

T4G

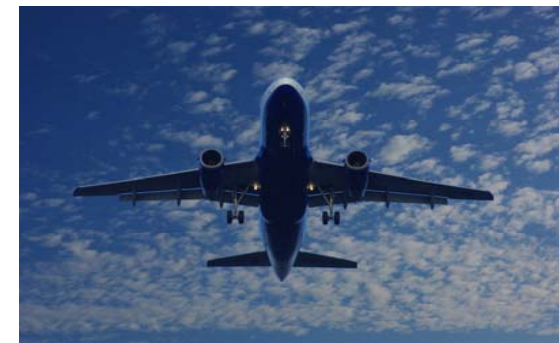
ENGINEERING

**Prediction of Thermoacoustic Instabilities in
Combustion Systems - Application to a Simplified
Model of a Domestic Boiler**

D. Tonon, Lausanne, 23/10/2018

Company Profile

- ▶ **T4G Engineering GmbH** has been founded in 2017 in Luzern, Switzerland
- ▶ T4G Engineering provides reliable and cost-effective **solutions** and **services** in:
 - ▶ Clean, Smart and Sustainable Energy and Power
 - ▶ Advanced Combustion Systems and Combustion Dynamics
 - ▶ Aeroacoustics
 - ▶ Technical Acoustics
 - ▶ Development of simulation and calculation software and tools
 - ▶ Training
- ▶ In particular, the team of T4G Engineering has cutting-edge skills and experience in **Aeroacoustic and Thermoacoustic Coupling in Energy Processes**
- ▶ T4G Engineering helps you **solving your challenges**



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Combustion Systems Development

Low pollutants emissions can be achieved with **lean-premixed combustion**, but there are **intrinsic problems** with a lean combustion zone

- ▶ Difficulties in **igniting the flame**
- ▶ High promptness to **unstable combustion** (i.e. combustion dynamics) process leading to high amplitude pressure oscillations (i.e. acoustic pulsations)
- ▶ Combustion dynamics is due to **aero-acoustic and thermo-acoustic coupling** processes
 - ▶ Aero-acoustic coupling between **flow instabilities** and acoustic pressure waves in the combustion system
 - ▶ Thermo-acoustic coupling between **heat release fluctuations** and acoustic pressure waves in the combustion system

Effect of combustor acoustic pulsations

Pressure oscillations → Structural vibrations → Pulsation Induced Damages

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Combustion Systems Development

Solution to the problem of Combustion Dynamics

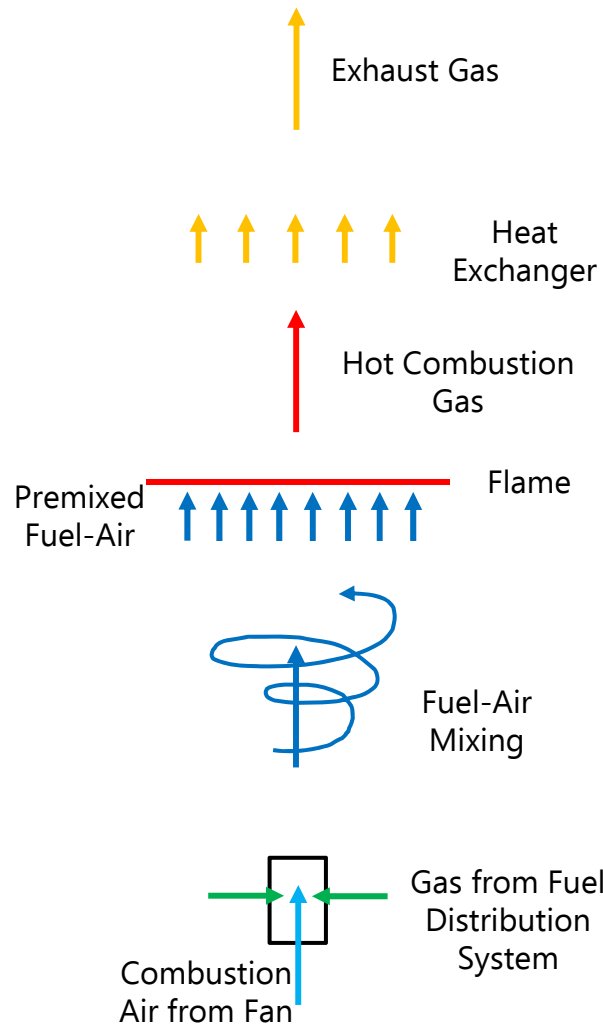
- ▶ Approach:
 - ▶ **Develop prediction tools of combustion dynamics** to aid the design of combustion systems
 - ▶ Use of **numerical and experimental tools** to find concepts to avoid high dynamics
 - ▶ **Monitor the combustion behavior** to precisely characterize the combustion dynamics of a combustion system
- ▶ Solution:
 - ▶ **Design optimization**: fuel streams/stages design, fuel line design, aeroacoustic design, thermoacoustic design
 - ▶ **Passive acoustic damping** solutions as integral part of the combustion system
 - ▶ **Active control** of pulsations/vibrations

Solution to the problem

Combustion Dynamics Modelling; Design optimization; Passive damping solutions;
Active control of pulsations

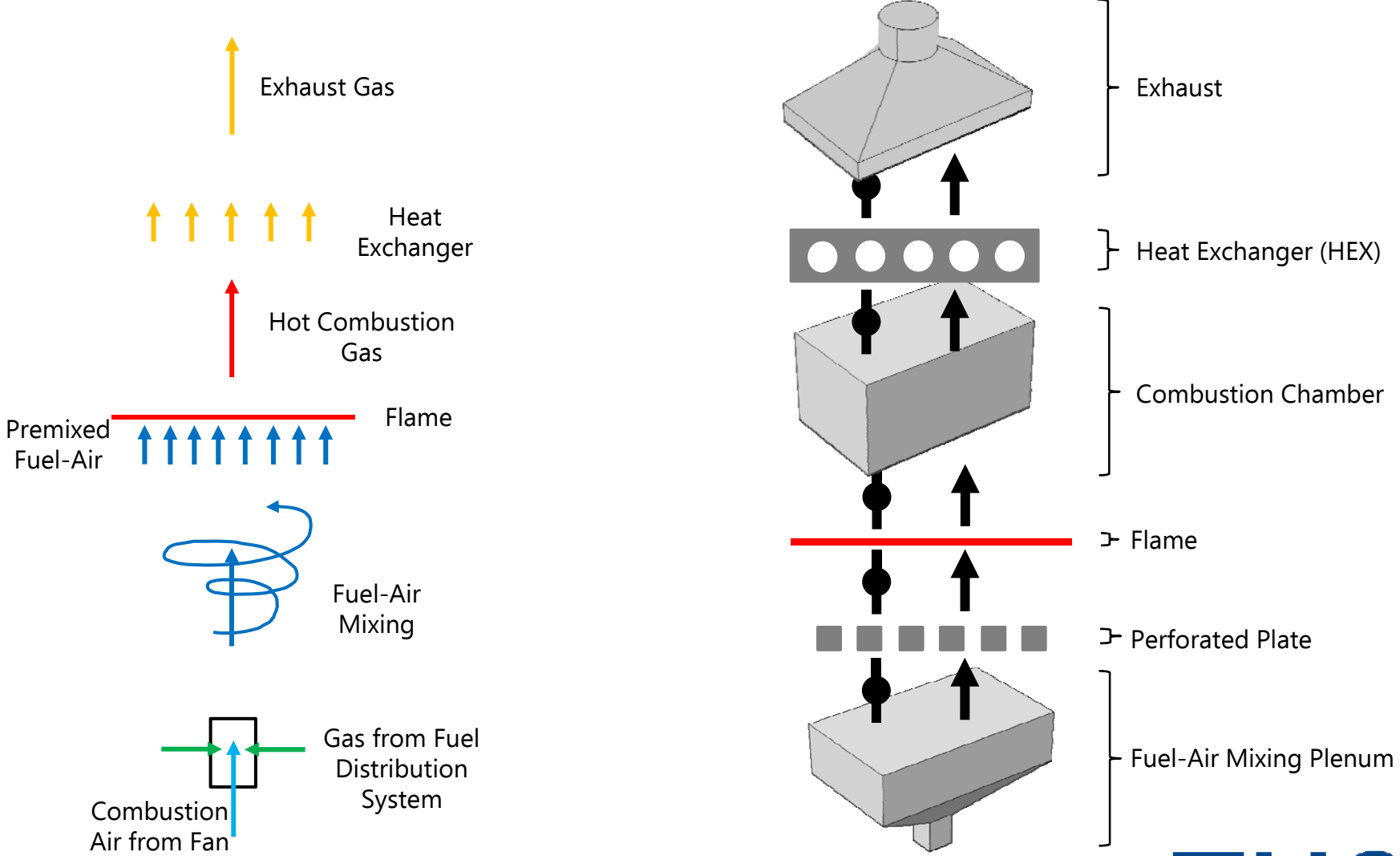
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Domestic Boiler Example



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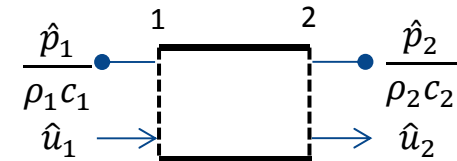
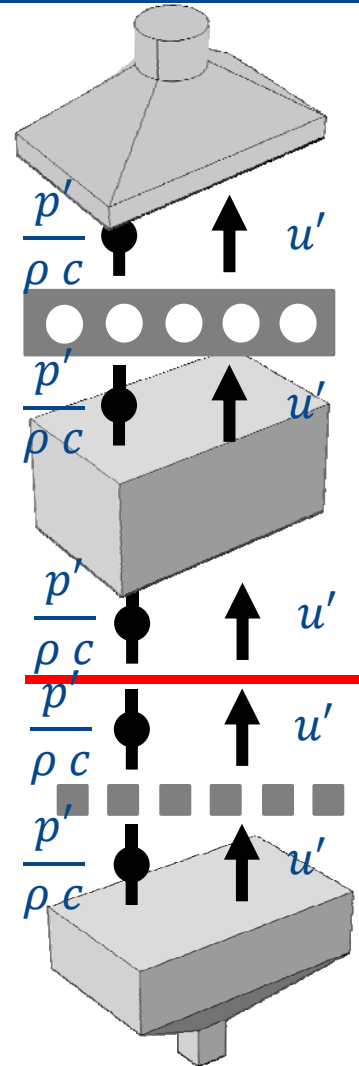
Domestic Boiler Example



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Acoustic Network Model

- ▶ Network elements connected by ports
- ▶ Acoustic compactness of flame and heat exchanger
 - ▶ Flame thickens much smaller than wavelength ($\delta_{flame} \ll \lambda$)
 - ▶ Heat exchanger tubes diameter much smaller than wavelength ($D_{hex} \ll \lambda$)
- ▶ Plane waves at the network ports
- ▶ Acoustic wave propagation in network elements:
 - ▶ **Analytical models:** Perforated Plate, Flame and Heat Exchanger
 - ▶ **FEM model (COMSOL):** Fuel-Air Mixing Plenum, Combustion Chamber, Exhaust



Transfer Matrix

$$\begin{bmatrix} \frac{p'}{\rho c} \\ u' \end{bmatrix}_2 = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \begin{bmatrix} \frac{p'}{\rho c} \\ u' \end{bmatrix}_1$$

Analytical and/or FEM

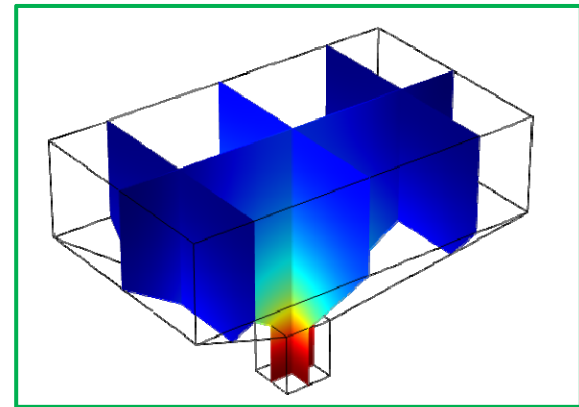
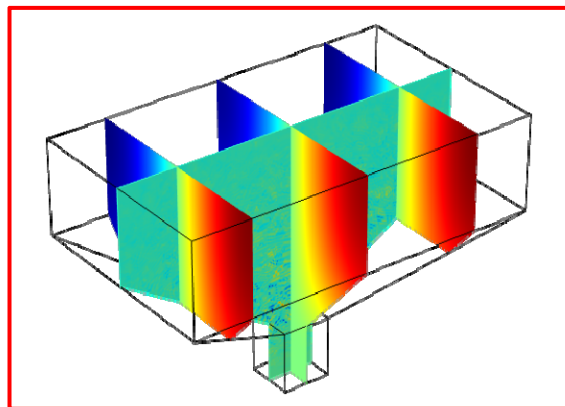
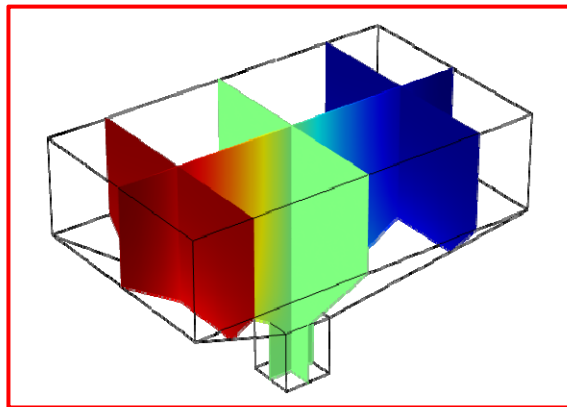
FEM Calculated Network Element Transfer Matrix

- ▶ Numerical evaluation of **acoustic transfer matrix** of network elements with **COMSOL Multiphysics**
 - ▶ *Pressure Acoustics, Frequency Domain (acpr)* physics interface with *Frequency Domain* study
 - ▶ *Pressure Acoustics, Frequency Domain (acpr)* physics interface with *Eigenfrequency* study
- ▶ Workflow to evaluate network elements transfer matrices with COMSOL Multiphysics:
 - ▶ Import geometry (CAD Import Module) in COMSOL Multiphysics
 - ▶ Divide the geometry in domains (partition objects) and save each domain (.stl binary)
 - ▶ Calculate the eigenfrequencies for each domain
 - ▶ Export mode shape at domain boundaries (corresponding to network ports) for each eigenfrequency; normalization factor of the modes; speed of sound and density in the domain
 - ▶ Take into account only modes with plane waves at the network ports
- ▶ Import COMSOL simulation results in **T4G's Acoustic Network Model**

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Selection of modes with plane waves at the network ports

- ▶ Only modes corresponding to plane waves at the network ports should be taken into account
 - ▶ Manual selection by visual inspection
 - ▶ Automated selection in COMSOL by means of *Volume Integration*, *Volume Average*, *Surface Average*, *Surface Minimum* and *Surface Maximum* of acoustic pressure



T4G's Acoustic Network Model

The screenshot displays the T4G Acoustic Network Model software interface. The main workspace shows a network diagram with various components connected in a series. The components are labeled as follows: CE (Closed Inlet), F (FEM), D (Duct), HE (Heat Exchanger), F (FEM), CF (Closed Inlet), D (Duct), AJ (Area Jump), D (Duct), F (FEM), AJ (Area Jump), and CI (Closed Inlet). The diagram is set against a blue and white checkerboard background.

The interface includes a menu bar (File, Edit, View, Tools, Settings, Help), a View Browser on the left, a Block Library on the left, and a Network Inspector and Property Editor on the right.

Block Library:

- AI Anechoic Inlet
- CI Closed Inlet
- II Impedance Inlet
- OI Open Inlet
- Connections
- AJ Area Jump
- IC Impedance Change
- SB Swirl Burner
- FEM
- F FEM
- Sources

Network Inspector:

Block	Type
Ⓜ Closed Inlet #1	Closed Inlet
Ⓜ FEM #1	FEM
Ⓜ Area Jump #1	Area Jump
Ⓜ Duct #1	Duct
Ⓜ Area Jump #2	Area Jump
Ⓜ FEM #2	FEM

Property Editor:

General

Type: **Heat Exchanger**
Name: Heat Exchanger #1

Acoustic Medium Properties

Upstream impedance: 413.211
Downstream impedance: 413.211
Impedance ratio: 1.000
Temperature ratio: 1.000

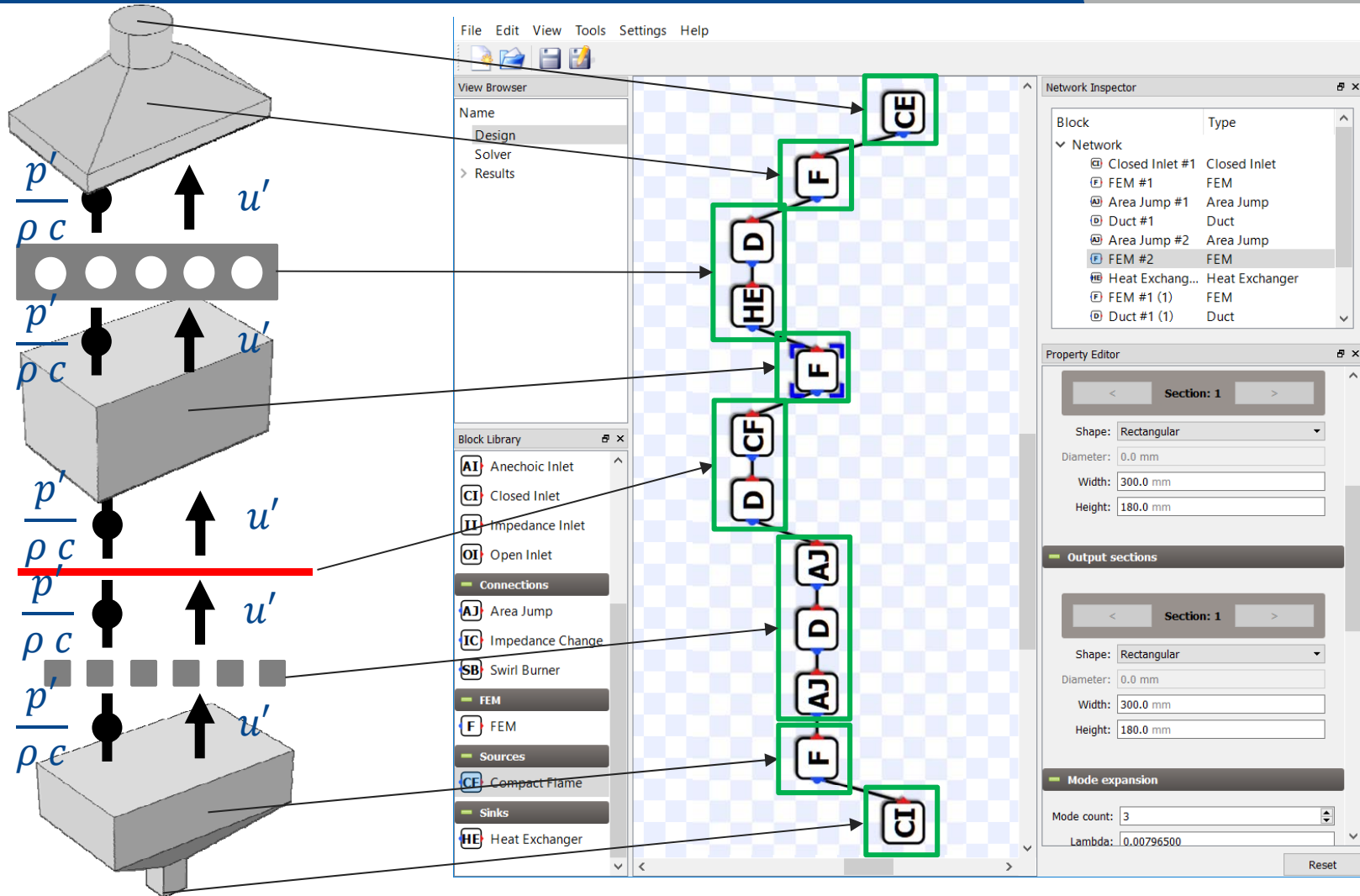
Flow Properties

Upstream velocity: 0.000
Upstream Mach: 0.000

Reset

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T4G's Acoustic Network Model



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T4G's Acoustic Network Model

The screenshot shows the COMSOL Multiphysics interface with an acoustic network model. The main window displays a vertical chain of components: Closed Inlet (CI), FEM, Area Jump (AJ), Duct (D), Area Jump (AJ), FEM, Heat Exchanger (HE), Duct (D), FEM, Closed End (CE). Three FEM components are highlighted with red boxes. A red arrow points from the middle FEM component to a detailed Property Editor window. The Property Editor shows coefficients for the selected FEM block.

Network Inspector

Block	Type
Network	
Closed Inlet #1	Closed Inlet
FEM #1	FEM
Area Jump #1	Area Jump
Duct #1	Duct
Area Jump #2	Area Jump
FEM #2	FEM
Heat Exchang...	Heat Exchanger
FEM #1 (1)	FEM
Duct #1 (1)	Duct

Property Editor - General

Type: FEM
Name: FEM #1

Ports

Input ports: 1
Output ports: 1

Acoustic Medium Properties

Fluid: Normal Air

Input sections

Section: 1

Shape: Rectangular
Diameter: 0.0 mm
Width: 40.0 mm
Height: 40.0 mm

Property Editor - Coefficients

ω coefficients

#	Re(ω)	Im(ω)
1	0.003476652205...	0.0089608288573...
2	6380.000731365...	3.2054805787846...

Input Ψ coefficients

Section: 1

#	Re(Ψ)	Im(Ψ)
1	0.999999999999...	9.0794663144...
2	6.102899755382...	-4.566905770...

Output Ψ coefficients

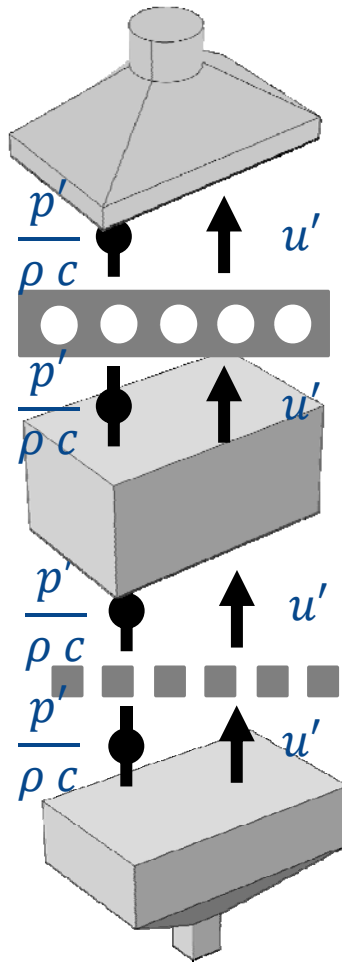
Section: 1

#	Re(Ψ)	Im(Ψ)
1	1.000000000000...	-7.877296120...
2	-0.55011585086...	4.1959773860...

COMSOL Integration

Import modes...
Reset

Validation Case with no acoustic sources or losses



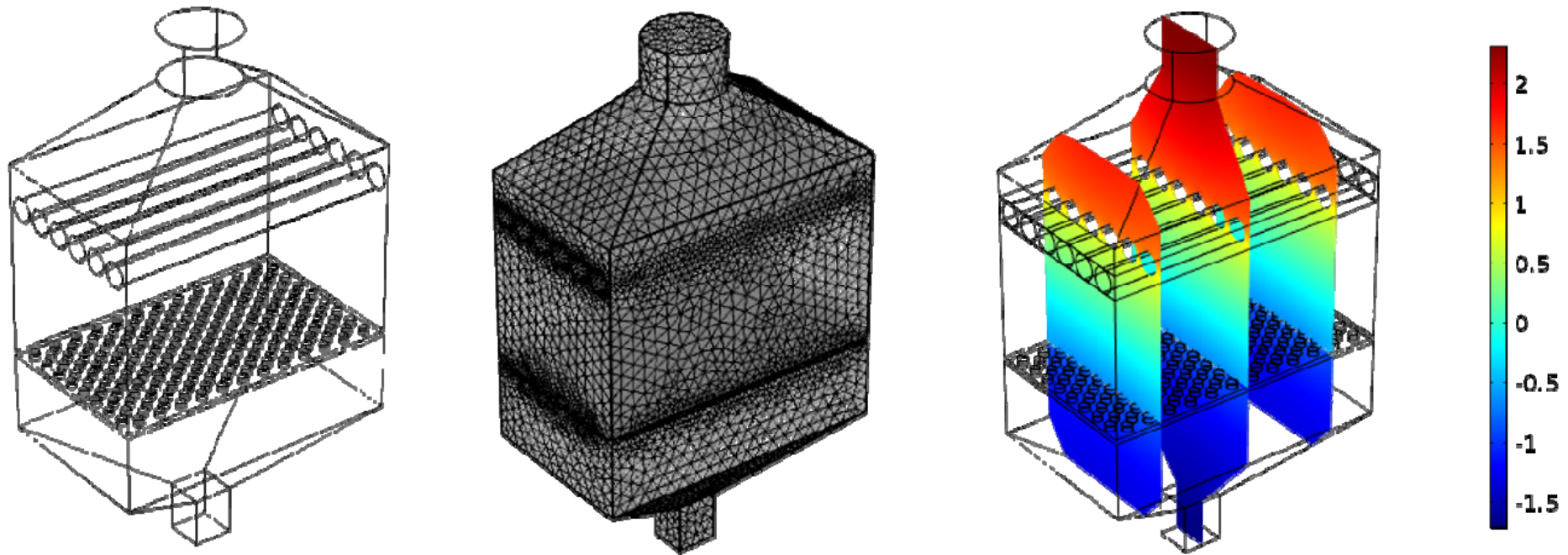
The screenshot shows the COMSOL Multiphysics software interface. The main window displays a vertical network diagram with the following components from top to bottom: Closed Inlet (CI), FEM (F), Area Jump (AJ), Duct (D), Heat Exchanger (HE), FEM (F), Area Jump (AJ), Duct (D), FEM (F), and Closed Inlet (CE). The Network Inspector panel on the right shows the following components:

Block	Type
Closed Inlet #1	Closed Inlet
FEM #1	FEM
Area Jump #1	Area Jump
Duct #1	Duct
Area Jump #2	Area Jump
FEM #2	FEM
Heat Exchang...	Heat Exchanger
FEM #1 (1)	FEM
Duct #1 (1)	Duct

The Property Editor panel on the right shows the properties for the selected FEM block:

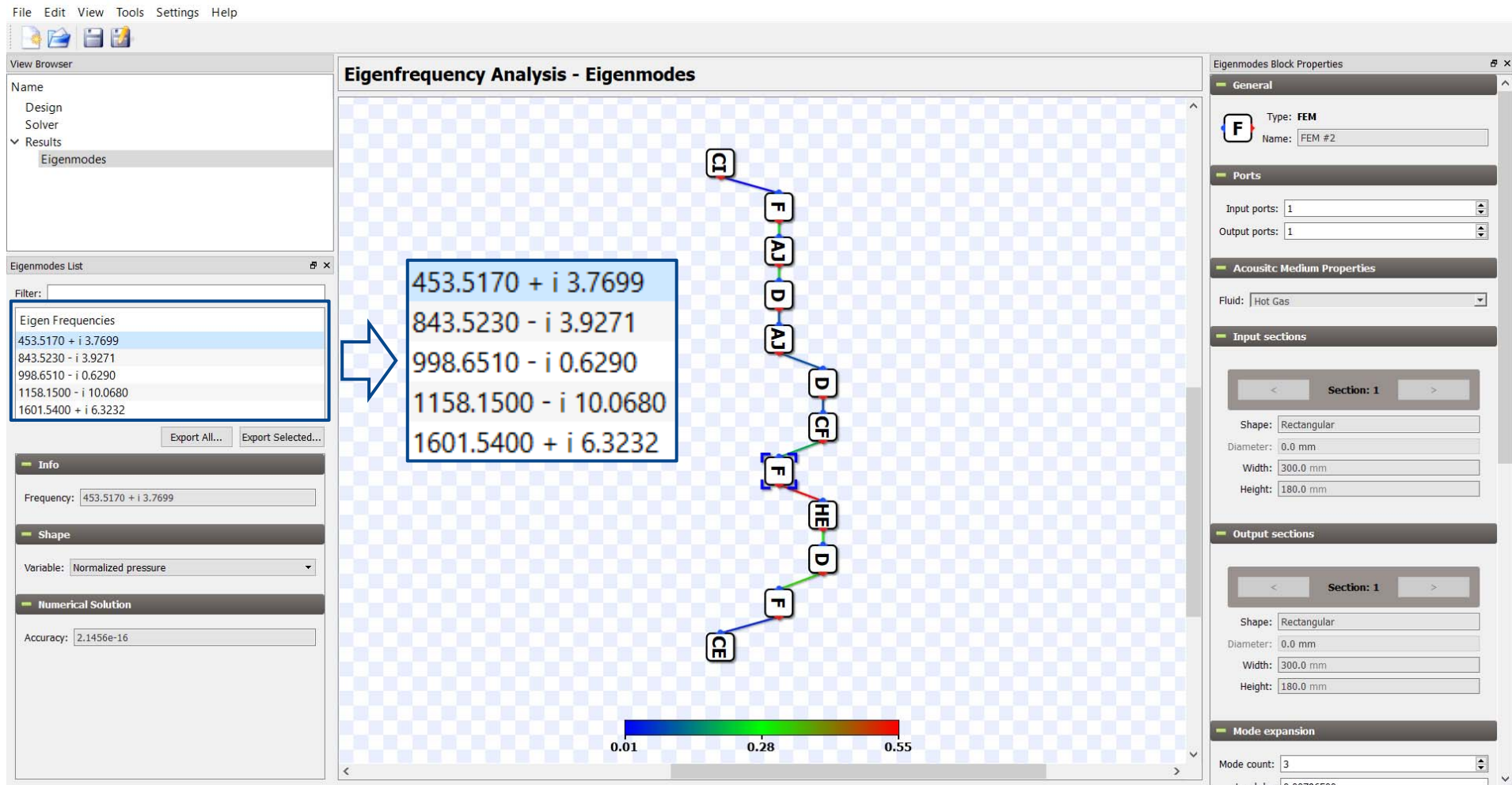
- Type: FEM
- Name: FEM #1
- Input ports: 1
- Output ports: 1
- Fluid: Normal Air
- Input sections: Section 1
- Shape: Rectangular
- Diameter: 0.0 mm
- Width: 40.0 mm
- Height: 40.0 mm

Validation Case with no acoustic sources or losses



- ▶ Comparison of Network Model and COMSOL simulation of the full domain without acoustic sources or losses
 - ▶ *Pressure Acoustics, Frequency Domain (acpr)* physics interface with *Eigenfrequency* study
 - ▶ Validation (i.e. cross-check) of the network model results

Analysis of Thermoacoustic Stability of a Simplified Model of a Domestic Boiler



Thank you for
listening