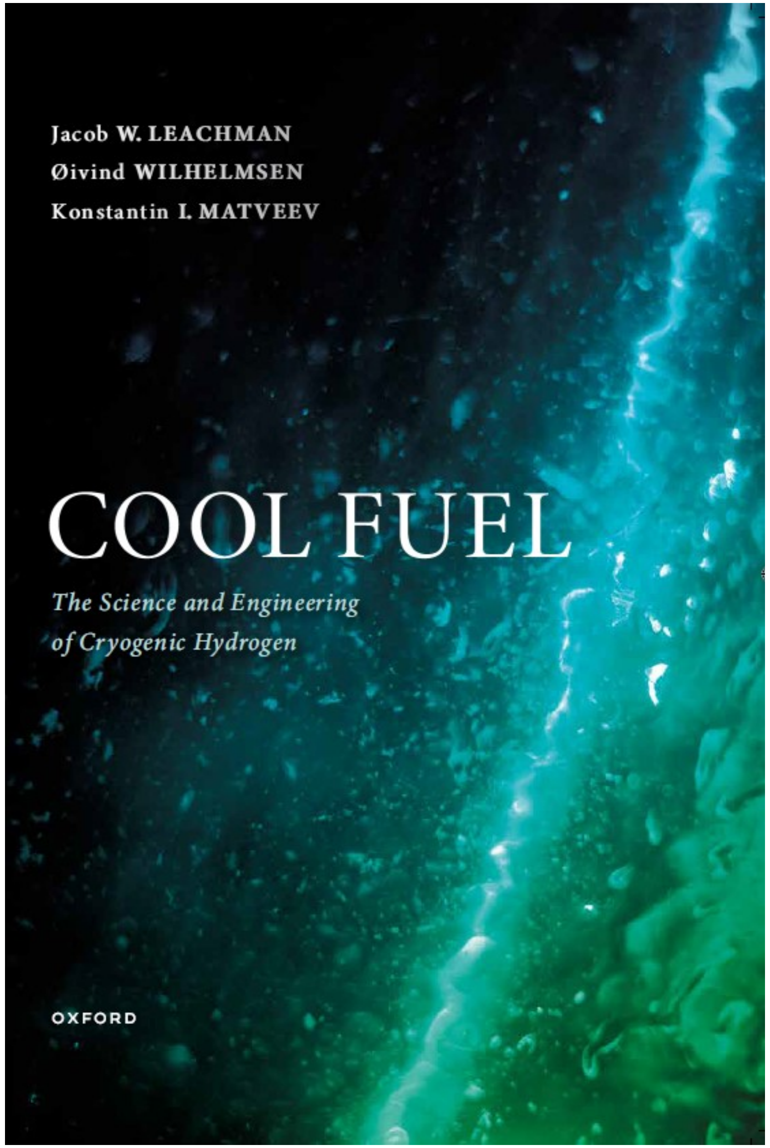
Conclusions

- **Thermoacoustic instabilities can appear in cryogenic systems and increase boil-off losses**
- **1D thermoacoustic model can be used to predict/avoid these instabilities**
- **Sounds waves are excited more easily in hydrogen than in helium systems**
- **Hydrogen cryocoolers can have higher efficiency than helium-based**
- **Catalyzed regenerators can improve hydrogen liquefaction process**



New Book on Cryogenic Hydrogen

- Our book **Cool Fuel: The Science and Engineering of Cryogenic Hydrogen** will be released by Oxford University Press in early 2025
- Available for pre-order now
- Authors: J.W. Leachman (WSU)
  Ø. Wilhelmsen (NTNU)
  K.I. Matveev (WSU)
- Chapters:
  1. Historical and future trends
  2. Thermophysical properties
  3. Para-orthohydrogen conversion
  4. Liquefaction
  5. Elements of transfer
  6. Storage
  7. Safety



Thank You!

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https://hydrogen.wsu.edu/