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Design Modification and Simulation of Thermo Acoustic Refrigerator

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ABSTRACT

Thermo acoustic have been known for over years but the use of this phenomenon to develop engines and pumps is fairly recent. Thermo acoustic refrigeration is one such phenomenon that uses high intensity sound waves in a pressurized gas tube to pump heat from one place to other to produce refrigeration effect. In this type of refrigeration all sorts of conventional refrigerants are eliminated and sound waves take their place. All we need is a loud speaker and an acoustically insulated tube. Also this system completely eliminates the need for lubricants and results in 40% less energy consumption. Thermo acoustic heat engines have the advantage of operating with inert gases and with little or no moving parts, making them highly efficient ideal candidate for environmentally-safe refrigeration with almost zero maintenance cost. Now we will look into a thermo acoustic refrigerator, its principle and functions.

In the field of thermo acoustic energy conversion, the application of numerical analysis techniques, specifically computational fluid dynamics (CFD) simulations, have gained ground in recent years. Previous efforts have focused on single thermo acoustic couples that were subjected to the thermo acoustic effect through an oscillatory boundary condition. CFD simulations of an entire thermo acoustic device are computationally expensive and few examples exist. The present work presents an extension of a simulation of a whole thermo acoustic engine that also includes a refrigeration stack. Through interaction of thermally generated sound waves, cooling of the working gas in this stack is demonstrated

INTRODUCTION

Nowadays, the destruction of the ozone layer by chlorofluorocarbons (CFCs) is increasing at an alarming rate. Generally CFCs are used in various applications, such as plastic insulation for building and appliance, solvent for cleaning and as refrigerants in domestic and industrial refrigeration and air-conditioning. In the last two decades, international regulations have been set to ultimately diminish the use of CFCs by developing alternative method that is environmentally benign. Lately, the enhanced use of renewable energies has become a major concern for the world energy policy to meet the target of sustainable development and focusing on decrease of global warming. One of green technology known as thermo acoustic technology can play a significant role in this context because of its advantages over conventional technologies. Thermo acoustic engines are sound heat energy conversion devices which operate with no moving components, use no-polluting working gases, can be powered by low-grade energetic inputs (waste heat, solar energy, etc.) and join with simple/reliable construction to low fabrication costs.

Thermo Acoustic Refrigerator

Thermo acoustic Refrigerator pumps heat from low temperature to high temperature region using energy of sound waves. The source of acoustic energy is called “acoustic driver’’ which can be a loud speaker. The acoustic driver emits sound waves in a temperature region using energy of sound waves. Schematic of thermo acoustic refrigerator pumps heat from low temperature to high long hollow tube filled with gas at high pressure. This long hollow tube is called ‘resonance tube’ or simply ‘resonator’. The frequency of the driver and the length of resonator are chosen so as to get a standing pressure wave in the resonator. A solid porous material like a stack of solid plates is kept in the path of sound waves in the resonator due to thermo acoustic effect, Heat starts to flow from one end of stack to the other. One end starts to heat up while other starts to cool down. By controlling temperature of hot side of stack (by removing heat by means of a heat exchanger), the cold end of stack can be made to cool down to lower and lower temperatures. A refrigeration load can then be applied at the cold end by means of a heat exchanger. Thermo acoustics' is a 'green' and a new technology. The working medium of TAR is an inert gas. There is no need of conventional refrigerants like CFCs that pose hazards to the environment. TAR has minimal moving parts and no valves to regulate fluid flow. Once designed efficiently, they require very less maintenance. Because of use of acoustic power, the pressure difference between which a TAR operates is very small. This means TAR can find immense application where noise or vibration can't be tolerated. Because this, they have no close tolerances and can be fabricated from easily available materials.

Thermo Acoustic Effect

Thermo acoustics combines The branches of acoustics and thermodynamics together to move heat by using sound. While acoustics is primarily concerned with the macroscopic effects of sound transfer like coupled pressure and motion oscillations, thermo acoustics focuses on the microscopic temperature oscillations that accompany these pressure changes. Thermo acoustics takes advantage of these pressure oscillations to move heat on a macroscopic level. This results in a large temperature difference between the hot and cold sides of the device and causes refrigeration. The most important piece of a Thermo acoustic device is the stack. The stack consists of a large number of closely spaced surfaces that are aligned parallel to the resonator tube. The purpose of the stack is to provide a medium for heat transfer as the sound wave oscillates through the resonator tube. A functional cross section of the stack we used. In typical standing wave devices, the temperature differences occur over too small of an area to be noticeable. In a usual resonator tube, heat transfer occurs between the walls of cylinder and the gas.

Thermo Acoustic Oscillations

Thermo acoustics, in its most general sense, is the study of interaction between heat and sound. The term has lately become slighter in its meaning so that it refers mostly to the field as functional to heat engines and refrigerators. Thermo acoustics is by no means a new field, but many of the major developments have happened fairly recently. As with many fields, thermo acoustics began as an anecdotal curiosity, but after a fairly long period with little development, a resurgence of attention has held to many improvements in theory and experimentally methods. Evidence of thermo acoustic occurrences dates back periods to when glass blowers first noticed that a hot bulb at the end of a cool tube produced tonal sound. According to Putnam and Dennis, studies in thermo acousticsbeganasearlyas1777, when Byron Higgins placed a hydrogen flame in a large pipe open at both ends, producing sound. Higgins noted that the acoustic oscillations produced by the tube depended upon the position of the flame.

Basic Functioning

A thermo acoustic engine changes heat from a high temperature region into acoustic energy while rejecting waste heat to a low temperature region. In case of thermo acoustic, by using sound energy to pump heat from a low temperature region (source) to high temperature region (sink). The performance of these devices can be increased by using the inert gases as their thermodynamic working fluids.

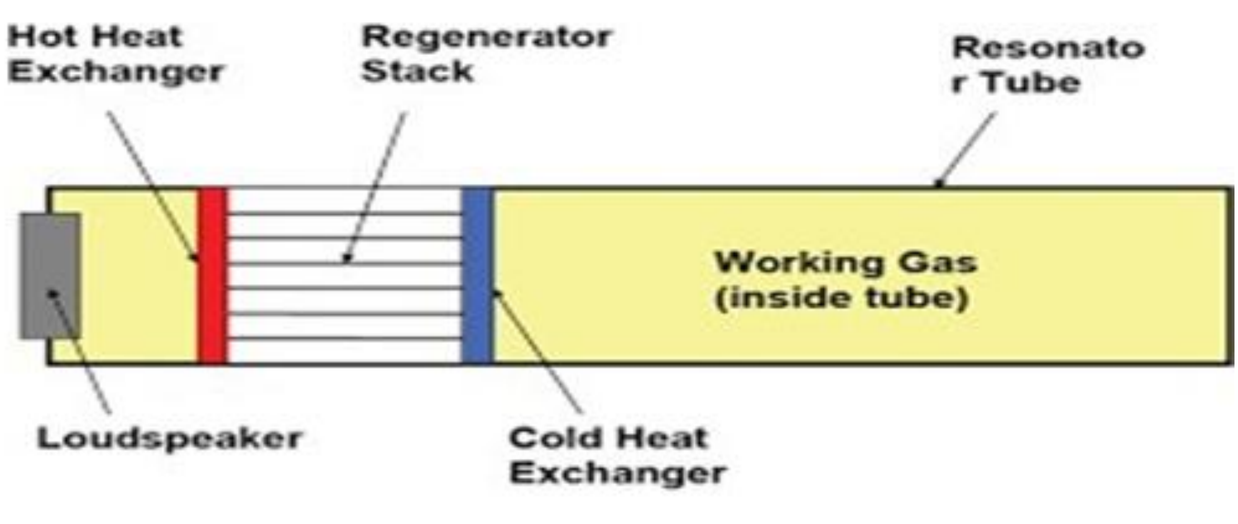


Fig1.1: Block Diagram of Thermo Acoustic Refrigeration

LITERATURE REVIEW

Gifford, Brandon, **T [1]** conducted the first experiment based on acoustic oscillations generated by heat. In this experiment he observed that when the hydrogen flame was placed at correct position within the organ pipe acoustic oscillations would take place. From this he concluded that heat energy can be converting into sound waves.

Rott, **B. [2]** gave the mathematical equations on thermo acoustic. In his papers he derives and solved linear equations based on thermo acoustic theory. His theories are the 7 foundation by which most of the parameters and calculations are considered while making thermo acoustic models. The model made by him was linear model.

Holfer [3] founded that when the cross section area of the stack also require diameter tube on quarter wavelength resonator, the surface area of the resonator can be reduced past the stack by using small diameter tube, this helps to reduces the losses that are proportional to the surface area of the resonator. He observed that as the diameter of second tube is shrunk in the ratio to the diameter of first tube the thermal losses with in resonator increases monotonically and the viscous losses have a steep drop and then remains steady.

WetzelM, and Herman C. [4] He makes an attempt in optimization of design of thermo acoustic refrigerators. He also developed algorithm for optimization. He noted that optimization of heat exchanger inside thermo acoustic refrigerator is an issue also optimizing of driver or speaker is another issue other than heat exchanger. His conclusion was theoretically efficient thermo acoustic refrigerators as compared to traditional refrigerators are possible if hang ups such better heat exchangers can be overcome.

Tijani [5] designed of stack in such a way as it must meet the cooling requirements by making choices for average pressure, dynamic pressure, frequency, and working gas. Resonator is designed by keep in mind the natural frequency and minimizing loss at the wall. The heat exchangers are designed in an oscillatory flow with zero mean displacement. Finally he performed a study on individual components of thermo acoustic refrigerator. Results shows that the COP achieved relative to Carnot COP was 11% , this was done using helium gas.

Gifford and Brandon [3] performed the experiment using low frequency pulse inside the resonator. Results are observed that cooling takes place inside the resonator.

Nor Atiqah Zolpakar, Normah Mohd-Ghazal. Discussed the initial investigation of the optimization of the thermo acoustic refrigerator stack parameters using a multi-objective genetic algorithm. The desired outputs, the maximization of the cooling load and the minimization of the acoustic power at the stack, are obtained with the parameters to be optimized set within some range of values. The stack length and center position are then optimized simultaneously.

Sondhauss [6] conducted the related experiment as the Higgins; He took a resonator with a glass ball attached to it and heating the junction of ball and the resonator. He observed that when the flame is kept near the junction the system first heat up or warm up and then the oscillation of the acoustic has been produce. But the solid review does not occur from this experiment. It was just an extension of Higgins setup.

Gardnerand Swift [7] discussed use of entrance of medium in thermo acoustic refrigerators. Experiments show that maximum efficiency takes place when the impedance of the acoustic is purely real. He observed that many refrigerators have large compliance tank at the end of resonator due to which it causes negative imaginary component of impedance, to introduce positive imaginary part to impedance interference can be used and make impedance purely real again.

EXPERIMENTAL SETUP

Principle

Thermo acoustic systems operate by using sound waves and a non-flammable mixture of inert gas (helium, argon, air) or a mixture of gases in a resonator to produce cooling. As the gas oscillates back and forth; it creates a temperature difference along the length of the stack.

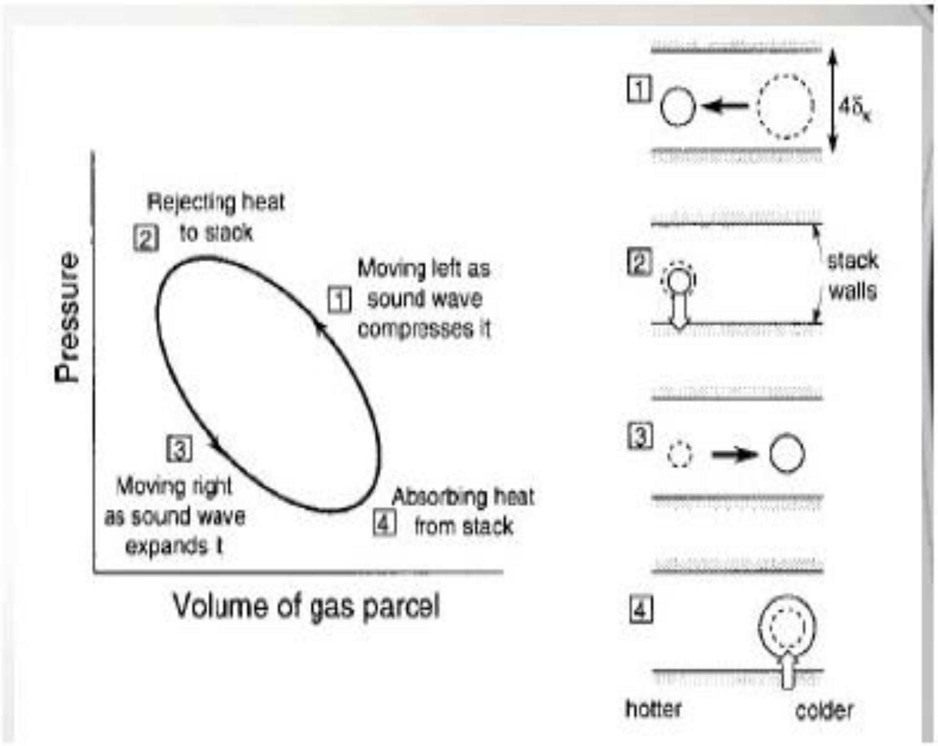


Fig 3.1: Working Principle

Acoustic Driver

A thermo acoustic cooling device requires an acoustic driver attached to one end of the resonator, in order to create an acoustic standing wave in the gas at the fundamental resonant frequency of the resonator. The acoustic driver converts electric power of 15watts and impedance of 8Ω at the operating frequency (450Hz) is used as the acoustic driver.

Fig3.2: Speaker

Stack

The most important component of a thermo acoustic device is the stack inside which, the thermo a caustic phenomenon occurs. Thus, the characteristics of the stack have a signify cant imp Acton the performance of the thermo caustic device. The stacked material should have good heat capacity but low thermal conductivity.

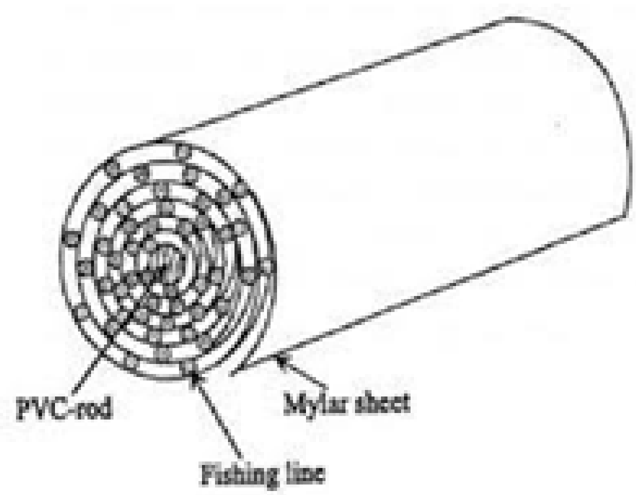


Fig3.3: Stack

Stack Construction
The stack spiral was made using 35 mm camera film. To enforce the spacing between the layers, nylon fishing line with a diameter of 0.35 mm was glued across the film . After the glue dried the film was rolled up and glued at the very end. The diameter of the rolled up stack is 0.875" (2.22 cm) and its height is 1.38 in (3.5 cm). The strip of film before being rolled up is approximately 20 in

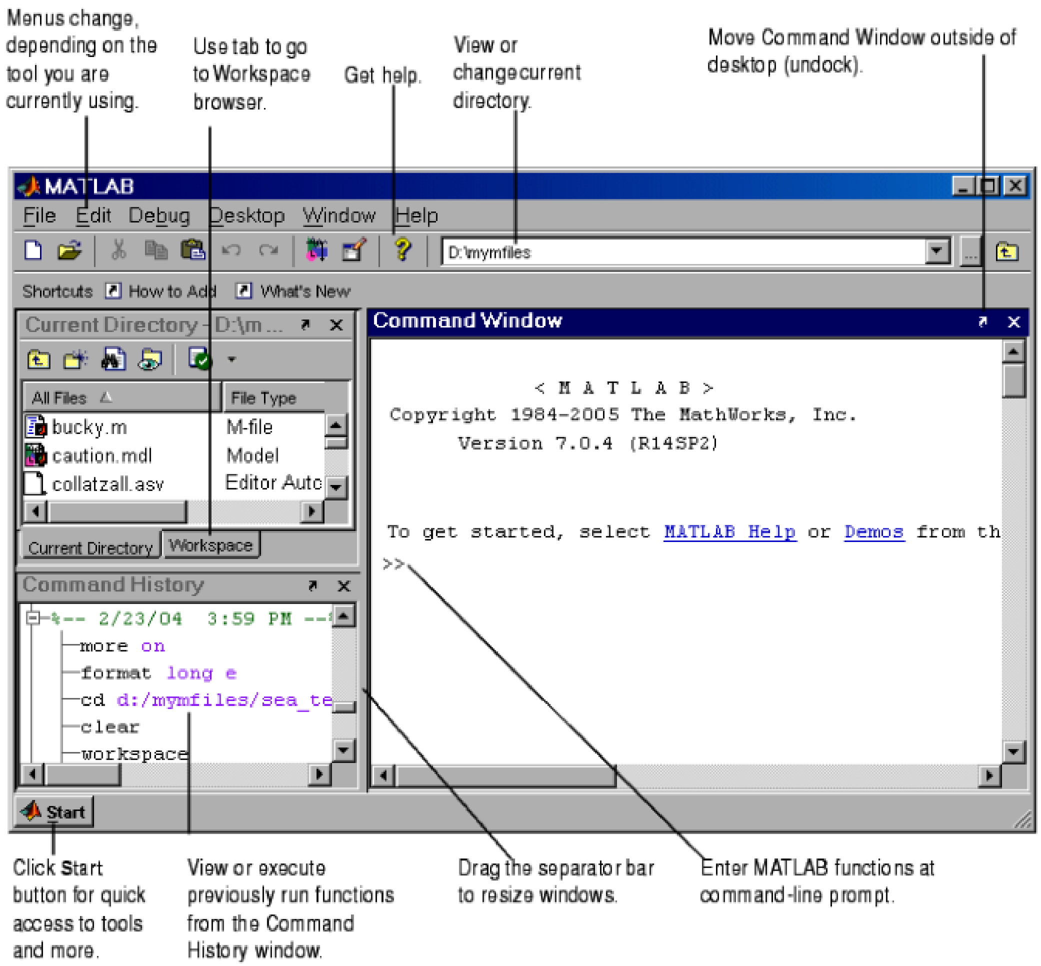
Resonator Construction
The resonator was constructed from acrylic tubing with a 1" (2.54 cm) outer diameter and0.875"(2.22cm)inner diameter. An aluminum cap was machined to fit into the end of the tube. An acrylic base plate was used to create an interface between the speaker and the resonator, which was fastened to the resonator tube using an adhesive. Holes were drilled in the base plate which matched the speaker mounting holes for easy attachment to the speaker. The resonator is pictured in0.8 cm).

Working Gas
The choice of working gas is as important as the choice of operating parameters. The working gas should have a high sound speed so that the energy density of acoustic field for a given operating frequency is high. This helps to reduce the system size for a certain cooling requirement. Simulation Procedure in Mat lab

Introduction to Mat lab:
The name MATLAB stands for Matrix Laboratory. MATLAB was written originally to provide easy access to matrix software developed by the LINPACK (linear system package) and EISPACK (Eigen system package) projects. MATLAB [1] is a high-performance language for technical computing. It integrates computation, visualization, and programming environment.

Starting Mat lab:
After logging into your account, you can enter MATLAB by double-clicking on the MATLAB shortcut icon (MATLAB 7.0.4) on your Windows desktop. When you start MATLAB, a special window called the MATLAB desktop appears. The desktop is a window that contains other windows. The major tools within or accessible from the desktop are:

- The Command Window
- The Command History
- The Workspace
- The Current Directory
- The Help Browser
- The Start button



The Graphical Interface to the MATLAB Workspace

When MATLAB is started for the first time, the screen looks like the one that shown in the Figure 1.1. This illustration also shows the default configuration of the MATLAB desktop. You can customize the arrangement of tools and documents to suit your needs. Now, we are interested in doing some simple calculations. We will assume that you have sufficient understanding of your computer under which MATLAB is being run.

You are now faced with the MATLAB desktop on your computer, which contains the prompt (>>) in the Command Window. Usually, there are 2 types of prompt:

>> For full version

EDU> for educational version

Note: To simplify the notation, we will use this prompt, >>, as a standard prompt sign, though our MATLAB version is for educational purpose.

Installation of Pc-Tas:

General:

PC-TAS (Phase Change Thermo Acoustic Simulator) is software for simulation of 1D acoustics, thermo acoustics and phase change thermoacoustics. This guide includes instructions for operation of PC-TAS and a full mathematical description of all the models and equations employed. Resources including installation files, video tutorials, code samples and example files are available at https://wetlab.net.technion.ac.il/pc-tas/

Installation:

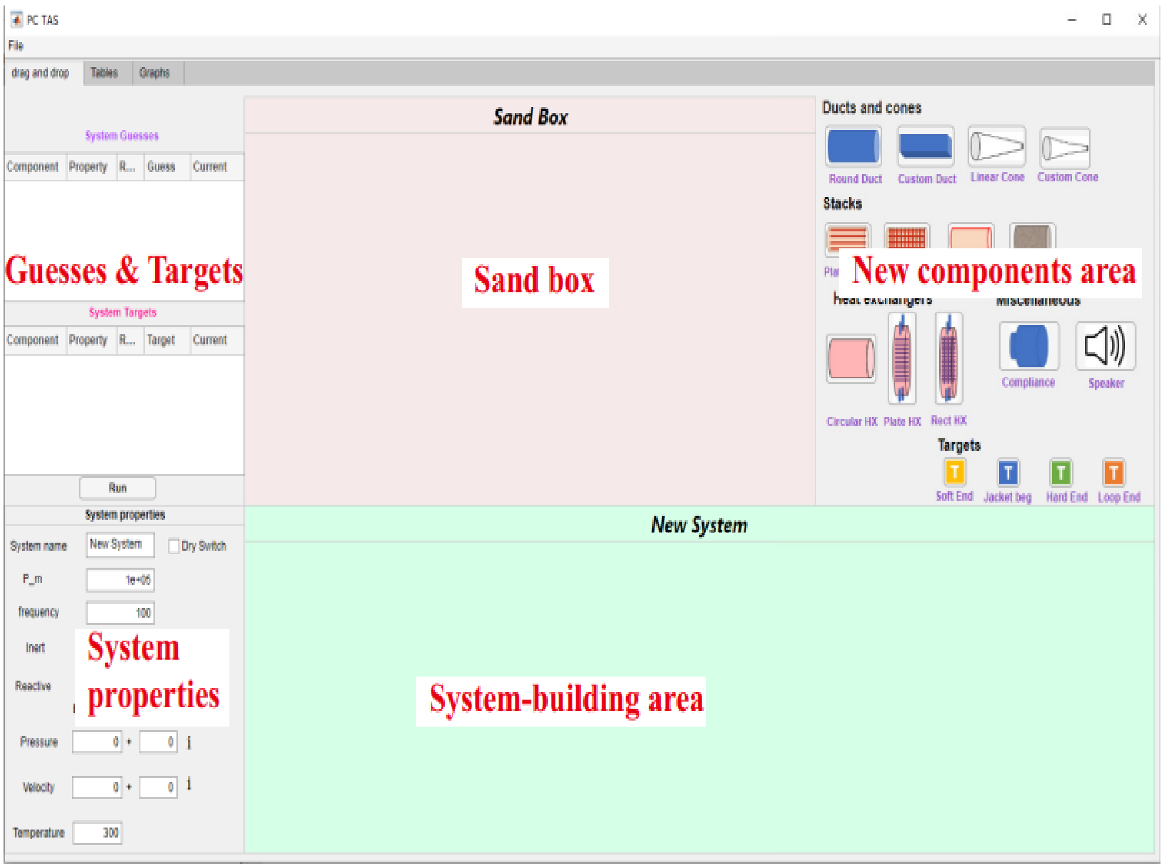
PC-TAS can be installed as a MATLAB application, requiring MATLAB 2020b or newer versions. This can be done by executing the .mlappinstall file with MATLAB running. PC-TAS can also be installed as a stand-alone desktop application on Windows 10 (tested and recommended), as well as on earlier versions of Windows, Linux and Mac (not tested). The stand-alone installation can be done by executing the .exe file, which will also install MATLAB runtime (a free software) automatically. Therefore, we recommend uninstalling all existing versions of MATLAB runtime before installation.

Interface:

We built an user-friendly interface for the simulation of Thermo acoustic systems. It consists of three tabs: Drag and drop, Tables and Graphs.

Drag & Drop:

This interface allows the users to drag a component from the new component list in the right top corner, and drop it in the system-building area to build a Thermo acoustic system. Guess & Targets in the left top corner lists all the values of guesses and targets. In the area of system properties, all the global parameters (e.g., frequency, mean pressure, working fluid, dry or wet, etc.) and the values of pressure, volumetric velocity and temperature and the beginning of the model, can be set here. The sand Box is used to investigate components separately, without insertion into the system. The component and its different properties can be reviewed, while system convergence is maintained.



Interface of Drag and Drop

A single component can be investigated and changed by right-clicking and then clicking "change properties".

Tables

The different system parameters, including both input parameters (length, diameter, area, etc.) and output parameters (pressure amplitude, volumetric velocity amplitude, temperature, etc.), are all listed in the "Tables" tab with a convenient interface, much like that in the software DELTAEC (Ward et al., 2008).

Graphs

After the system is run, the distributions of pressure, volumetric velocity, temperature, acoustic power, total power and mass flux are plotted and displayed here automatically.

Building a System:

We provide various components that cover the requirement for building most Thermo acoustic systems. A system can be built by the following simple steps:

1. Drag the first component of your system from the component list and drop it into the system-building area. You need to set the name and parameters of the component (listed as "Initial Parameters Definition") when you drop it.
2. Repeat the first step to drag and drop all the components of your system one by one, until the full system is assembled.
3. Set the begin parameters in the left bottom corner.
4. Set guesses and targets in the left top corner. Note that the numbers of guesses and targets must be identical.
5. Set initial values to all the guesses. Note that it is very important to give relatively precise initial values, otherwise the algorithm may diverge.
6. Press "Run" button. The users are suggested to start with the examples we offered.

Save and Load a Model

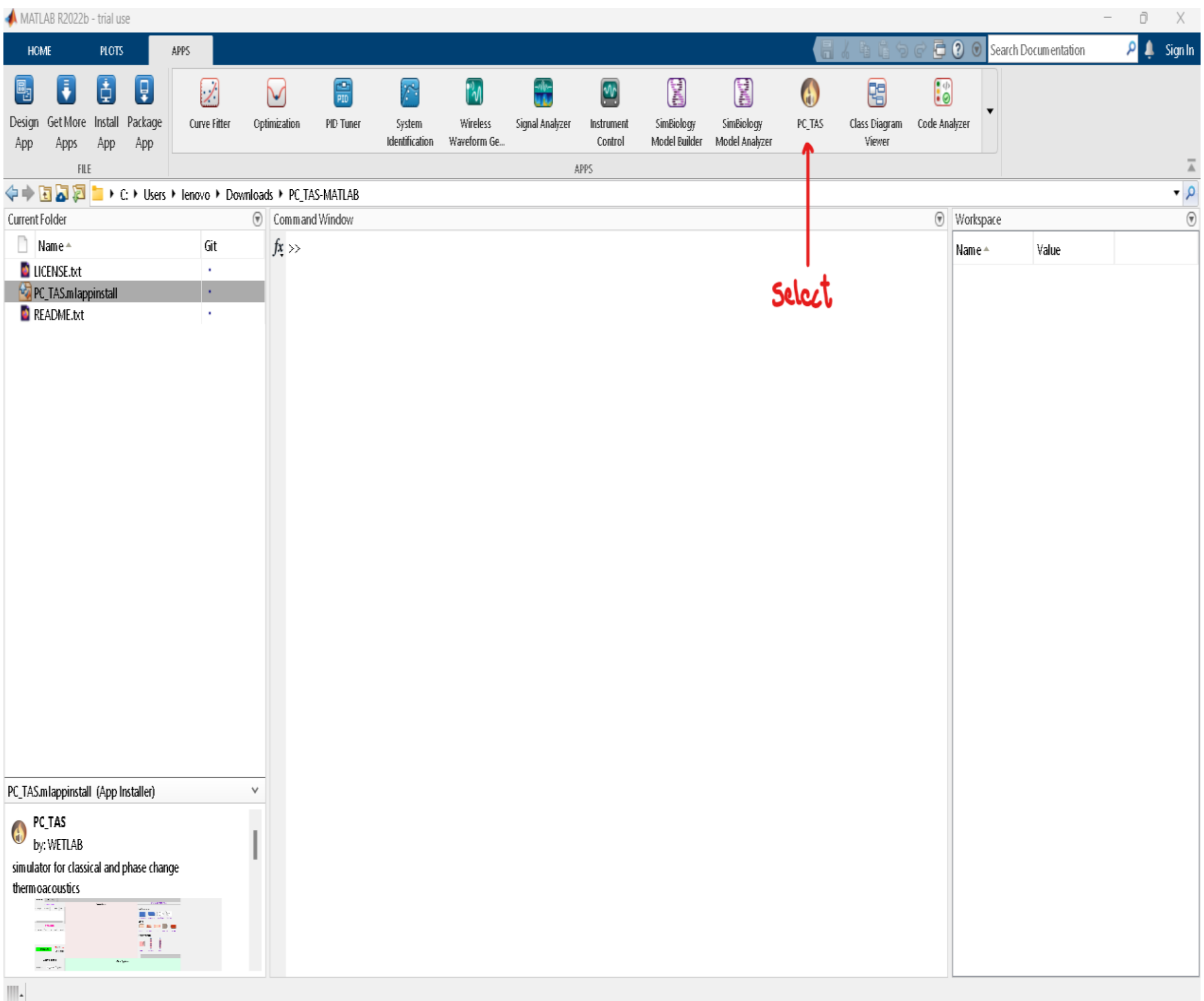
The model can be saved and loaded through the file menu at the top of the screen.

Data Acquisition

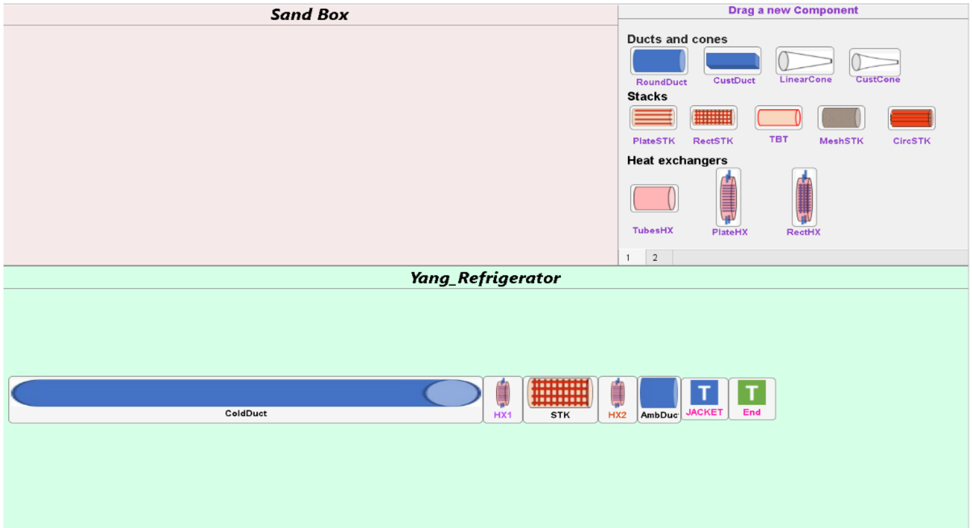
After the run operation is done, the converged results and the general information of the model can be output into two .mat files, through click the "Export Data" in the "File" list. Table files and pictures of the graphs will be generated as well.

Mat lab Procedure

Select the PC-TAS App from Apps Section



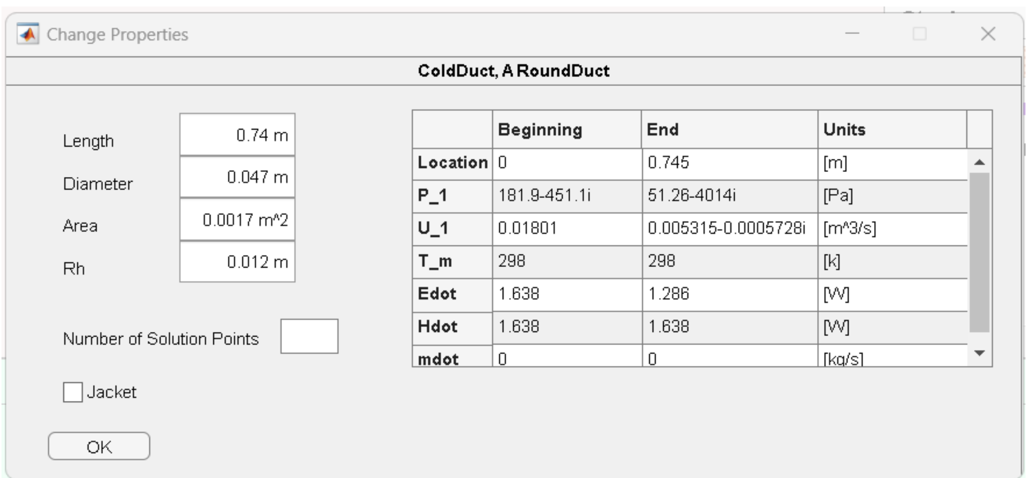
Selecting of PC_TAS from Apps Section Drag and Drop the Components and give the dimensions.



Work Space

Giving Properties

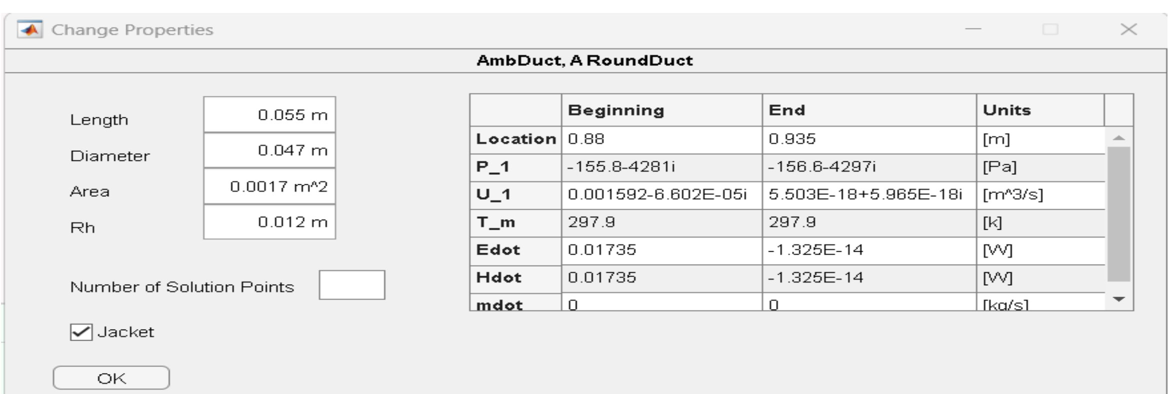
Giving properties for Duct1



	Beginning	End	Units
Location	0	0.745	[m]
P_1	181.9-451.1i	51.26-4014i	[Pa]
U_1	0.01801	0.005315-0.0005728i	[m^3/s]
T_m	298	298	[k]
Edot	1.638	1.286	[W]
Hdot	1.638	1.638	[W]
mdot	0	0	[kg/s]

Duct 1 Property

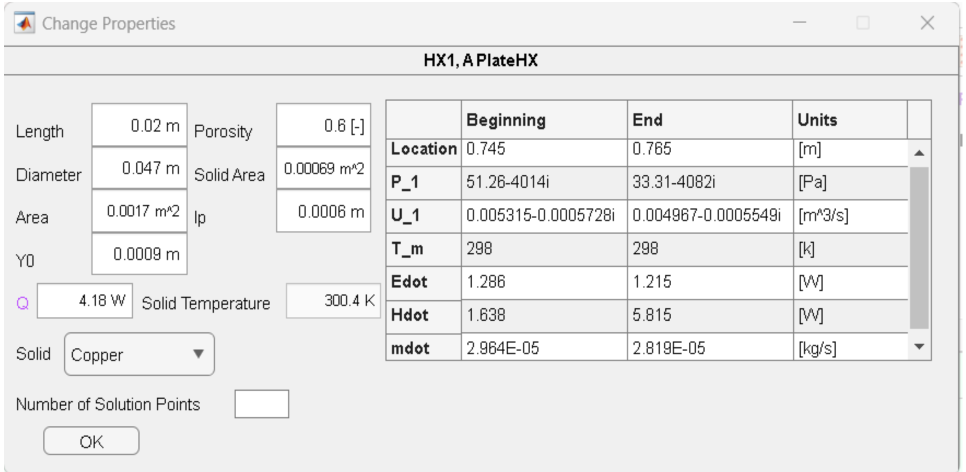
Give the required properties for Duct2



	Beginning	End	Units
Location	0.88	0.935	[m]
P_1	-155.8-4281i	-156.6-4297i	[Pa]
U_1	0.001592-6.602E-05i	5.503E-18+5.965E-18i	[m^3/s]
T_m	297.9	297.9	[k]
Edot	0.01735	-1.325E-14	[W]
Hdot	0.01735	-1.325E-14	[W]
mdot	0	0	[kg/s]

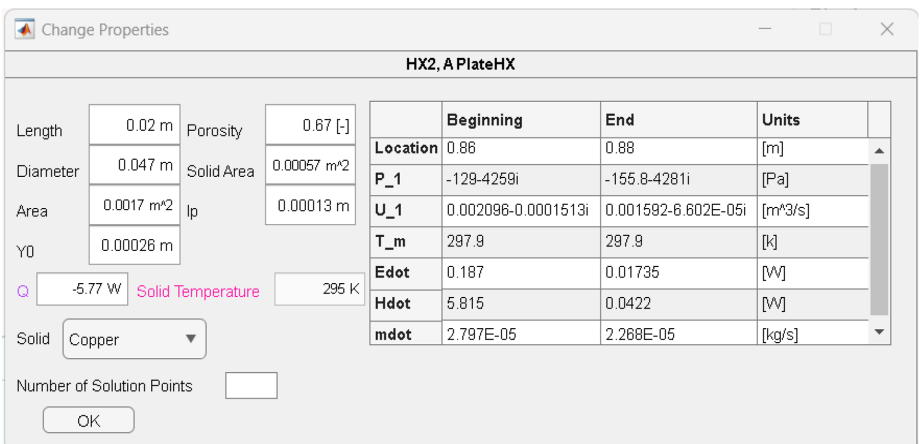
Duct 2 Properties

Give the Required Properties for Cold Heat Exchanger



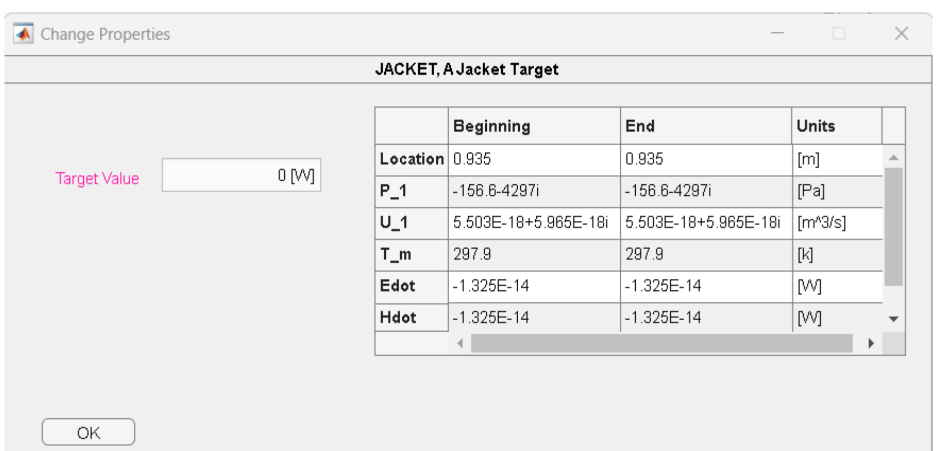
Cold Heat Exchanger

Give the Required Properties for Ambent



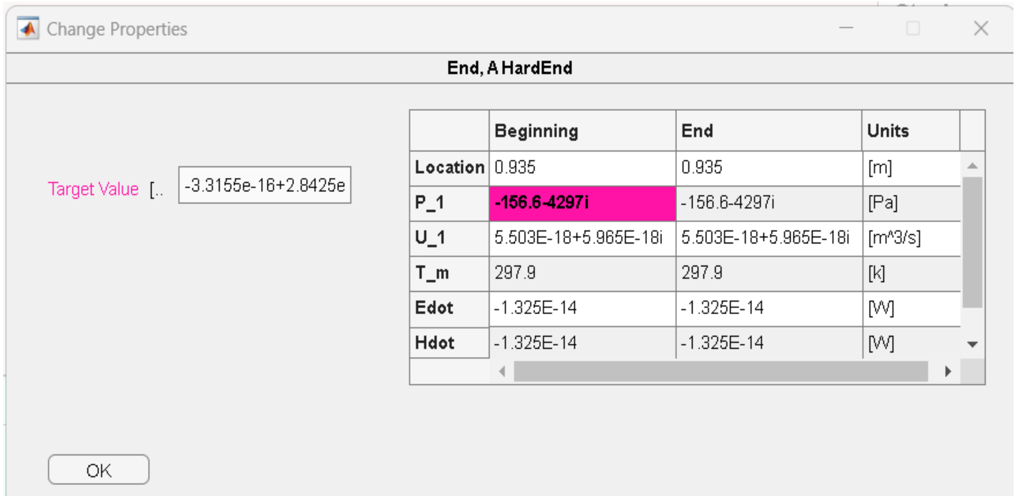
Ambent Heat Exchanger

Give the Required Properties for Jacket Target



Jacket Target

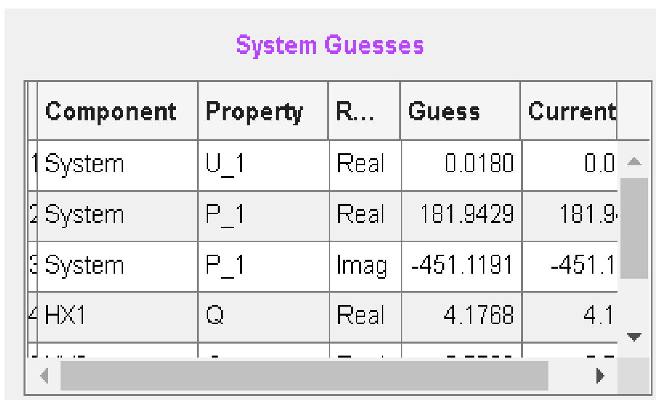
Give the required properties for End target



	Beginning	End	Units
Location	0.935	0.935	[m]
P_1	-156.6-4297i	-156.6-4297i	[Pa]
U_1	5.503E-18+5.965E-18i	5.503E-18+5.965E-18i	[m^3/s]
T_m	297.9	297.9	[k]
Edot	-1.325E-14	-1.325E-14	[W]
Hdot	-1.325E-14	-1.325E-14	[W]

End Target

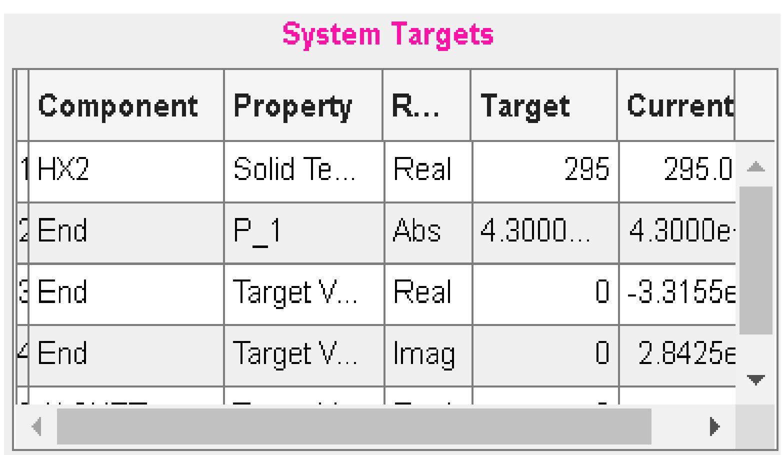
Giving System Guess



	Component	Property	R...	Guess	Current
1	System	U_1	Real	0.0180	0.0
2	System	P_1	Real	181.9429	181.9
3	System	P_1	Imag	-451.1191	-451.1
4	HX1	Q	Real	4.1768	4.1

System Guesses

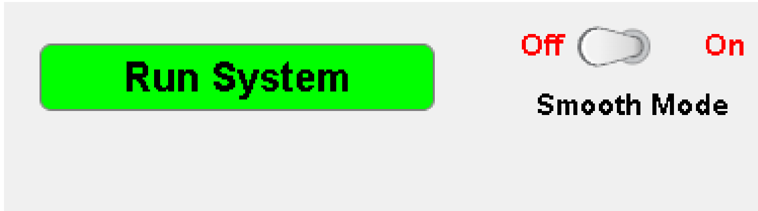
Giving System Targets'



	Component	Property	R...	Target	Current
1	HX2	Solid Te...	Real	295	295.0
2	End	P_1	Abs	4.3000...	4.3000e
3	End	Target V...	Real	0	-3.3155e
4	End	Target V...	Imag	0	2.8425e

System Target

Run the System



Run the System

RESULTS AND DISCUSSIONS

Simulation Results

Table 1

Components

ColdDuct, A RoundDuct

Length	0.74 m
Diameter	0.047 m
Area	0.0017 m^2
Rh	0.012 m
Number of Solution Points	
Jacket	☐

	Beginning	End	Units
Location	0	0.745	[m]
P_1	181.9-451.1i	51.26-4014i	[Pa]
U_1	0.01801	0.005315-0.0005728i	[m^3/s]
T_m	298	298	[k]
Edot	1.638	1.286	[W]
Hdot	1.638	1.638	[W]
mdot	0	0	[kg/s]

HX1, A PlateHX

Length	0.02 m	Porosity	0.6 [-]
Diameter	0.047 m	Solid Area	0.00069 m^2
Area	0.0017 m^2	lp	0.0006 m
Y0	0.0009 m		
Q	4.18 W	Solid Temperature	300.4 K
Solid	Copper		
Number of Solution Points			

	Beginning	End	Units
Location	0.745	0.765	[m]
P_1	51.26-4014i	33.31-4082i	[Pa]
U_1	0.005315-0.0005728i	0.004967-0.0005549i	[m^3/s]
T_m	298	298	[k]
Edot	1.286	1.215	[W]
Hdot	1.638	5.815	[W]
mdot	2.964E-05	2.819E-05	[kg/s]

Components of Cold Duct and HX1

Table 2

Components

STK, A RectSTK

Length	0.095 m	Porosity	0.85 [-]
Diameter	0.047 m	Solid Area	0.00026 m^2
Area	0.0017 m^2	lp	8.8E-05 m
Y1	0.00046 m	Y2	0.00046 m
Solid	Ceramic		
Number of Solution Points			

	Beginning	End	Units
Location	0.765	0.86	[m]
P_1	33.31-4082i	-129-4259i	[Pa]
U_1	0.004967-0.0005549i	0.002096-0.0001513i	[m^3/s]
T_m	298	297.9	[k]
Edot	1.215	0.187	[W]
Hdot	5.815	5.815	[W]
mdot	3.137E-07	1.193E-06	[kg/s]

HX2, A PlateHX

Length	0.02 m	Porosity	0.67 [-]
Diameter	0.047 m	Solid Area	0.00057 m^2
Area	0.0017 m^2	lp	0.00013 m
Y0	0.00026 m		
Q	-5.77 W	Solid Temperature	295 K
Solid	Copper		
Number of Solution Points			

	Beginning	End	Units
Location	0.86	0.88	[m]
P_1	-129-4259i	-155.8-4281i	[Pa]
U_1	0.002096-0.0001513i	0.001592-6.602E-05i	[m^3/s]
T_m	297.9	297.9	[k]
Edot	0.187	0.01735	[W]
Hdot	5.815	0.0422	[W]
mdot	2.797E-05	2.268E-05	[kg/s]

Components of STK and HX2

Table 3

Components

AmbDuct, A RoundDuct

Length	0.055 m
Diameter	0.047 m
Area	0.0017 m^2
Rh	0.012 m
Number of Solution Points	
☑ Jacket	

	Beginning	End	Units
Location	0.88	0.935	[m]
P_1	-155.8-4281i	-156.6-4297i	[Pa]
U_1	0.001592-6.602E-05i	5.503E-18+5.965E-18i	[m^3/s]
T_m	297.9	297.9	[k]
Edot	0.01735	-1.325E-14	[W]
Hdot	0.01735	-1.325E-14	[W]
mdot	0	0	[kg/s]

Components of Ambent Duct

Table 4

Components

JACKET, A Jacket Target

Target Value: 0 [W]

	Beginning	End	Units
P_1	-156.6-4297i	-156.6-4297i	[Pa]
U_1	5.503E-18+5.965E-18i	5.503E-18+5.965E-18i	[m^3/s]
T_m	297.9	297.9	[k]
Edot	-1.325E-14	-1.325E-14	[W]
Hdot	-1.325E-14	-1.325E-14	[W]
mdot	0	0	[kg/s]

End, A HardEnd

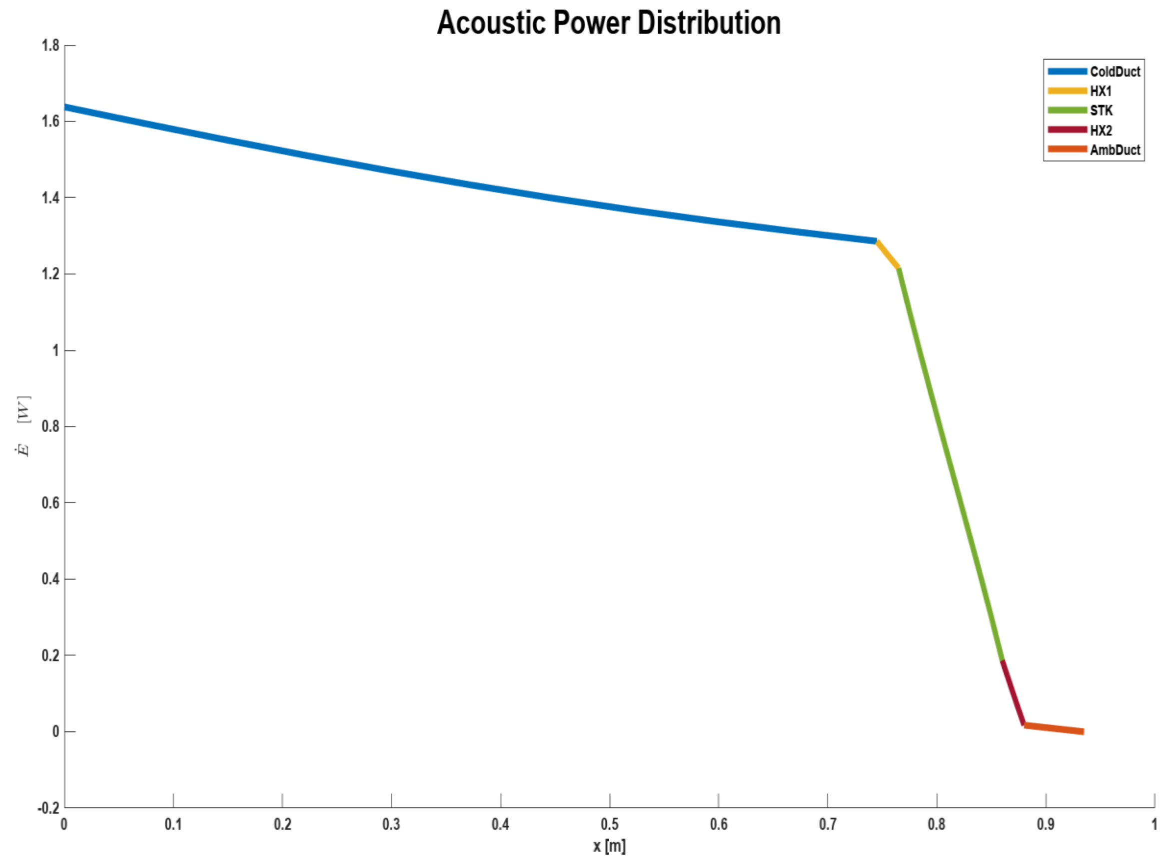
Target Value [.. -3.3155e-16+2.8425e

	Beginning	End	Units
Location	0.935	0.935	[m]
P_1	-156.6-4297i	-156.6-4297i	[Pa]
U_1	5.503E-18+5.965E-18i	5.503E-18+5.965E-18i	[m^3/s]
T_m	297.9	297.9	[k]
Edot	-1.325E-14	-1.325E-14	[W]
Hdot	-1.325E-14	-1.325E-14	[W]

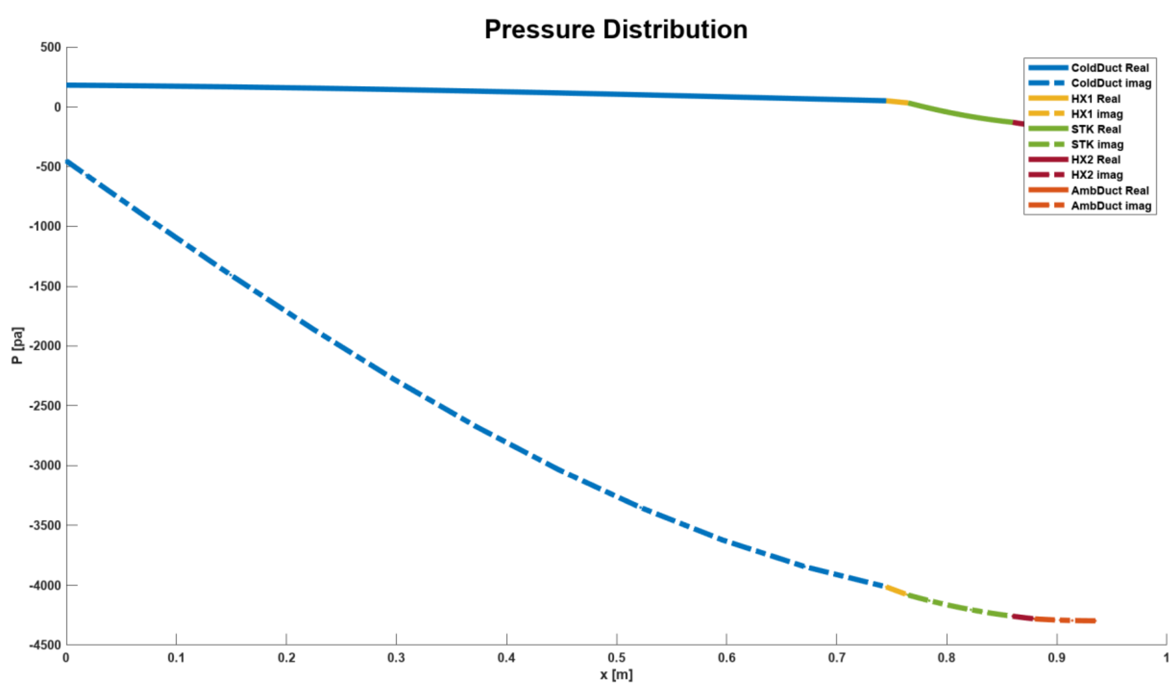
Components of Jacket Target and Hard End

EXPERIMENTAL RESULTS

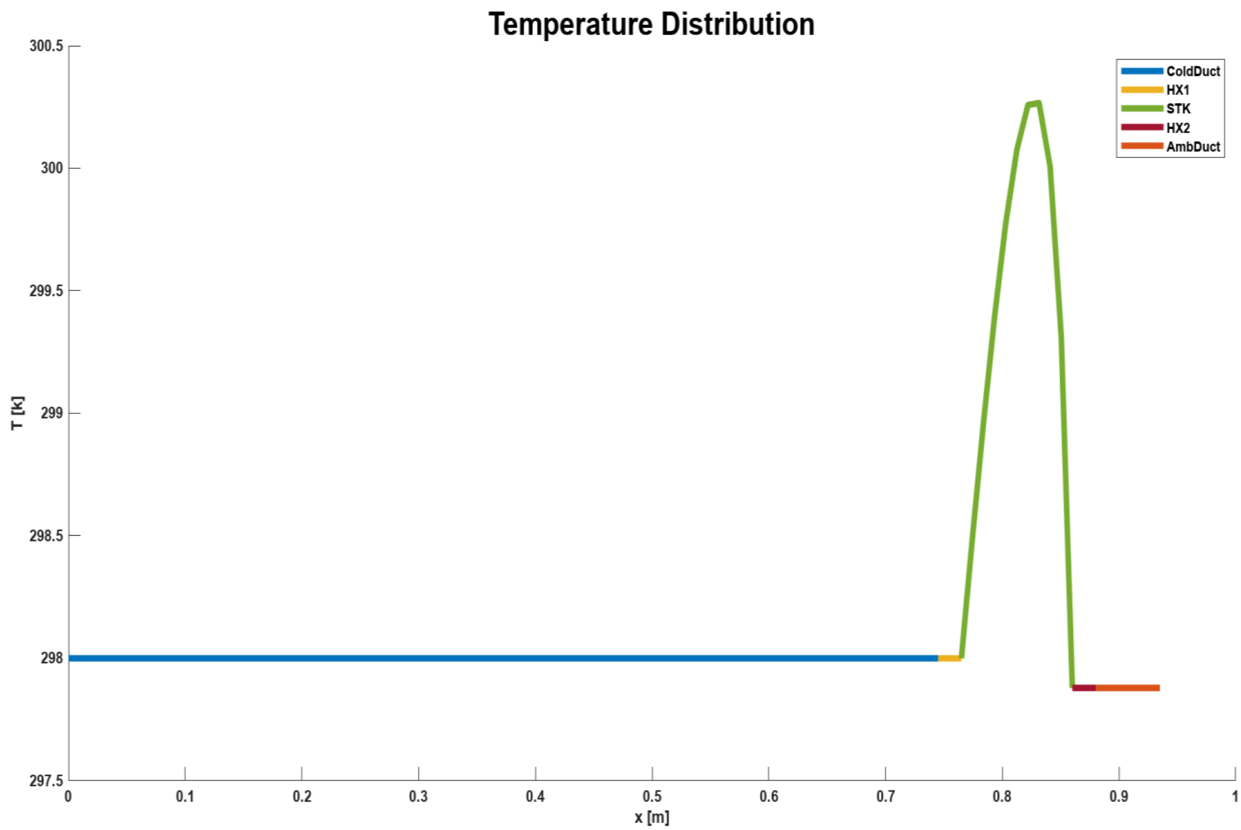
From the Experimental set up we will get following results



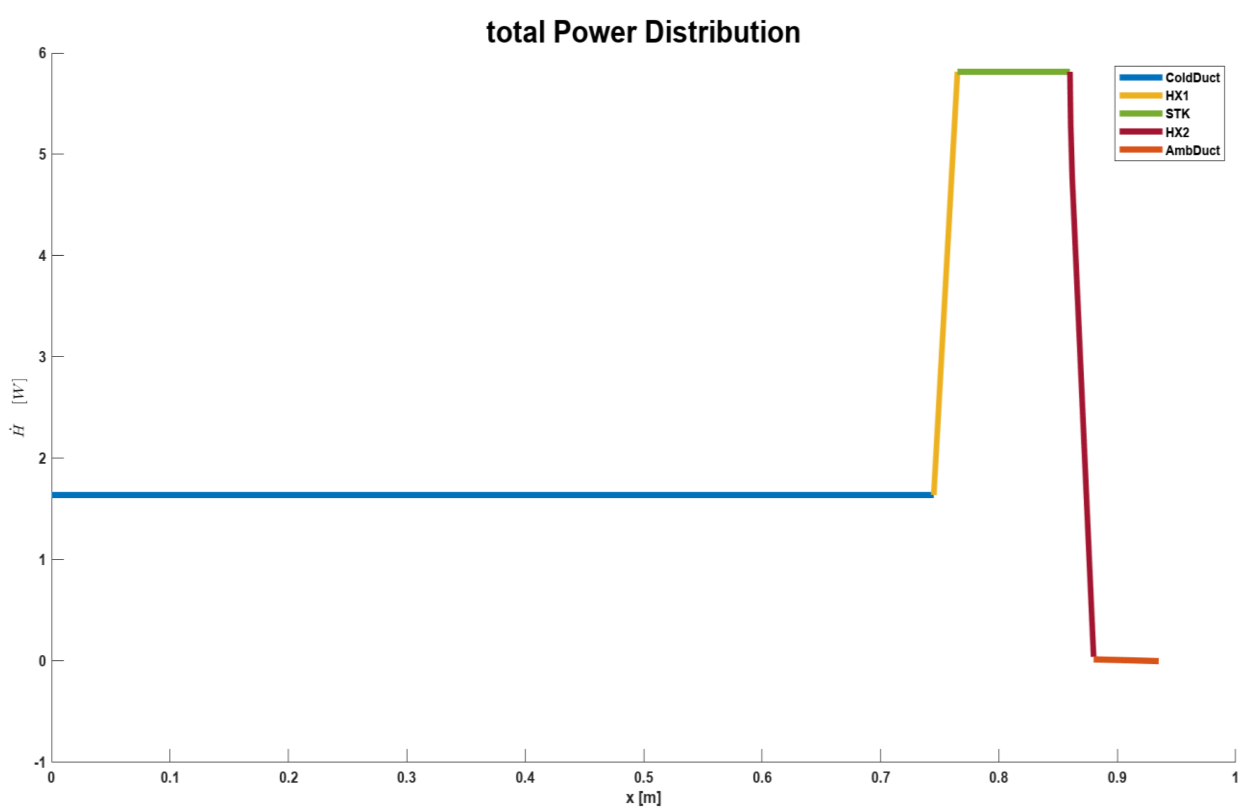
Acoustic Power



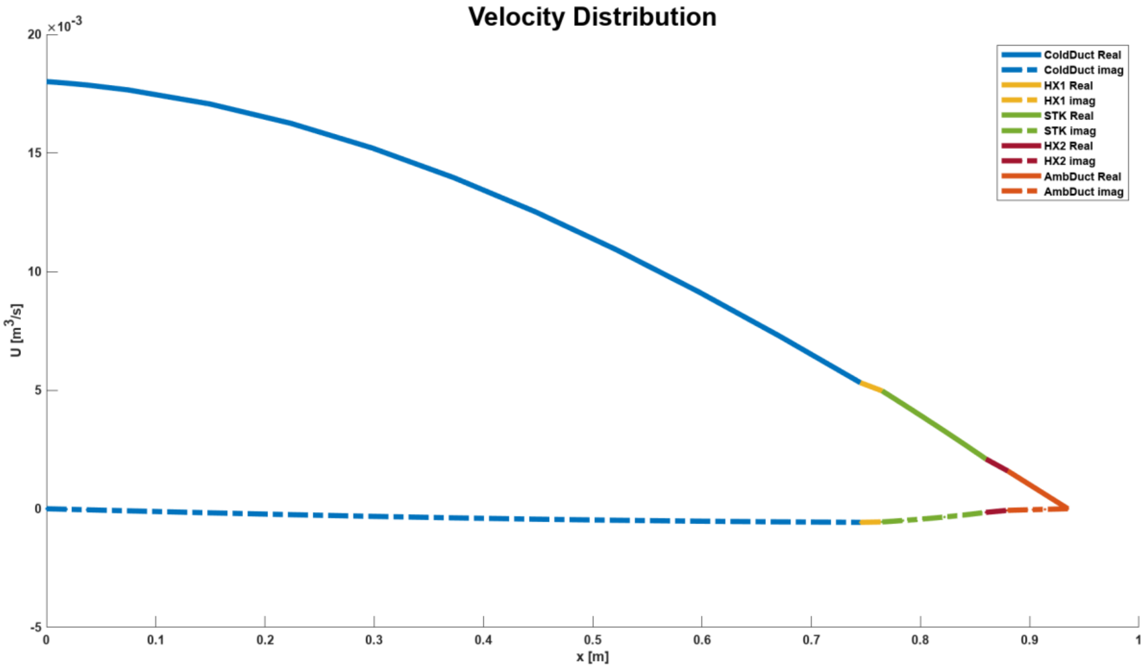
Power Distribution



Temperature Distribution



Total Power Distribution



Velocity Distribution

CONCLUSIONS

It can be summarized from the literature that the theory of standing wave thermo acoustics is well established. Several theoretical models as well as simulation software to forecast the performance of a TAR at steady state are also available. However, there are only a few notable instances, where a fully functional standing wave TAR is designed, constructed and experimentally investigated. In view of this, it is possible to improve the efficiency of the thermo acoustic refrigeration system by increase the surface area by cutting the groves on it

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