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Passive control of thermoacoustic instabilities by heat exchangers

Workshop on Analytical methods in thermo- and aeroacoustics

POLKA

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Outline of Talk

How?

What?, Why? & Where?

Passive control of thermoacoustic instabilities

by heat exchangers

By use of

- Background - Thermoacoustic Instability
- Control Strategies - Active and Passive
- Motivation - Use of Heat exchangers
- Applications

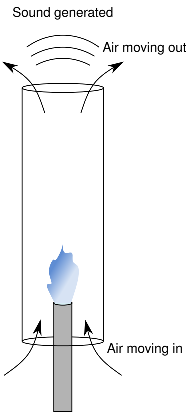
What?, Why? & Where?

Passive control of thermoacoustic instabilities by heat exchangers

- What physical phenomenon are we looking at?
- Why is this important?
- Where does this occur?

Background
WHAT is Thermoacoustic Instability?

- Simple thermoacoustic device
  - Rijke tube



Courtesy: Prof. Maria Heckl
Keele University

Background
WHAT is Thermoacoustic Instability?

- Simple thermoacoustic device
  - Rijke tube
- Thermo + Acoustics

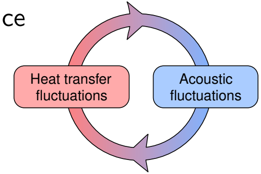
Sound waves perturb flame

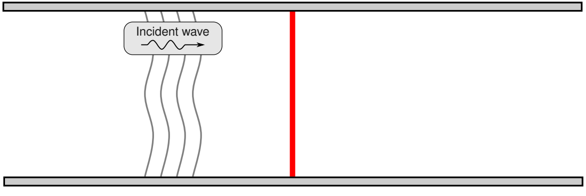
Flame generating sound waves

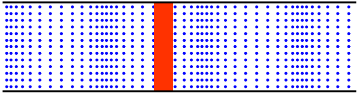
Courtesy: Prof. Maria Heckl,
Dr. Sreenath Malamal Gopinathan
Keele University

Background
WHAT is Thermoacoustic Instability?

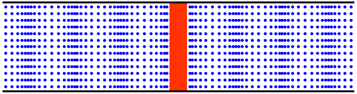
- Simple thermoacoustic device
  - Rijke tube
- Thermo + Acoustics
  - Positive Feedback







Sound waves perturb flame



Flame generating sound waves

Courtesy: Prof. Maria Heckl,
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Keele University

Background
WHY Thermoacoustic Instability?

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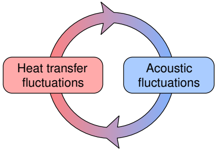
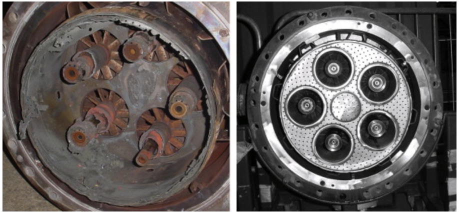
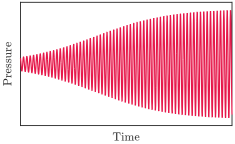
- Positive Feedback
  - Increasing pressure amplitudes → *Thermoacoustic Instability*
  - Damage to structure



Positive feedback



Damaged and undamaged burner assembly

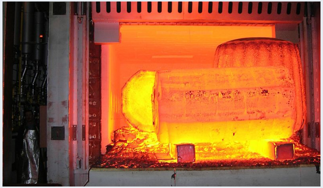


High amplitude pressure fluctuations

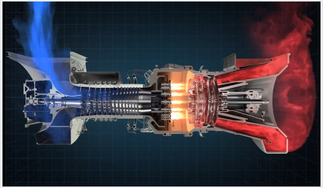
Y. Huang and V. Yang, "Dynamics and stability of lean-premixed swirl-stabilized combustion", *Progress in Energy and Combustion Science*, Vol. 35, Issue 4, pp 293-364, (2009)

Background
WHERE does this occur?

- Confined Heat source (or sink) + Acoustics

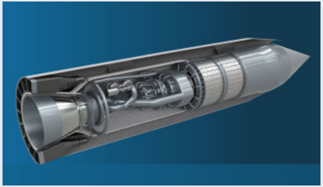


Industrial furnace



Gas turbine engine

Domestic boiler



Rocket engine (SABRE)

Control Strategies

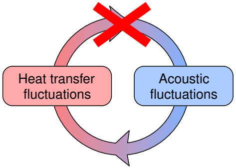
How?

Passive control of thermoacoustic instabilities

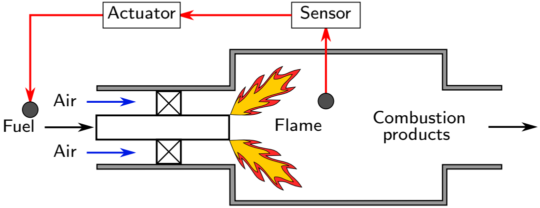
by heat exchangers

- How can we control this?

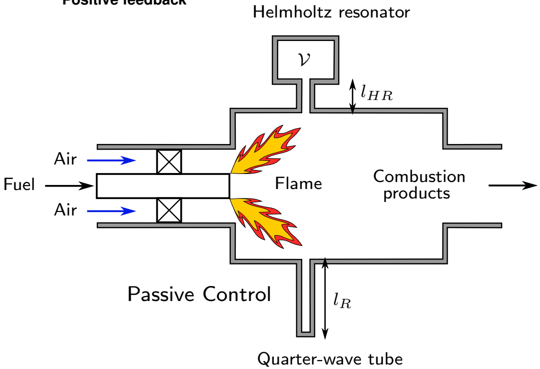
- Break positive feedback
  - Active Control or Passive Control



Positive feedback

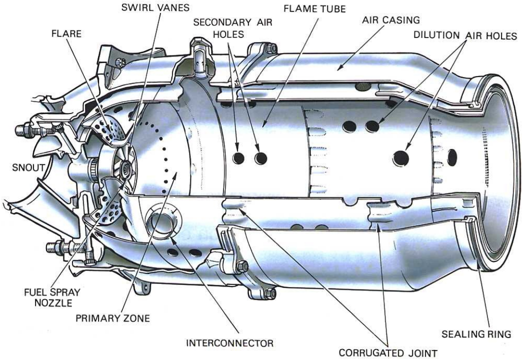


Active Control

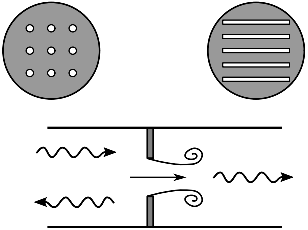


Passive Control

- Other passive control devices
  - Acoustic liners



The jet engine, 5th Ed., Rolls-Royce plc, Derby, UK, (1996)



Dissipative mechanism in liners

Motivation

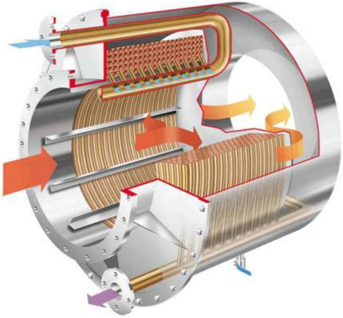
Passive control of thermoacoustic instabilities

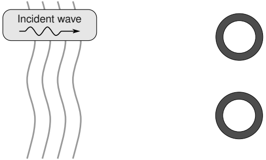
by heat exchangers

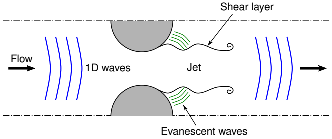
By use of

- What is so special about heat exchangers?

- Heat exchangers
  - Integral component of combustion systems
    - No additions needed
  - Act as both *heat sink* and *acoustic scatterer/ dissipator*
    - Active/passive acoustic element
  - Positive feedback → Thermoacoustic instability







Summary

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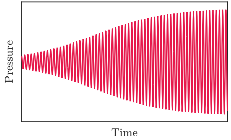
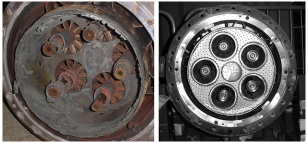
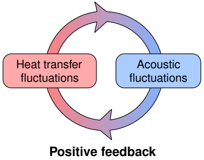
- Thermoacoustic instability
  - Characterised by high amplitude pressure fluctuations
  - Often lead to structural damage
  - Caused by positive feedback







Summary

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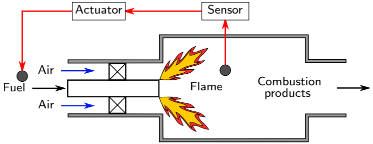
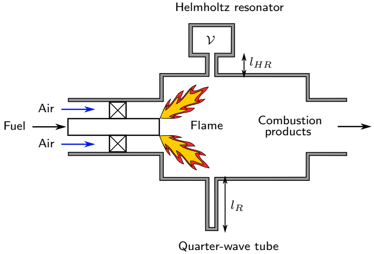
- Control Strategies
  - Active and Passive





Summary

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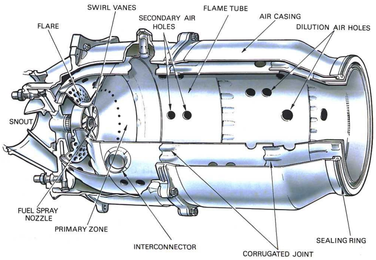
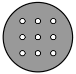
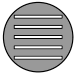
- Control Strategies
  - Active and Passive
  - Passive: Acoustic liners

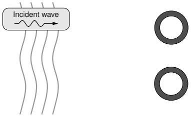






Summary

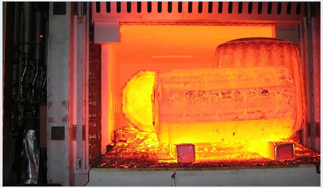
- Thermoacoustic instability
  - Characterised by high amplitude pressure fluctuations
  - Often lead to structural damage
  - Caused by positive feedback
- Control Strategies
  - Active and Passive
  - Passive: Acoustic liners
- Heat exchangers
  - Heat sink and Acoustic dissipator
  - Active acoustic element



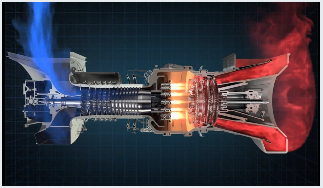
Applications...

WHERE does this occur?
Domestic Boilers

- Confined Heat source (or sink) + Acoustics

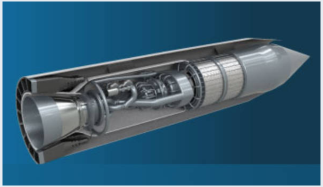


Industrial furnace



Gas turbine engine

Domestic boiler



Rocket engine (SABRE)

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Prediction of thermoacoustic instabilities in domestic boilers

Collaborators

Maria A. Heckl — Keele University

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Susann Boij
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Avraham Hirschberg
Naseh Hosseini
(also Bekaert) — TU/e

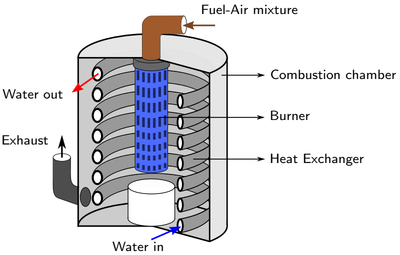
Joan Teerling — BEKAERT

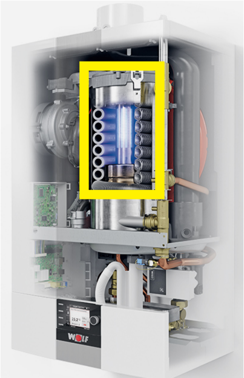
Outline

- Modelling of Boiler
- Heat exchanger modelling
- Solution methodology
- Stability predictions
- Summary & Conclusions

Modelling of Boiler
Idealised system

- Domestic boilers
  - Burner + Heat exchanger

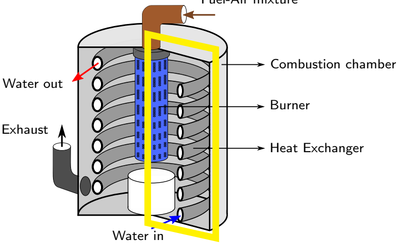


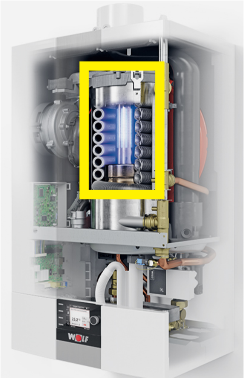


Courtesy: Wolf (http://en.wolf-heiztechnik.de)

Modelling of Boiler
Idealised system

- Domestic boilers
  - Burner + Heat exchanger
  - Radially symmetric

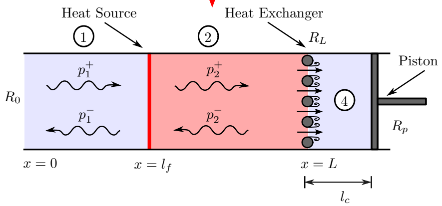


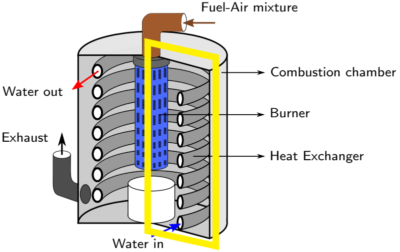


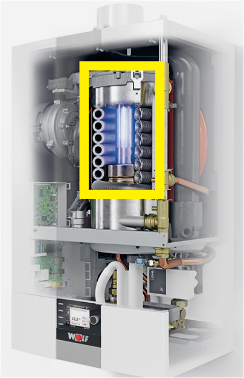
Courtesy: Wolf (http://en.wolf-heiztechnik.de)

Modelling of Boiler
Idealised system

- Domestic boilers
  - Burner + Heat exchanger
  - Radially symmetric
  - Idealised combustion system

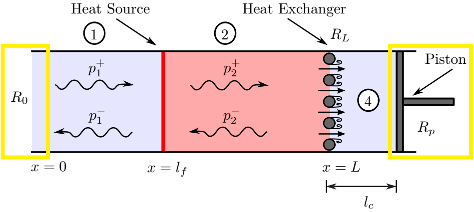






Courtesy: Wolf (http://en.wolf-heiztechnik.de)

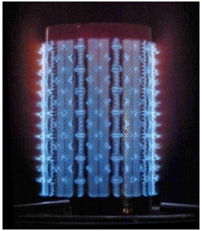
- 1-D acoustic waves, perpendicular to the rods
- Acoustically compact heat source
  - Heat source thickness $\ll$ acoustic wavelength
- Heat exchanger : Heat sink + Acoustic scatterer
- Inlet - open end and Outlet - closed end



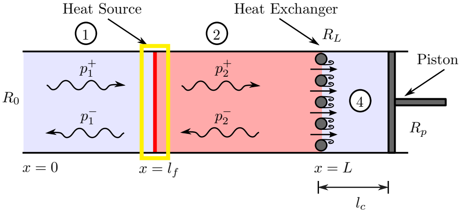
Modelling of Boiler
Heat Source

- Infinitesimally thin, acoustically compact heat source
- Obeys "Simple" $n - \tau$ law

$$\hat{Q}_f(x, \omega) = n\, u_1(x)\, e^{i\omega\tau} \delta(x - l_f)$$

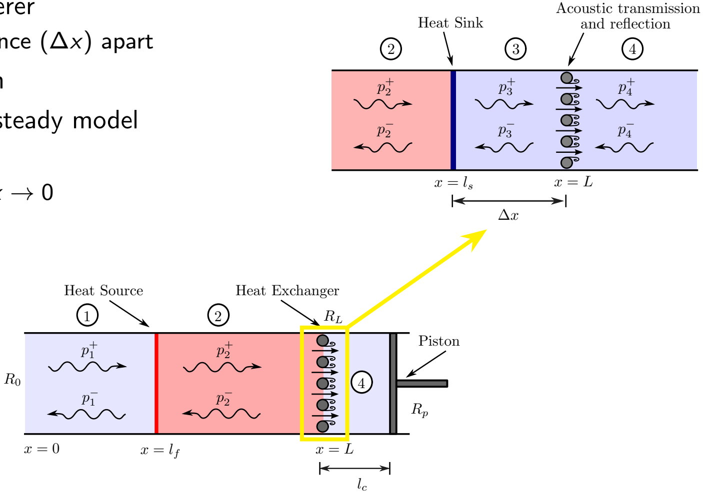


Courtesy: Dr. O. J. Teerling, Bekaert Combustion Technology



Modelling of Boiler
Heat Exchanger

- Heat Sink + Acoustic Scatterer
  - Spaced infinitesimal distance (Δx) apart
- Heat sink - Transfer function
- Acoustic scattering - Quasi-steady model
- Net scattering behaviour
  - Combine both and let $\Delta x \to 0$

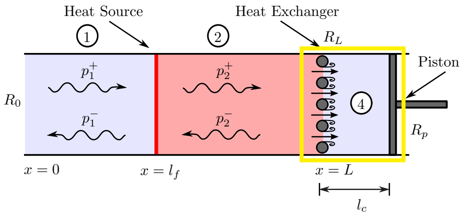


- Rigid end $\rightarrow$ Cavity backing

$$R_L = R_u + \frac{T_{d\rightarrow u} T_{u\rightarrow d} R_p e^{2ik_4 l_c}}{1 - R_d R_p e^{2ik_4 l_c}}$$

$$\Delta_L = 1 - |R_L|^2$$

- R_L : effective reflection coefficient at $x = L$
- Heat exchanger scattering coefficients : $T_{u\rightarrow d}, R_u, T_{d\rightarrow u}$ & R_d



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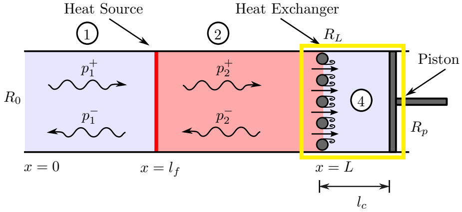
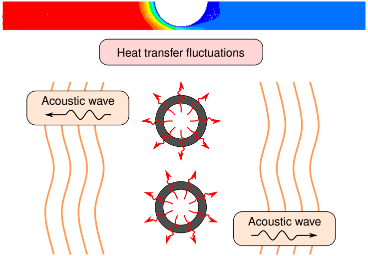


Heat exchanger modelling
Heat sink

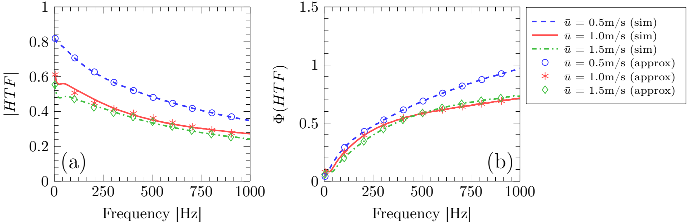
- Transfer Function (HTF) : complex quantity

$$HTF = \frac{\hat{Q}_h/\bar{Q}_h}{\hat{u}_2/\bar{u}_2}$$

$$\hat{Q}_h = \left(u_2^+ + u_2^-\right)\left(\bar{Q}_h/\bar{u}_2\right)\left\{|HTF|\, e^{i\Phi(HTF)}\right\}$$



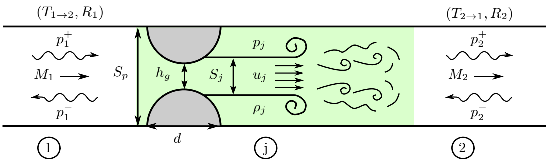
- Obtained from numerical simulations
- Approximated using Least squares

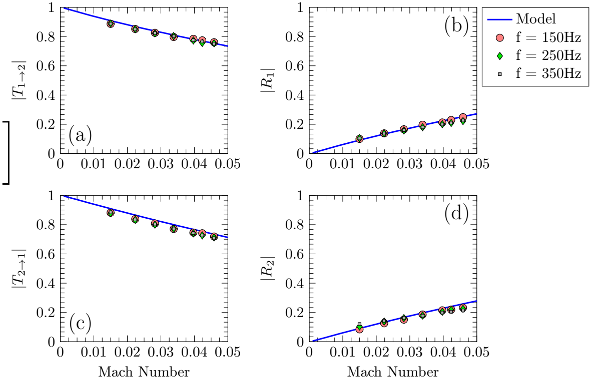


Heat exchanger modelling
Acoustic scattering

- Quasi-steady model
  - Approximated geometry
- Experimentally validated

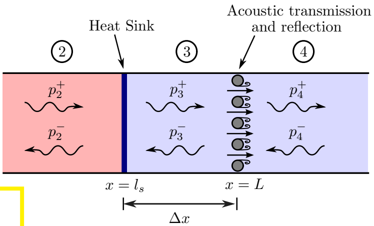
$$\begin{bmatrix}(1+M_2)\,p_2^+\\(1-M_1)\,p_1^-\end{bmatrix}=\begin{bmatrix}T_{1\to2} & R_2\\ R_1 & T_{2\to1}\end{bmatrix}\begin{bmatrix}(1+M_1)\,p_1^+\\(1-M_2)\,p_2^-\end{bmatrix}$$





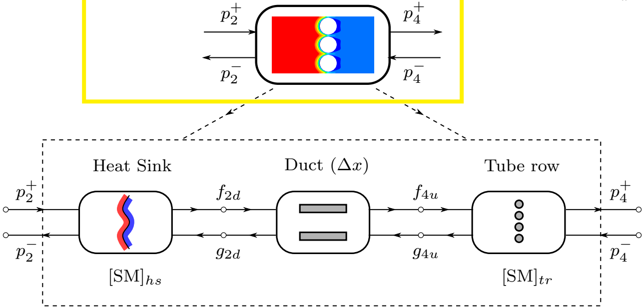
Surendran, A., Heckl, M. A., Peerlings, L., Boij, S., Bodén, H., and Hirschberg, A., "Aeroacoustic response of an array of tubes with and without bias-flow", *Journal of Sound and Vibration*, Vol. 434, pp. 1–16,(2018).

Heat exchanger modelling
Total Scattering Matrix



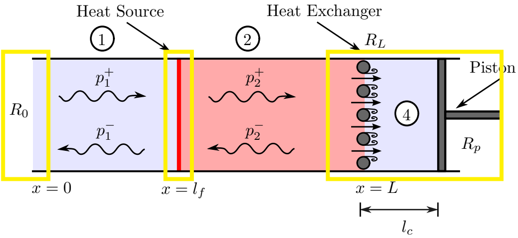
- Heat Sink + Acoustic Scatterer
- Combine at $\Delta x \to 0$

$$\begin{bmatrix} p_4^+ \\ p_2^- \end{bmatrix} = \underbrace{\begin{bmatrix} T_{u\to d} & R_d \\ R_u & T_{d\to u} \end{bmatrix}}_{[SM]_{hex}} \begin{bmatrix} p_2^+ \\ p_4^- \end{bmatrix}$$



Solution methodology

Eigenvalue problem



Open end

$$p_1^+ e^{-ik_1 l_f} = R_0 p_1^- e^{ik_1 l_f}$$

At $x = L$ end

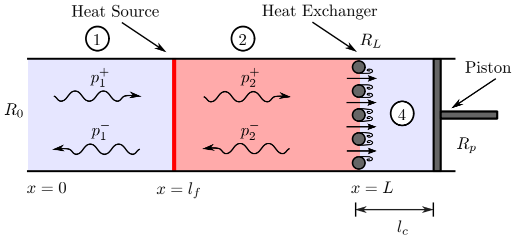
$$p_2^- e^{-ik_2(L-l_f)} = R_L p_2^+ e^{ik_2(L-l_f)}$$

Across heat source

$$p_1^+ + p_1^- = p_2^+ + p_2^-$$

$$-\frac{\left(p_1^+ - p_1^-\right)}{\bar{\rho}_1 c_1} + \frac{\left(p_2^+ - p_2^-\right)}{\bar{\rho}_2 c_2} = \frac{(\gamma-1)\hat{Q}(l_f)}{\bar{\rho}_1 c_1^2 \mathcal{S}}$$

Solution methodology
Eigenvalue problem

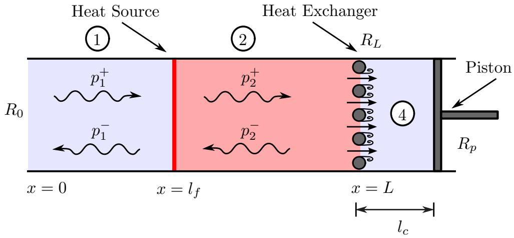


$$[Y(\Omega)]\begin{bmatrix} p_1^+ \\ p_1^- \\ p_2^+ \\ p_2^- \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\det[Y(\Omega)] = 0 \xrightarrow[\text{Raphson}]{\text{Newton}} \Omega_m = \omega_m + i\,\delta_m$$

$$\boxed{\delta_m \begin{cases} < 0 & \text{Stable} \\ > 0 & \text{Unstable} \end{cases}}$$

Solution methodology
Eigenvalue problem



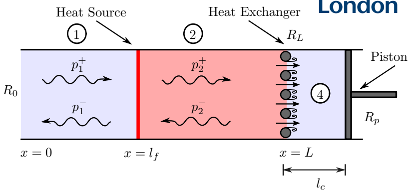
$$[Y(\Omega)] \begin{bmatrix} p_1^+ \\ p_1^- \\ p_2^+ \\ p_2^- \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\det [Y(\Omega)] = 0 \xrightarrow[\text{Raphson}]{\text{Newton}} \Omega_m = \omega_m + i\,\delta_m$$

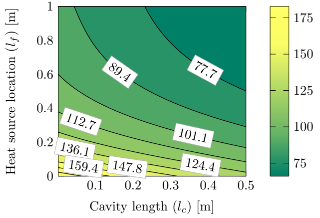
$$\boxed{\delta_m \begin{cases} < 0 & \text{Stable} \\ > 0 & \text{Unstable} \end{cases}}$$

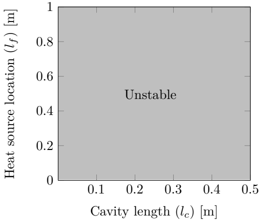
Linear stability of the first mode

Stability predictions



- l_c - l_f plane
- Time lag : $0 < \tau < T_{period}/2$
  - Unstable (Rayleigh criterion)





Surendran, A., Heckl, M. A., Hosseini, N., and Teerling, O. J., "Passive control of instabilities in combustion systems with heat exchanger", *International Journal of Spray and Combustion Dynamics*, Vol. 10, Issue 4, pp 362–379, (2018).

Surendran, A., Heckl, M. A., Hosseini, N., and Teerling, O. J., "Corrigendum - Passive control of instabilities in combustion systems with heat exchanger", *International Journal of Spray and Combustion Dynamics*, Vol. 10, Issue 4, pp 393–398, (2018).

Stability predictions

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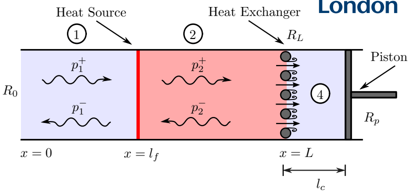
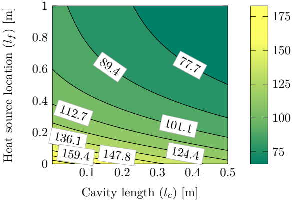
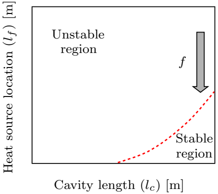
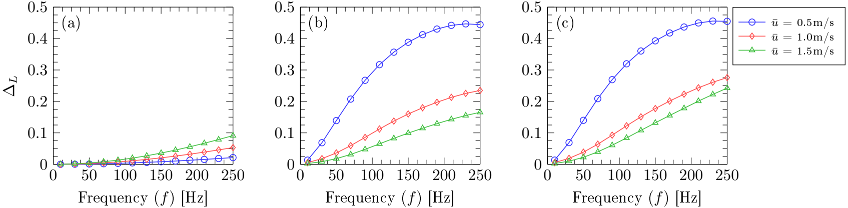
- l_c - l_f plane
- Influence of frequency









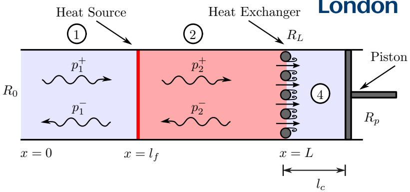
Tube row

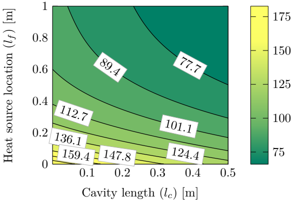
Heat Sink

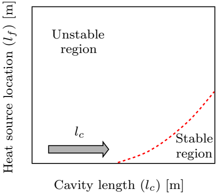
Hex - combined

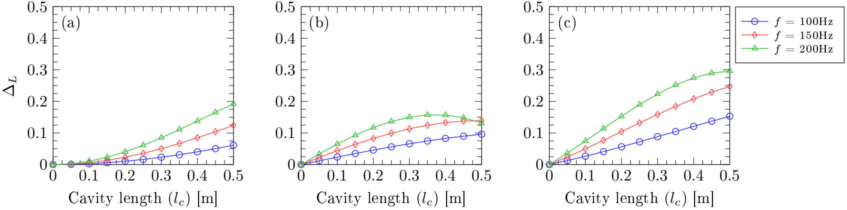
Stability predictions

- l_c - l_f plane
- Influence of cavity length









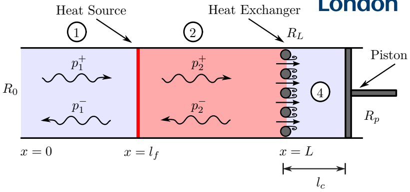
Tube row

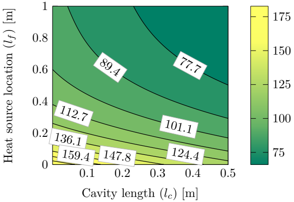
Heat Sink

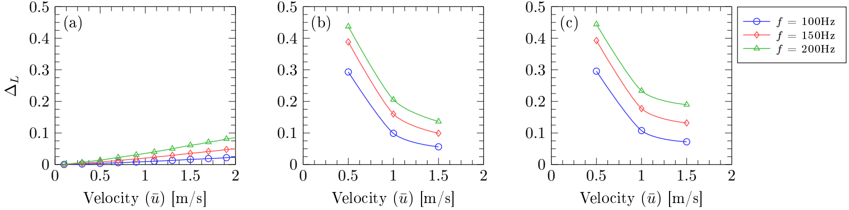
Hex - combined

Stability predictions

- l_c - l_f plane
- Influence of velocity



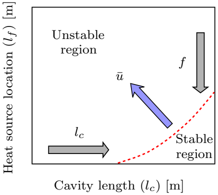




Tube row

Heat Sink

Hex - combined



Stability predictions

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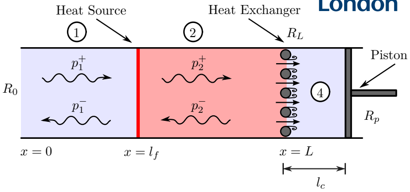
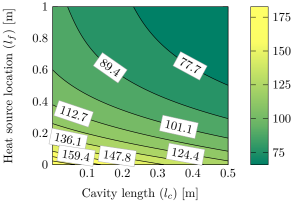
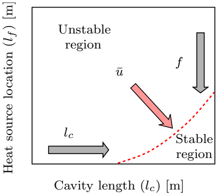
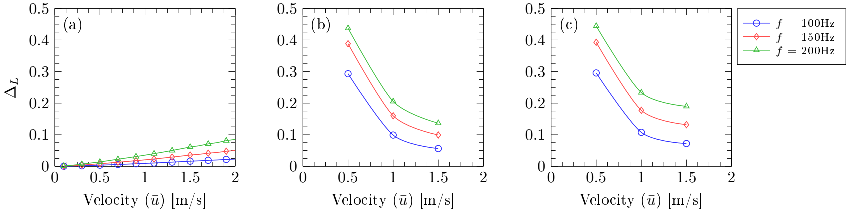
- l_c - l_f plane
- Influence of velocity









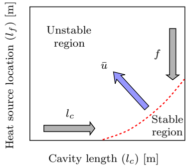
Tube row

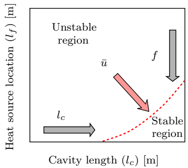
Heat Sink

Hex - combined

Stability predictions

Stability maps

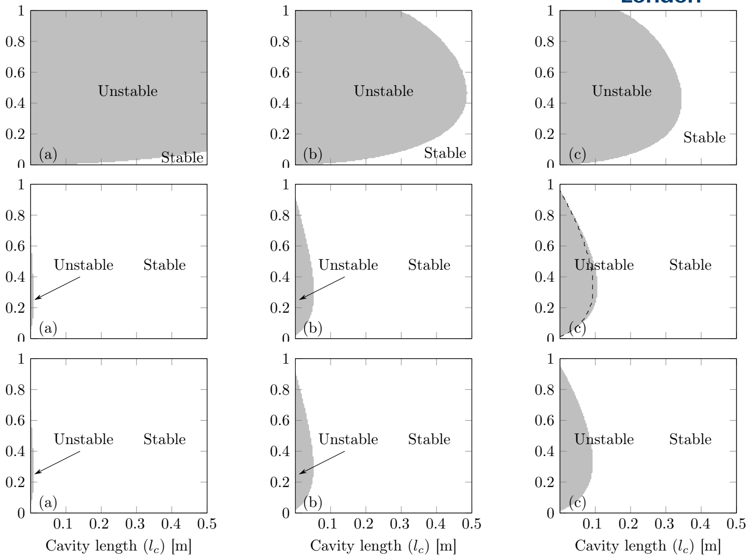




Tube row

Heat Sink

Hex - combined



Summary & Conclusions

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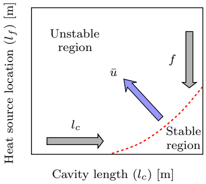
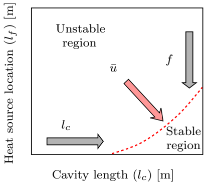
- Aim: To study the passive instability control potential of heat exchangers
- Crucial parameters
  - Cavity length and Mean velocity
  - Also depends on the dominant phenomenon
- Outlook:
  - Aimed at clean and compact combustion units with hex
  - Improved design flexibility

Tube row



Heat Sink



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Passive control of thermoacoustic instabilities by heat exchangers

Workshop on Analytical methods in thermo- and aeroacoustics

POLKA

THANK YOU

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