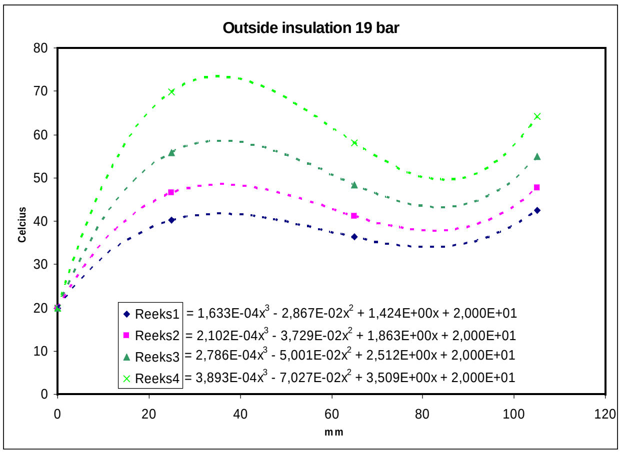
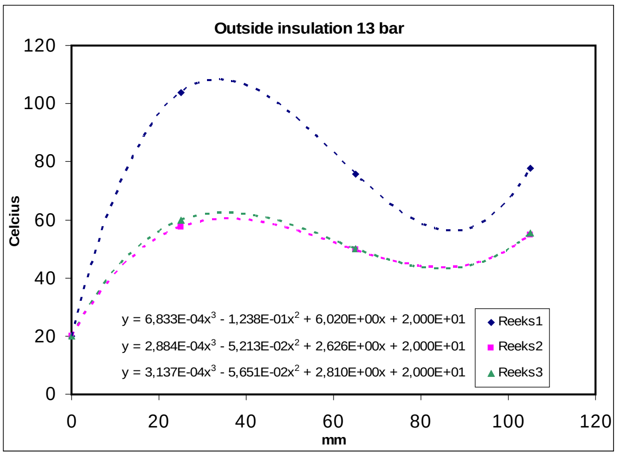
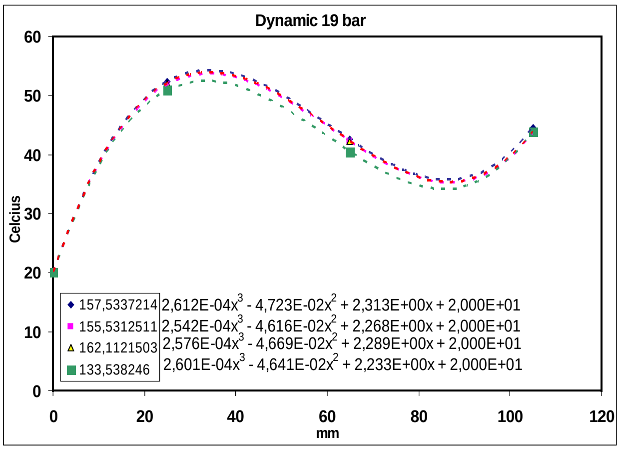
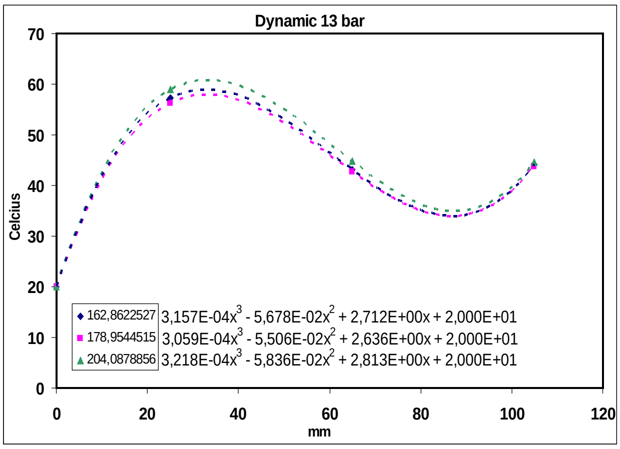
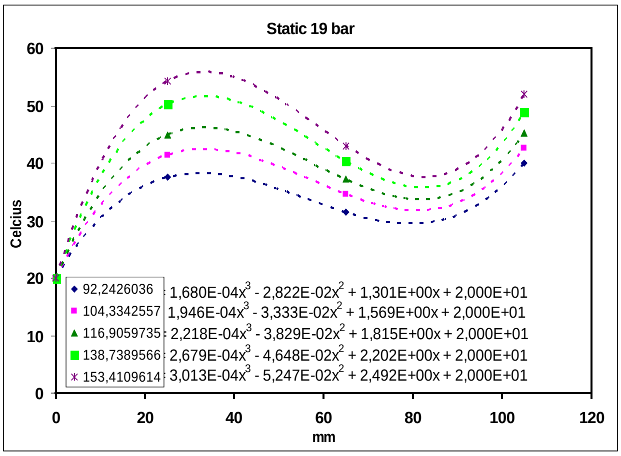
Appendix A1: Temperature profiles single stage

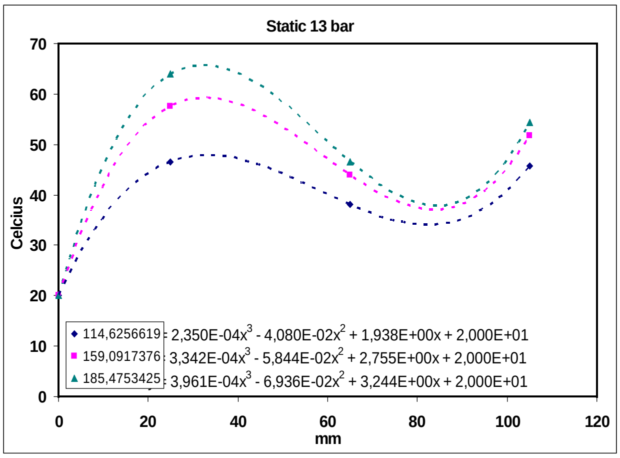


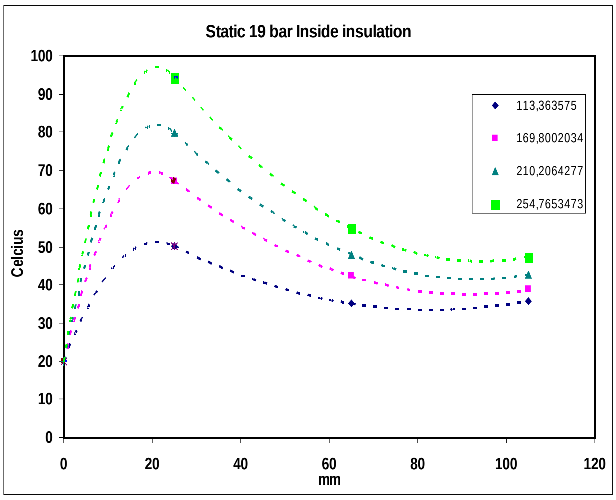


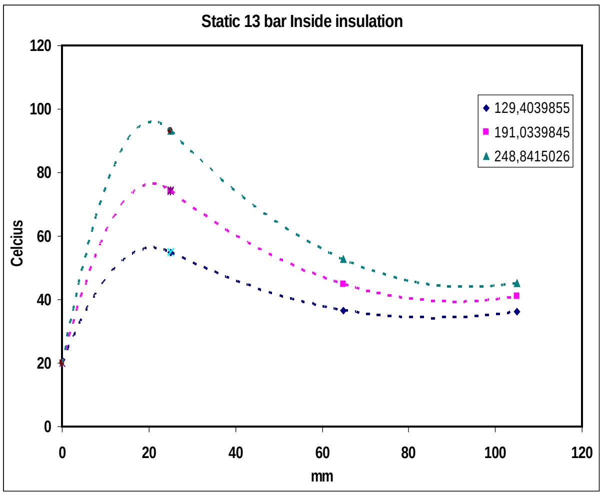




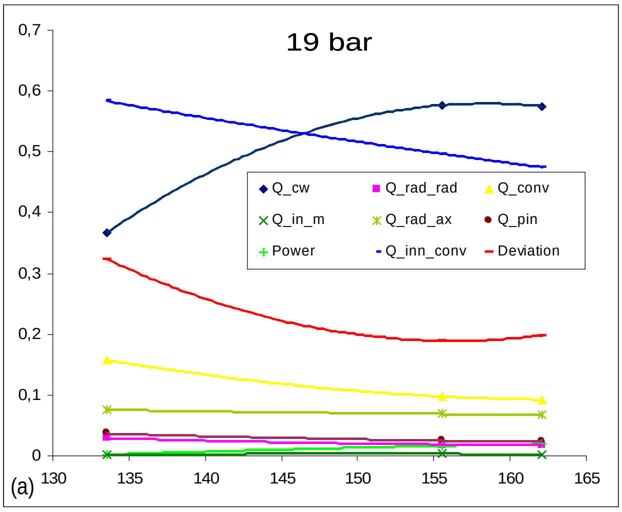


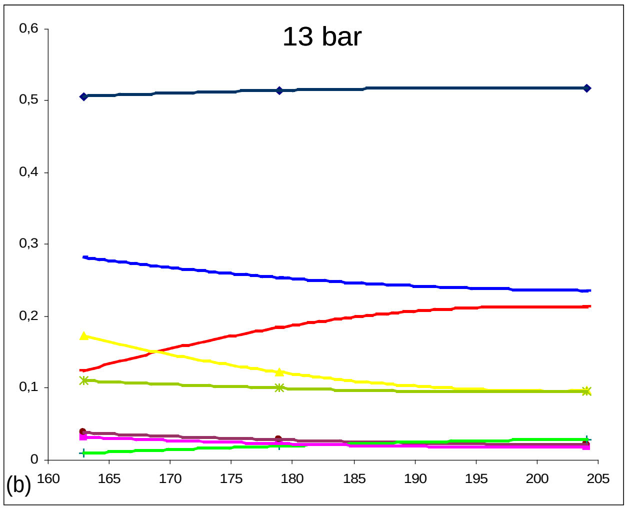




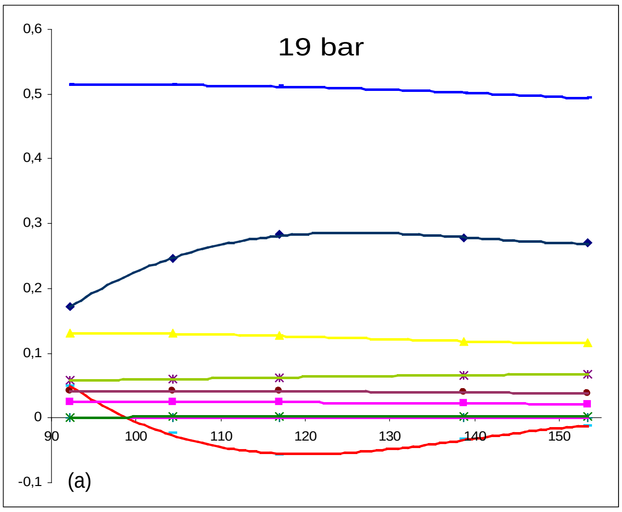


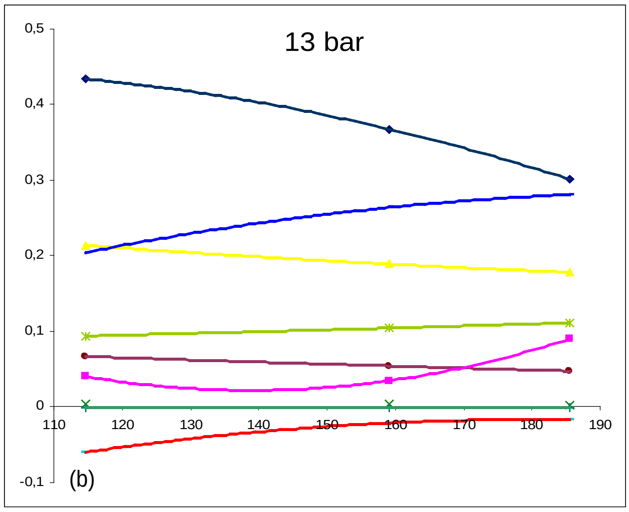
Appendix A2: Heat losses

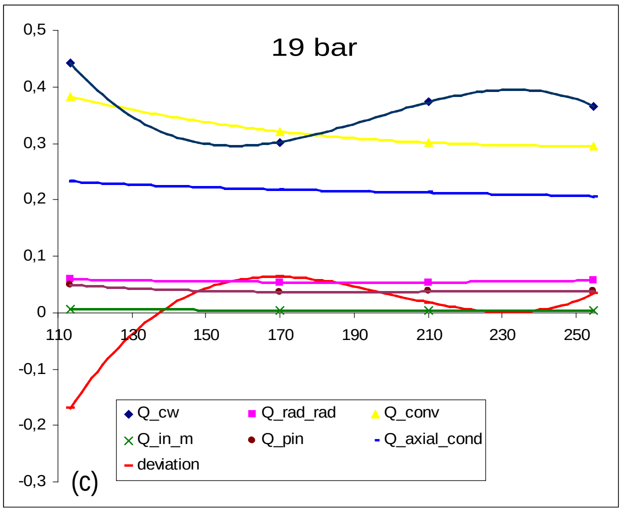


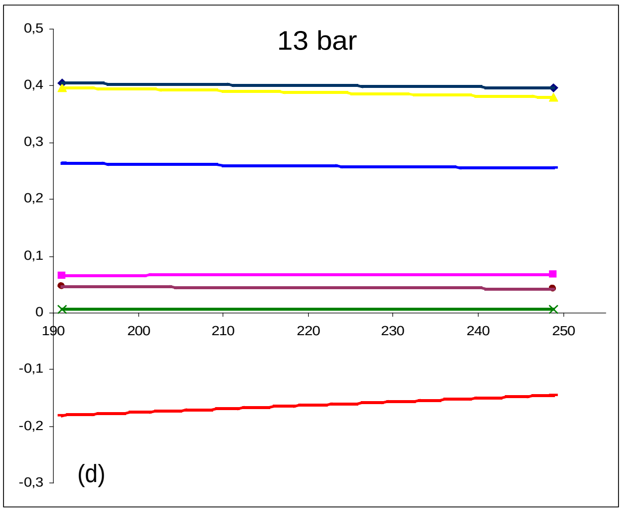


Dynamic state









Static State (a-b) Inside insulation (c-d) no insulation

Figure A2 On the x axis is the hot regenerator temperature in ºC. On the y-axes is the fraction of the heat input

Appendix B The DeltaEC Program

At the university of Los Alamos, New Mexico in the United States of America a software tool was developped in order to predict the behavior of thermoacoustic systems, this software is called DeltaEC.
The program is quite extensive, for this reason the only modules described in this chapter are those used in the simulation of the experimental setup that will be described in chapter 4.

Model Backgrounds

DeltaEC is designed to numerically integrate the wave equation, and other equations in one spatial dimension. It assumes, low amplitudes or low mach numbers and a time dependence of:

$$\alpha(t) = \alpha_0 + \alpha_a \, e^{i\omega t} \tag{3.1}$$

DeltaEC consists of different modules, they can be standardized parts, or user defined equations. Standardized parts have inputs, such as the dimensions of a geometrical shape. These inputs are presented on the left side of the screen, and use a small letter. Outputs are presented at the right side with a capital. In this way, user defined functions (RPN-blocks) can call these values, use them for calculations, and produce values as inputs for other blocks.
All conservation laws (mass, momentum, Temperature, and energy) apply at all times at all connections between elements. Friction, and other conversion processes are programmed for the segments, and will be stated in this appendix.

Calculation is done by numerical methods. This enables the user to calculate more values at the same time. There is no limit to number of values that can be calculated simultaneously. The user needs to define a guess and a target in order to start the calculation. When the target is met by the correct value of the guess the calculation ends. The user can define multiple guesses as long as the number of targets is equal to the number of guesses, while the calculation decreases in stability as the number of guesses increases. It could also be that the solution is not singular when there are too many guesses defined. Because of the instability of the calculation method, it is important to input guess values in close approximation to their actual values. This can be done by building up the model gradually, and inserting new elements with initial zero length or work, then adjusting the guess values gradually or precalculated by hand a result in more simple geometries in order to establish an initial equilibrium.

When a new calculation is started first of all the program tries to alter the frequency of the acoustic wave to meet the boundary and preset conditions, this is done with the shooting method, start conditions, and frequency variations. When the acoustic equation meets the preset boundaries temperatures are calculated with the shooting method, and so on. Communication between different modules goes through temperature, acoustic energy, gas temperature, phase, pressure, pressure amplitude, and direct current velocity.

There is also a 'begin' module, and 'hardends'. In 'hardends' boundary conditions, such as energy transport, and velocity can be stated. In the begin module general properties for gas, and additional conditions for calculation are inputs. In other modules the material of the solid is an input, although this doensn't have far more consequences than the conductivity. It would be adequate to state all inputs are geometries, material types, and externally connected properties (such as temperature).
The boundary condition for solid hardends are no volumetric flow through the wall (real value equals zero) and no volumetric flow along the wall due to friction (imaginary value equals zero) will go through to the next element. The condition is described as a target. This can only happen

when the right frequency, and pressure amplitude occur in the entire geometry. Because these values are correlated, the pressure amplitude and frequency are set as guesses.

<u>*Duct, and cone*</u>
The duct is the most basic form of element. It is a volume with surface friction and dynamic phase delay. The relation between these is determined by the geometry.

$$\frac{\mathrm{d}p_a}{\mathrm{d}x} = -\frac{i\omega p_m}{(1-f_v)A}U_a$$
$$\frac{\mathrm{d}U_a}{\mathrm{d}x} = -\frac{iA\omega}{\rho_m a^2}\left(1+\frac{\gamma-1}{1+\varepsilon_s}f_T\right)p_a \qquad \text{(B2)}$$

Where a is the speed of sound in m/s

$$r_0 = 2A/\Pi \qquad \text{(B3)}$$

The Rott functions B3b are f_T the thermal relaxation dissipation and the f_v viscous dissipation given:

$$\text{if: } r_0/\delta < 25 \qquad \text{(B3a)}$$
$$f_T = \frac{2J_1\left((i-1)r_0/\delta_T\right)}{(i-1)(r_0/\delta_T)J_0(i-1)r_0/\delta_T}$$
$$f_v = \frac{2J_1\left((i-1)r_0/\delta_v\right)}{(i-1)(r_0/\delta_v)J_0(i-1)r_0/\delta_v} \qquad \text{(B3b)}$$
$$\text{if: } r_0/\delta > 30, \text{ boundary layer oppriximation;}$$
$$f_T = (1-i)\Pi\,\delta_T/2A, \quad f_v = (1-i)\Pi\,\delta_v/2A \qquad \text{(B3c)}$$

Where Π is the perimeter.
There also is an approximation of the Moody diagram for intermediate values.

The ratio between heat transport through the working fluid, and the wall:

$$\varepsilon_s = \left(\frac{k\rho_m c_p}{k_s\rho_s c_s}\right)^{1/2} \qquad \text{(B4)}$$

For a cone are two additional functions stated for perimeters, and areas

$$\Pi(x) = \Pi_1 + (\Pi_2 - \Pi_1)\frac{x-x_0}{\Delta x}$$
$$A(x) = \left(\sqrt{A_1} + \left(\sqrt{A_2}-\sqrt{A_1}\right)\frac{x-x_0}{\Delta x}\right)^2 \qquad \text{(B5)}$$

A_1 start area, A_2 final area, Π_1 start perimeter, Π_2 final perimeter, and Δx the length are inputs.
Turbulence can be chosen from two options called pessimistic and optimistic turbulence, this is done in the begin module. In optimistic turbulence solely the formulas stated above are valid, there are viscous losses independent on the roughness of the surface. In the case of pessimistic turbulence the turbulent velocity and velocity from the cycle are added to be calculated together in order to increase friction according to the roughness.
When there is pessimistic turbulence, the resistive component of the pressure that could be described by pressure multiplication factor G, and hence the viscous power dissipation is increased.

$$G = \frac{\delta_v^2 N_R}{24\pi r_h^2}\frac{f_M - (1-9\pi/32)Rn\,\mathrm{d}f_M/\mathrm{d}\,Rn}{\mathrm{Re}\left(i/(1-f_v)\right)} \qquad \text{(B6)}$$

Where Rn is the Reynolds number, and f_M the Moody friction factor:

$$\frac{1}{f_M} = 1.74 - 2\log_{10}\left(2\in + \frac{18.7}{Rn\sqrt{f_M}}\right) \qquad \text{(B7)}$$

ϵ being the roughness of the surface, which is an input.
More information on the subject of turbulence, and direct current addition and Doppler effects can

be found in the DeltaEC manual chapter 10.1.1. This is left out, because the membranes in our setup eliminate direct currents.

Surface

At the surface acoustic power is dissipated, by thermo-viscous effects Temperature and pressure amplitude are assumed constant, but the volume flow is changed according to the theory of thermal-hysteresis, equation 3.8.

$$U_{a,out} = U_{a,in} - \frac{\omega p_a}{\rho_m a^2}\frac{\gamma - 1}{1+\varepsilon_s} A_s \frac{\delta_T}{2}\text{, equation 3.4 applies} \quad \text{(B8)}$$

A_s is the surface area, which is an input.

Impedance

In the impedance volumetric flow rate and temperature are constant. The pressure amplitude is:

$$p_{a,out} = p_{a,in} - ZU_a \quad \text{(B9)}$$

This comes from the analogy with alternating currents, where Z is the resistance in oscillation. Z is an input, which consists of a real part (due to friction losses), and an imaginary part as the electrical impedance does.

Minor (user defined additional friction) losses

Additional friction can be added by using a minor loss element. Because of sharp angles in the flow, like hard turns, sudden expansion, and geometrical disturbances.

$$\Delta p = -\tfrac{1}{2} K u^2 \quad \text{(B10)}$$

The friction constant K is an input.

Regenerator =Stkscreen

Regenerators can be modeled with a STK segment where a temperature gradient is present.

$$\dot{H}_{total} = \dot{H}_{2,k} + Nmw_m \quad \text{(B11)}$$

$$\dot{H}_{2,k} = \tfrac{1}{2}\mathrm{Re}\left[p_a \tilde{U}_a\left(1 - \frac{T_m\beta\left(f_T - \tilde{f}_v\right)}{(1+\varepsilon_s)(1+\sigma)\left(1-\tilde{f}_v\right)}\right)\right] + \frac{\rho_m c_p}{2A_{cs,fluid}\,\omega(1+\sigma)\left|1-f_v\right|^2}\frac{T_m}{\mathrm{d}x}U_a^2 Y - \left(A_{cs,fluid}k_{fluid} + A_{cs,solid}k_{solid}\right)\frac{\mathrm{d}T_m}{\mathrm{d}x} \quad \text{(B12)}$$

$$Y = \mathrm{Im}\left[\tilde{f}_v + \frac{\left(f_T - \tilde{f}_v\right)\left(1+\varepsilon_s f_v/f_T\right)}{(1+\varepsilon_s)(1+\sigma)}\right]$$

The velocity is changed indirectly through the temperature gradient. For pressure gradients two formulas apply.

$$\frac{\mathrm{d}p_{2,0}}{\mathrm{d}x} = -\frac{\mu G N_{2,0}}{8r_h^2 A_{cs} B}\left(c_1(B) + c_2(B) Rn_{2,0}\left(1 + \frac{1}{2\varepsilon_{2,0}^2} + \frac{|p_a|}{p_m}\frac{\cos B}{\varepsilon_{2,0}}\right)\right),\ \text{for } \left|\varepsilon_{2,0}\right| \geq 1 \quad \text{(B13)}$$

B being the input volume porosity, and:

$$\frac{\mathrm{d}p_{2,0}}{\mathrm{d}x} = -\frac{\mu G N_{2,0}}{8r_h^2 A_{cs} B}\left(c_1(B) + \frac{c_2(B)\mathrm{Rn}_{2,0}}{\pi\varepsilon_{s2,0}^2}\left[\left(1 + 2\varepsilon_{s2,0}^2 + 2\varepsilon_{2,0}\frac{|p_a|}{p_m}\cos B\right)\sin^{-1}\left|\varepsilon_{2,0}\right| + \frac{\varepsilon_{2,0}}{\left|\varepsilon_{2,0}\right|}\left(3\varepsilon_{2,0} + \frac{2(2+\varepsilon_{2,0}^2)|p_a|\cos B}{3p_m}\right)\right]\sqrt{1-\varepsilon_{2,0}^2}\right)$$

$$\text{for } \left|\varepsilon_{2,0}\right| \geq 1 \quad \text{(B14)}$$

$$\mathrm{Rn} = \frac{G\left|N_{2,0}\right| 4r_h}{A_{cs} B\mu}$$

Where r_h is the hydraulic diameter, which is an input, which should be chosen as ¼ $D_{wire}B/(1-B)$, D_{wire} is the wire diameter, $N_{2,0}$ is the molar flux at the end of the segment, and:

$$\varepsilon_{2,0} = GN_{2,0} / \rho_m \left|U_a\right| \quad \text{(B15)}$$

Thermal Buffer Tube =Stkduct

In a thermal buffer tube the same wave-function applies as in a normal tube, however here thermoacoustics are not negligible, and a temperature gradient is added.

The thermal buffer tube acts like a stack with a single channel. Consequently a heating effect takes place along the wall.

$$\frac{\mathrm{d}p_a}{\mathrm{d}x} = -\frac{i\omega p_m}{\left(1-f_v\right)A} U_a$$

$$\frac{\mathrm{d}U_a}{\mathrm{d}x} = -\frac{iA\omega}{\rho_m a^2}\left(1+\frac{\gamma-1}{1+\varepsilon_s} f_k\right) p_a + \frac{\beta\left(f_T - f_v\right)}{\left(1-f_v\right)\left(1-\sigma\right)\left(1+\varepsilon_s\right)} \frac{\mathrm{d}T_m}{\mathrm{d}x} U_a \tag{B16}$$

$$\frac{\mathrm{d}T_m}{\mathrm{d}x} = \frac{\dot{H}_{2,k} - \frac{1}{2}\mathrm{Re}\left[p_a \tilde{U}_a \left(1 - \frac{T_m \beta\left(f_T - \tilde{f}_v\right)}{\left(1+\varepsilon_s\right)\left(1+\sigma\right)\left(1-\tilde{f}_v\right)}\right)\right]}{\frac{\rho_m c_p}{2A_{cs,fluid}\,\omega\left(1+\sigma\right)\left(1-\tilde{f}_v\right)^2}\mathrm{Im}\left[\tilde{f}_v + \frac{\left(f_T - \tilde{f}_v\right)\left(1+\varepsilon_s f_v / f_T\right)}{\left(1+\varepsilon_s\right)\left(1+\sigma\right)}\right] - \left(A_{cs,fluid}k_{fluid} + A_{cs,solid}k_{solid}\right)} \tag{B17}$$

Here formula 3.3c and 3.16 apply

$$\varepsilon_s = \left(\frac{k\rho_m c_p}{k_s \rho_s c_s}\right)^{1/2} \frac{1}{\tanh\left(\left(1+i\right)l/\delta_s\right)} \tag{B18}$$

where: $l = A_{cs,wall} / \prod_{wall}$

HX, and TX (heat exchangers)

Heat exchangers HX have parallel plates, while TX have a shell and tube geometry. Equations 3.2, 3.3, and 3.4 also apply.

if: $25 < r_0 / \delta < 30$

$$f_T = \frac{\tanh\left(\left(1+i\right)y_0/\delta_T\right)}{\left(1+i\right)y_0/\delta_T}, \quad f_v = \frac{\tanh\left(\left(1+i\right)y_0/\delta_v\right)}{\left(1+i\right)y_0/\delta_v} \tag{B19}$$

$$\frac{\mathrm{d}T_m}{\mathrm{d}x} = 0$$

$$T_{solid} = T_m + \frac{\dot{Q}}{hA_{cs,gas}x_{eff}/r} \tag{B20}$$

Appendix B 1 Predictions by DeltaEC

The program has been proven to effectively find simple optimum geometries. This is used, so both the series, and parallel configurations are optimized for the resonator dimensions of the laboratory setup.
The effect of deviation from this optimum, and the possibility of improvement on the resonator dimension will also be done in DeltaEC. After the experiments the DeltaEC model is compared with the results.

Optimization in Series.

In DeltaEC it is easy to optimize the setup. In this section two hypothetical dimensions are changed, and two real dimensions are changed. Dimensions are called hypothetical when the shell that is provided for these experiments doesn't allow free manipulation of these dimensions. Real dimensions can be changed without the need of new components for the setup.

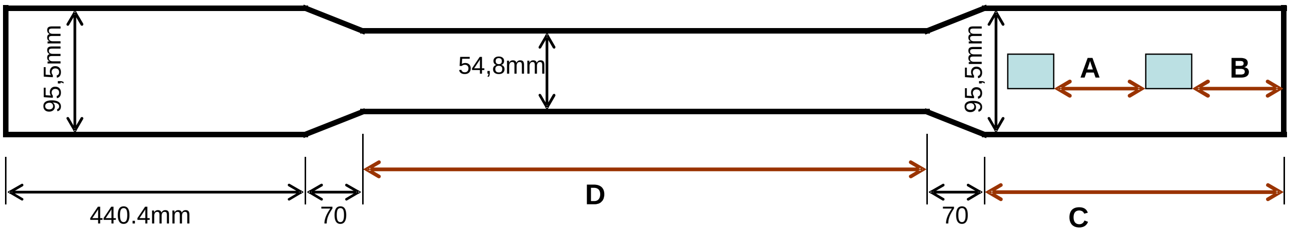


Figure 3.1 Dimension Analyzes

The most important issue is optimization of the distance between the regenerator blocks was found to peak at no distance between the blocks. However the difference between 0 mm and 75 mm (75 being the geometrical maximum when not placing the generator inside the cone) was less than 0,05% of 11,55% thermal efficiency. One may argue that this doesn't represent a serial multistage setup, because one connection between the compliance, and impedance is missing. On the other hand thermal buffer tubes can be shortened to overcome this issue, or the issue could simply be ignored considering the lower thermal power would be the only point of interest. When series are compared to parallel it is preferable the series is a real series configuration, besides no spacing would mean a high power input to the second stage, and a high difference in operating conditions of both stages.

Figure B2.1 Efficiency as a function of the distance between generator 1, and the thermal buffer tube of generator 2. of the overall thermoacoustic system in series from deltaE simulation. The value A on the x-axis goes from 0 to 75mm. The first compliance was 120mm (value B) the first regenerator 130mm, and the second regenerator was 100mm.

When the thermal efficiency is plotted against the distance between the first stage/generator, and the wall the correlation is alarmingly high. The thermal efficiency could drop 9 % from the total of 12 % when the first stage is placed incorrectly (figure B2.2). Since there is a lot of space used by cooling pipes, and signal lines, and electrical wires for the heater it would be best to place the first stage just over 120 mm from the wall.

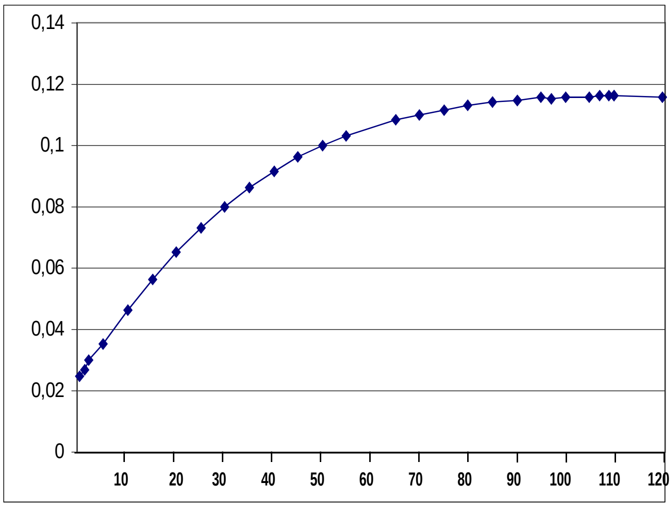


Figure B2.2 Efficiency as a function of distance between outer regenerator, and end seal of the overall thermoacoustic system in series from deltaE simulation. The x-axis goes from 0 to 120mmspacing between the first generator, and the compliance wall. The distance between the two generators was 1mm. The first regenerator was 130mm, and the second regenerator was 100mm.

Optimization of the values for C and D is removed from this report, because the resonator in which the experiments are conducted was already built and can not easily undergo changes in geometry.

The DeltaEC code was made by ECN and only needed adjustments for geometry and data retrieval.

Appendix B2: Parallel configuration

```
C:\Users\CHRIS\Documents\Parrespet\masterfile_parallel Two stage engine (symmetric
located on either ends)
Two engines in a half wavelength resonator. We call this parallel
arrangement in contrast with series multi stage engine. THis exercise helps
us examine the merits and demerits of series or parallel config. THe main
objective is to look for configurations that offer low temperature driven
systems.
  0 BEGIN
             1.9000E+06 a Mean P Pa
Gues             71.318 b Freq   Hz
                 300.00 c TBeg   K
Gues         1.0317E+05 d |p|    Pa
                 0.0000 e Ph(p)  deg
                 0.0000 f |U|    m^3/s
                 0.0000 g Ph(U)  deg
Optional Parameters
nitrogen       Gas type
    1 RPN          Drive ratio
                 0.0000 a G or T                    5.4298E-02 A ChngeMe
0d 0a /
    2 DUCT         compliance
             7.1630E-03 a Area   m^2      Mstr     1.0210E+05 A |p|     Pa
                0.30002 b Perim  m        2a       1.1297E-03 B Ph(p)   deg
                 0.1130 c Length m                 1.4027E-02 C |U|     m^3/s
             2.0000E-03 d Srough                      -90.034 D Ph(U)   deg
Master-Slave Links                                     0.0000 E Htot    W
Optional Parameters                                  -0.44484 F Edot    W
ideal          Solid type
    3 TBRANCH      Change Me
Gues        -5.8580E+05 a Re(Zb) Pa-s/m^3          1.0210E+05 A |p|     Pa
Gues         6.9314E+06 b Im(Zb) Pa-s/m^3          1.1297E-03 B Ph(p)   deg
Master-Slave Links                                 1.4678E-02 C |U|     m^3/s
                                                       -94.83 D Ph(U)   deg
Optional Parameters                                   -63.107 E HtotBr  W
                                                      -63.107 F EdotBr  W
                                                       62.662 G EdotTr  W
      4 DUCT         Change Me
             4.4660E-03 a Area   m^2               9.6750E+04 A |p|     Pa
                0.48412 b Perim  m                     0.2134 B Ph(p)   deg
                 0.1280 c Length m                 2.4269E-02 C |U|     m^3/s
             2.0000E-03 d Srough                      -92.913 D Ph(U)   deg
Master-Slave Links                                    -63.107 E Htot    W
Optional Parameters                                   -64.039 F Edot    W
ideal          Solid type
      5 SOFTEND      Change Me
                                                   9.6750E+04 A |p|     Pa
                                                       0.2134 B Ph(p)   deg
                                                   2.4269E-02 C |U|     m^3/s
                                                      -92.913 D Ph(U)   deg
                                                      -63.107 E Htot    W
Possible targets                                      -64.039 F Edot    W
                                                     -0.12889 G Re(z)
                                                       2.3594 H Im(z)
                                                       300.00 I T       K
    6 DUCT         Change Me
             2.5072E-03 a Area   m^2      Mstr     1.0212E+05 A |p|     Pa
                 0.1775 b Perim  m        6a      -2.5210E-02 B Ph(p)   deg
             1.0000E-02 c Length m                 1.2382E-03 C |U|     m^3/s
```

```
Master-Slave Links                                         63.107 E Htot    W
Optional Parameters                                        62.639 F Edot    W
ideal          Solid type
    7 MINOR          Change Me
    Same   6a 2.5072E-03 a Area    m^2              1.0211E+05 A |p|     Pa
                  4.0000 b K+                      -2.5882E-02 B Ph(p)   deg
                  4.0000 c K-                       1.2382E-03 C |U|     m^3/s
                                                        7.7581 D Ph(U)   deg
                                                        63.107 E Htot    W
                                                        62.634 F Edot    W
    8 TX             Change Me
    Same   6a 2.5072E-03 a Area    m^2              1.0211E+05 A |p|     Pa
                  0.3460 b GasA/A                     -0.14673 B Ph(p)   deg
              1.5000E-02 c Length m                 1.2219E-03 C |U|     m^3/s
              1.0000E-03 d radius m                    -2.9641 D Ph(U)   deg
Gues             -160.26 e HeatIn W                    -97.157 E Htot    W
Master-Slave Links                                      62.306 F Edot    W
Possible targets                                        300.00 G GasT    K
ideal          Solid type                               259.53 H SolidT K
    9 STKSCREEN  Change Me
              2.3578E-03 a Area    m^2              9.7673E+04 A |p|     Pa
                  0.7866 b VolPor                      0.62041 B Ph(p)   deg
              1.4500E-02 c Length m                 2.8998E-03 C |U|     m^3/s
              2.7650E-05 d rh      m                   -24.343 D Ph(U)   deg
                  0.2000 e ksFrac                      -97.157 E Htot    W
Master-Slave Links                                      128.38 F Edot    W
                                                        300.00 G TBeg    K
stainless      Solid type                               677.93 H TEnd    K
   10 HX             Change Me
    Same   6a 2.5072E-03 a Area    m^2              9.7648E+04 A |p|     Pa
                  0.3800 b GasA/A                       0.5950 B Ph(p)   deg
              3.6000E-03 c Length m                 2.9232E-03 C |U|     m^3/s
              9.0000E-04 d y0      m                   -25.394 D Ph(U)   deg
    OPlt          250.00 e HeatIn W                     152.84 E Htot    W
Master-Slave Links                                      128.29 F Edot    W
Possible targets                                 P      677.93 G GasT    K
ideal          Solid type                               879.22 H SolidT K
   11 RPN            ChangeMe
                  393.97 a G or T                    677.93     A ChngeMe
10G
   12 STKDUCT        Change Me
    Same   6a 2.5072E-03 a Area    m^2     Mstr     9.7025E+04 A |p|     Pa
                  0.1775 b Perim   m       12a         0.29234 B Ph(p)   deg
              8.1400E-02 c Length m                 5.3147E-03 C |U|     m^3/s
              2.9500E-04 d WallA   m^2                 -59.928 D Ph(U)   deg
Master-Slave Links                                      152.84 E Htot    W
                                                        128.05 F Edot    W
                                                        677.93 G TBeg    K
stainless      Solid type                               308.00 H TEnd    K
   13 RPN            ChangeMe
                  0.0000 a G or T                    -24.94     A ChngeMe
14F 12E -
   14 TX             Change Me
    Same   6a 2.5072E-03 a Area    m^2              9.6750E+04 A |p|     Pa
                  0.3460 b GasA/A                       0.2134 B Ph(p)   deg
              5.0000E-03 c Length m                 5.3771E-03 C |U|     m^3/s
              1.0000E-03 d radius m                    -60.333 D Ph(U)   deg
    Same 13A      -24.94 e HeatIn W                     127.90 E Htot    W
```

```
Targ               300.00 f SolidT K                     127.90 F Edot    W
Master-Slave Links                                        308.00 G GasT    K
ideal             Solid type                              300.00 H SolidT K
   15 UNION        Change Me
      5 a          SegNum                             9.6750E+04 A |p|     Pa
TargSame   5A 9.6750E+04 b |p|Sft Pa                      0.2134 B Ph(p)   deg
TargSame   5B      0.2134 c Ph(p)S deg                2.8945E-02 C |U|     m^3/s
Possible targets                                         -87.172 D Ph(U)   deg
                                                          64.796 E Htot    W
                                                          63.864 F Edot    W
                                                          308.00 G T       K
   16 DUCT         Change Me
              7.1630E-03 a Area    m^2      Mstr      9.1702E+04 A |p|     Pa
                 0.30002 b Perim   m        16a          0.10013 B Ph(p)   deg
                  0.1100 c Length  m                  4.1470E-02 C |U|     m^3/s
              2.0000E-03 d Srough                         -87.99 D Ph(U)   deg
Master-Slave Links                                        64.796 E Htot    W
Optional Parameters                                       63.376 F Edot    W
ideal             Solid type
   17 DUCT         Change Me
              7.1630E-03 a Area    m^2      Mstr      8.6932E+04 A |p|     Pa
                 0.30002 b Perim   m        17a       1.0348E-02 B Ph(p)   deg
              8.0000E-02 c Length  m                  5.0101E-02 C |U|     m^3/s
              2.0000E-03 d Srough                        -88.333 D Ph(U)   deg
Master-Slave Links                                        64.796 E Htot    W
Optional Parameters                                       62.938 F Edot    W
ideal             Solid type
   18 CONE         Change Me
              7.1630E-03 a AreaI   m^2      Mstr      8.2053E+04 A |p|     Pa
                 0.30002 b PerimI  m        18a      -7.0489E-02 B Ph(p)   deg
              4.5000E-02 c Length  m                  5.3215E-02 C |U|     m^3/s
              2.8000E-03 d AreaF   m^2      Mstr         -88.437 D Ph(U)   deg
                 0.18758 e PerimF  m        18d           64.796 E Htot    W
              2.0000E-03 f Srough                         62.232 F Edot    W
Master-Slave Links
Optional Parameters
ideal             Solid type
   19 MINOR        Change Me
     Same 20a 2.8000E-03 a Area    m^2                8.2023E+04 A |p|     Pa
                  0.5000 b K+                             1.0423 B Ph(p)   deg
                  0.5000 c K-                         5.3215E-02 C |U|     m^3/s
                                                         -88.437 D Ph(U)   deg
                                                          64.796 E Htot    W
                                                          19.832 F Edot    W
   20 DUCT         Change Me
     Same 18d 2.8000E-03 a Area    m^2      Mstr      6.6940E-10 A |p|     Pa
                 0.18758 b Perim   m        20a          -179.64 B Ph(p)   deg
                  0.4200 c Length  m                  6.1562E-02 C |U|     m^3/s
     Same 18f 2.0000E-03 d Srough                        -88.539 D Ph(U)   deg
Master-Slave Links                                        64.796 E Htot    W
Optional Parameters                                  -3.9762E-13 F Edot    W
ideal             Solid type
   21 RPN          dr
                  0.0000 a G or T                        29.482    A ChngeMe
                                       P                 5.4298    B ChngeMe
0d 0a / 100 * 21A 21A *
   22 RPN          phase difference between pressure and velocity
                  180.00 a G or T                       -91.106    A ChngeMe
```

```
20B 20D -
   23 SOFTEND      Change Me
Targ               0.0000 a Re(z)                             6.6940E-10 A |p|     Pa
Targ               0.0000 b Im(z)                               -179.64 B Ph(p)   deg
                                                              6.1562E-02 C |U|     m^3/s
                                                                -88.539 D Ph(U)   deg
                                                                 64.796 E Htot    W
Possible targets                                             -3.9762E-13 F Edot    W
                                                             -7.9007E-17 G Re(z)
                                                             -4.0934E-15 H Im(z)
                                                                 308.00 I T       K
   24 RPN          Eta Carnot
                   0.0000 a G or T    P                          0.25546 A Eta
                                                                 0.55747 B Eta Car
1 9G 9H / - 15F 10e /
   25 RPN          Etar
                   0.0000 a G or T    P                          0.45824 A ChngeMe
24A 24B /
```

Appendix B3 Serial configuration

```
C:\Users\CHRIS\Documents\Parrespet\masterfile_series Two stage engine in series (
stage)
Minor losses are made zero to compare with parallel configuration
  0 BEGIN       0
             1.9000E+06 a Mean P Pa
Gues             72.223 b Freq   Hz
                 300.00 c TBeg   K
Gues         1.1128E+05 d |p|    Pa
                 0.0000 e Ph(p)  deg
                 0.0000 f |U|    m^3/s
                 0.0000 g Ph(U)  deg
Optional Parameters
nitrogen       Gas type
    1 SURFACE     Closed end
    Same   2a 7.1630E-03 a Area    m^2                 1.1128E+05 A |p|     Pa
                                                           0.0000 B Ph(p)   deg
                                                       1.9627E-06 C |U|     m^3/s
                                                           180.00 D Ph(U)   deg
                                                           0.0000 E Htot    W
ideal          Solid type                                -0.10921 F Edot    W
    2 DUCT        tube
             7.1630E-03 a Area    m^2                  1.1011E+05 A |p|     Pa
                 0.3000 b Perim   m                    1.3071E-03 B Ph(p)   deg
                 0.1130 c Length  m                    1.5321E-02 C |U|     m^3/s
             2.0000E-03 d Srough                          -90.041 D Ph(U)   deg
Master-Slave Links                                         0.0000 E Htot    W
Optional Parameters                                      -0.63012 F Edot    W
ideal          Solid type
    3 TBRANCH     split
Gues        -6.1395E+05 a Re(Zb)  Pa-s/m^3             1.1011E+05 A |p|     Pa
Gues         6.8468E+06 b Im(Zb)  Pa-s/m^3             1.3071E-03 B Ph(p)   deg
Master-Slave Links                                     1.6017E-02 C |U|     m^3/s
                                                          -95.123 D Ph(U)   deg
Optional Parameters                                       -78.754 E HtotBr  W
                                                          -78.754 F EdotBr  W
                                                           78.124 G EdotTr  W
      4 RPN           Larea
    Same   4A 4.6558E-03 a G or T                        4.6558E-03 A ChngeMe
2a 9a -
      5 DUCT          Change Me
             4.4660E-03 a Area    m^2                  1.0419E+05 A |p|     Pa
                0.48412 b Perim   m                       0.23158 B Ph(p)   deg
                 0.1280 c Length  m                    2.6481E-02 C |U|     m^3/s
             2.0000E-03 d Srough                          -93.087 D Ph(U)   deg
Master-Slave Links                                        -78.754 E Htot    W
Optional Parameters                                       -79.857 F Edot    W
stainless      Solid type
      6 SOFTEND       Change Me
                                                       1.0419E+05 A |p|     Pa
                                                          0.23158 B Ph(p)   deg
                                                       2.6481E-02 C |U|     m^3/s
                                                          -93.087 D Ph(U)   deg
                                                          -78.754 E Htot    W
Possible targets                                          -79.857 F Edot    W
                                                         -0.13499 G Re(z)
                                                           2.3281 H Im(z)
                                                           300.00 I T       K
    7 DUCT        dummy duct
```

```
                       1.0000 b Perim  m               1.3071E-03 B Ph(p)  deg
                       0.0000 c Length m               1.5533E-03 C |U|    m^3/s
                       0.0000 d Srough                     23.998 D Ph(U)  deg
Master-Slave Links                                         78.754 E Htot   W
Optional Parameters                                        78.124 F Edot   W
ideal         Solid type
  8 BEGIN
    Same   0a 1.9000E+06 a Mean P Pa
    Same   0b     72.223 b Freq   Hz
                  300.00 c TBeg   K
    Same   7A 1.1011E+05 d |p|    Pa
    Same   7B 1.3071E-03 e Ph(p)  deg
    Same   7C 1.5533E-03 f |U|    m^3/s
    Same   7D     23.998 g Ph(U)  deg
Optional Parameters
Sameas   0     nitrogen Gas type
    9 DUCT        10
              2.5072E-03 a Area   m^2     Mstr     1.1012E+05 A |p|    Pa
                 0.17749 b Perim  m       9a      -2.7289E-02 B Ph(p)  deg
              1.0000E-02 c Length m                1.4275E-03 C |U|    m^3/s
              3.0000E-04 d Srough                      6.4470 D Ph(U)  deg
Master-Slave Links                                     78.124 E Htot   W
Optional Parameters                                    78.098 F Edot   W
stainless     Solid type
   10 MINOR         Change Me
    Same   9a 2.5072E-03 a Area   m^2              1.1012E+05 A |p|    Pa
                  4.0000 b K+                     -2.7633E-02 B Ph(p)  deg
                  0.0000 c K-                      1.4275E-03 C |U|    m^3/s
                                                       6.4470 D Ph(U)  deg
                                                       78.124 E Htot   W
                                                       78.094 F Edot   W
   11 TX            Rhx1             9
    Same   9a 2.5072E-03 a Area   m^2              1.1011E+05 A |p|    Pa
                  0.3460 b GasA/A                    -0.15867 B Ph(p)  deg
              1.5000E-02 c Length m                1.4142E-03 C |U|    m^3/s
              1.0000E-03 d radius m                   -3.6968 D Ph(U)  deg
Gues                -164.7 e HeatIn W                 -86.579 E Htot   W
Master-Slave Links                                     77.709 F Edot   W
Possible targets                                       300.00 G GasT   K
stainless     Solid type                               263.77 H SolidT K
   12 STKSCREEN  regen 1
              2.3578E-03 a Area   m^2              1.0520E+05 A |p|    Pa
                  0.7866 b VolPor                     0.64047 B Ph(p)  deg
              1.5000E-02 c Length m                3.0477E-03 C |U|    m^3/s
              2.7650E-05 d rh     m                   -25.152 D Ph(U)  deg
                  0.2000 e ksFrac                     -86.579 E Htot   W
Master-Slave Links                                     144.34 F Edot   W
                                                       300.00 G TBeg   K
stainless     Solid type                               610.49 H TEnd   K
   13 RPN           ChangeMe
                  0.0000 a G or T                  18.663    A ChngeMe
16e 11e + 11F + 12F -
   14 RPN           Tc-Reg
                  297.70 a G or T                 300.00     A FreeT
12G
   15 RPN           temp.R1
                  400.00 a G or T                 610.49     A FreeT
12H
```

```
    16 HX          hhx1
     Same   9a 2.5072E-03 a Area    m^2             1.0518E+05 A |p|     Pa
                   0.3800 b GasA/A                     0.61287 B Ph(p)   deg
               3.6000E-03 c Length m                3.0741E-03 C |U|     m^3/s
               9.0000E-04 d y0      m                   -26.23 D Ph(U)   deg
                   250.00 e HeatIn W                    163.42 E Htot    W
Master-Slave Links                                      144.24 F Edot    W
Possible targets                                        610.49 G GasT    K
stainless     Solid type                                807.92 H SolidT K
    17 STKDUCT     Change Me
     Same   9a 2.5072E-03 a Area    m^2             1.0449E+05 A |p|     Pa
     Same   9b    0.17749 b Perim   m                  0.30954 B Ph(p)   deg
     Same 18A 7.9400E-02 c Length m                 5.6523E-03 C |U|     m^3/s
               2.9500E-04 d WallA   m^2                -60.509 D Ph(U)   deg
Master-Slave Links                                      163.42 E Htot    W
                                                        143.99 F Edot    W
                                                        610.49 G TBeg    K
stainless     Solid type                                321.31 H TEnd    K
    18 RPN         cal. L-tbz
               2.5000E-02 a G or T                   7.9400E-02 A ChngeMe
5c 9c - 11c - 12c - 16c - 19c -
    19 TX          Rhx1
               2.3758E-03 a Area    m^2             1.0419E+05 A |p|     Pa
                   0.3460 b GasA/A                     0.23158 B Ph(p)   deg
               5.0000E-03 c Length m                5.7172E-03 C |U|     m^3/s
               1.0000E-03 d radius m                   -60.897 D Ph(U)   deg
                  -63.029 e HeatIn W                    100.39 E Htot    W
Targ               300.00 f SolidT K                    143.81 F Edot    W
Master-Slave Links                                      321.31 G GasT    K
stainless     Solid type                                300.00 H SolidT K
    20 UNION       Rejoin
       6 a         SegNum                           1.0419E+05 A |p|     Pa
TargSame   5A 1.0419E+05 b |p|Sft Pa                   0.23158 B Ph(p)   deg
TargSame   5B    0.23158 c Ph(p)S deg               3.1467E-02 C |U|     m^3/s
Possible targets                                       -87.533 D Ph(U)   deg
                                                        21.638 E Htot    W
                                                        63.954 F Edot    W
                                                        321.31 G T       K
    21 RPN         power output
                   5.0000 a G or T                      63.954   A FreeT
20F
    22 RPN         COP1
                   0.1000 a G or T                     0.10476 A ChngeMe
20F 16G /
    23 DUCT        Room temp duct
     Same   5a 4.4660E-03 a Area    m^2             1.0355E+05 A |p|     Pa
     Same   5b    0.48412 b Perim   m                  0.21936 B Ph(p)   deg
               1.0000E-02 c Length m                3.2260E-02 C |U|     m^3/s
               2.0000E-03 d Srough                     -87.591 D Ph(U)   deg
Master-Slave Links                                      21.638 E Htot    W
Optional Parameters                                     63.825 F Edot    W
ideal         Solid type
    24 TBRANCH     split
Gues          -7.1457E+04 a Re(Zb) Pa-s/m^3         1.0355E+05 A |p|     Pa
Gues           3.1581E+06 b Im(Zb) Pa-s/m^3            0.21936 B Ph(p)   deg
Master-Slave Links                                  3.2778E-02 C |U|     m^3/s
                                                       -91.077 D Ph(U)   deg
Optional Parameters                                    -38.388 E HtotBr W
```

```
                                                         -38.388 F EdotBr W
                                                          102.21 G EdotTr W
    25 RPN          Byp2-L
                    0.1000 a G or T                       0.1890  A ChngeMe
0.44 2c - 5c - 23c -
    26 RPN          Larea2
                4.3800E-03 a G or T                   4.6558E-03 A ChngeMe
2a 31a -
    27 DUCT         Change Me
   Same 26A 4.6558E-03 a Area   m^2     Mstr       9.6374E+04 A |p|    Pa
                   0.50883 b Perim  m       27a           0.32115 B Ph(p)  deg
                    0.1000 c Length m              4.0740E-02 C |U|    m^3/s
                3.0000E-04 d Srough                   -90.833 D Ph(U)  deg
Master-Slave Links                                    -38.388 E Htot   W
Optional Parameters                                   -39.537 F Edot   W
stainless     Solid type
    28 SOFTEND      Change Me
                                                   9.6374E+04 A |p|    Pa
                                                      0.32115 B Ph(p)  deg
                                                   4.0740E-02 C |U|    m^3/s
                                                      -90.833 D Ph(U)  deg
                                                      -38.388 E Htot   W
Possible targets                                      -39.537 F Edot   W
                                                  -3.0465E-02 G Re(z)
                                                       1.5124 H Im(z)
                                                       321.31 I T      K
  29 DUCT         dummy duct used to get input properties  23
                    1.0000 a Area   m^2            1.0355E+05 A |p|    Pa
                    1.0000 b Perim  m                 0.21936 B Ph(p)  deg
                    0.0000 c Length m              2.0452E-03 C |U|    m^3/s
                    0.0000 d Srough                    15.351 D Ph(U)  deg
Master-Slave Links                                     60.026 E Htot   W
Optional Parameters                                    102.21 F Edot   W
ideal         Solid type
 30 BEGIN
   Same   0a 1.9000E+06 a Mean P Pa
   Same   0b     72.223 b Freq   Hz
                 300.00 c TBeg   K
   Same 29A  1.0355E+05 d |p|    Pa
   Same 29B     0.21936 e Ph(p)  deg
   Same 29C  2.0452E-03 f |U|    m^3/s
   Same 29D      15.351 g Ph(U)  deg
Optional Parameters
Sameas    0    nitrogen Gas type
  31 DUCT         10
   Same   9a 2.5072E-03 a Area   m^2     Mstr      1.0356E+05 A |p|    Pa
                0.17752 b Perim  m       31a          0.17706 B Ph(p)  deg
             1.0000E-02 c Length m                 1.9757E-03 C |U|    m^3/s
             3.0000E-04 d Srough                       2.8448 D Ph(U)  deg
Master-Slave Links                                     102.21 E Htot   W
Optional Parameters                                    102.19 F Edot   W
stainless     Solid type
  32 MINOR        Change Me
   Same   9a 2.5072E-03 a Area   m^2               1.0353E+05 A |p|    Pa
                 4.0000 b K+                          0.17648 B Ph(p)  deg
                 4.0000 c K-                       1.9757E-03 C |U|    m^3/s
                                                       2.8448 D Ph(U)  deg
                                                       102.21 E Htot   W
```

```
                                                       102.17 F Edot    W
     33 TX          Rhx1             9
      Same 31a 2.5072E-03 a Area   m^2           1.0351E+05 A |p|     Pa
      Same 11b     0.3460 b GasA/A              -1.7146E-02 B Ph(p)   deg
      Same 11c 1.5000E-02 c Length m             1.9721E-03 C |U|     m^3/s
      Same 11d 1.0000E-03 d radius m               -4.0237 D Ph(U)   deg
   Gues            -233.38 e HeatIn W               -131.17 E Htot    W
   Master-Slave Links                                101.82 F Edot    W
   Possible targets                                  300.00 G GasT    K
   stainless     Solid type                          263.05 H SolidT  K
     34 STKSCREEN  regen 2
               2.3578E-03 a Area   m^2           9.6966E+04 A |p|     Pa
      Same 12b     0.7866 b VolPor                  0.79601 B Ph(p)   deg
               1.3200E-02 c Length m             4.0874E-03 C |U|     m^3/s
      Same 12d 2.7650E-05 d rh     m                -17.726 D Ph(U)   deg
      Same 12e     0.2000 e ksFrac                  -131.17 E Htot    W
   Master-Slave Links                                187.90 F Edot    W
                                                     300.00 G TBeg    K
   stainless     Solid type                          610.49 H TEnd    K
     35 RPN         ChangeMe
                    0.0000 a G or T                 29.113   A ChngeMe
   39e 33e + 33F + 34F -
     36 RPN         Tc-reg2
                    301.40 a G or T                 300.00   A FreeT
   34G
     37 RPN         temp.R2
   TargSame 15A     610.49 a G or T                 610.49   A FreeT
   34H
     38 RPN         ChangeMe
                    0.0000 a G or T                 348.58   A ChngeMe
   39e
     39 HX          hhx1
      Same 31a 2.5072E-03 a Area   m^2           9.6936E+04 A |p|     Pa
      Same 16b     0.3800 b GasA/A                  0.75328 B Ph(p)   deg
      Same 16c 3.6000E-03 c Length m             4.1047E-03 C |U|     m^3/s
      Same 16d 9.0000E-04 d y0     m                -18.507 D Ph(U)   deg
   Gues             348.58 e HeatIn W                217.41 E Htot    W
   Master-Slave Links                                187.81 F Edot    W
   Possible targets                                  610.49 G GasT    K
   stainless     Solid type                          885.78 H SolidT  K
     40 STKDUCT     Change Me
      Same 31a 2.5072E-03 a Area   m^2           9.6586E+04 A |p|     Pa
      Same 31b    0.17752 b Perim  m                0.44177 B Ph(p)   deg
      Same 41A 5.3200E-02 c Length m             5.2489E-03 C |U|     m^3/s
               2.9500E-04 d WallA  m^2              -41.833 D Ph(U)   deg
   Master-Slave Links                                217.41 E Htot    W
                                                     187.56 F Edot    W
                                                     610.49 G TBeg    K
   stainless     Solid type                          320.18 H TEnd    K
     41 RPN         calc.of tbz length
               5.0000E-02 a G or T               5.3200E-02 A ChngeMe
   27c 31c - 33c - 34c - 39c - 42c -
     42 TX          Rhx1
      Same 31a 2.5072E-03 a Area   m^2           9.6374E+04 A |p|     Pa
                    0.3460 b GasA/A                 0.32115 B Ph(p)   deg
               5.0000E-03 c Length m             5.2971E-03 C |U|     m^3/s
               1.0000E-03 d radius m                -42.437 D Ph(U)   deg
                   -63.029 e HeatIn W                154.39 E Htot    W
```

```
Targ              300.00 f SolidT K                        187.41 F Edot    W
Master-Slave Links                                         320.18 G GasT    K
stainless        Solid type                                300.00 H SolidT K
   43 RPN        ChangeMe
                  0.0000 a G or T                           0.0000 A ChngeMe
0.212 rho * 42C * 41a / 41a / 43a *
   44 IMPEDANCE  minor loss
    Same 43A      0.0000 a Re(Zs) Pa-s/m^3             9.6374E+04 A |p|     Pa
                  0.0000 b Im(Zs) Pa-s/m^3                0.32115 B Ph(p)   deg
Master-Slave Links                                     5.2971E-03 C |U|     m^3/s
                                                          -42.437 D Ph(U)   deg
                                                           154.39 E Htot    W
                                                           187.41 F Edot    W
   45 UNION      Rejoin
     28 a         SegNum                               9.6374E+04 A |p|     Pa
TargSame 27A 9.6374E+04 b |p|Sft Pa                       0.32115 B Ph(p)   deg
TargSame 27B     0.32115 c Ph(p)S deg                  4.4434E-02 C |U|     m^3/s
Possible targets                                          -85.719 D Ph(U)   deg
                                                           116.00 E Htot    W
                                                           147.87 F Edot    W
                                                           320.18 G T       K
   46 DUCT       tube
             7.1630E-03 a Area   m^2                   9.1406E+04 A |p|     Pa
                 0.3000 b Perim  m                        0.13149 B Ph(p)   deg
             8.0000E-02 c Length m                     5.3608E-02 C |U|     m^3/s
             2.0000E-03 d Srough                           -86.42 D Ph(U)   deg
Master-Slave Links                                         116.00 E Htot    W
Optional Parameters                                        147.35 F Edot    W
ideal            Solid type
   47 CONE       cone
             7.1630E-03 a AreaI  m^2                   8.6328E+04 A |p|     Pa
                 0.3000 b PerimI m                    -4.9885E-02 B Ph(p)   deg
             4.5000E-02 c Length m                     5.6920E-02 C |U|     m^3/s
             2.8000E-03 d AreaF  m^2                       -86.63 D Ph(U)   deg
                 0.1720 e PerimF m                         116.00 E Htot    W
             2.0000E-03 f Srough                           146.56 F Edot    W
Master-Slave Links
Optional Parameters
stainless        Solid type
   48 MINOR      Change Me
    Same 47d 2.8000E-03 a Area   m^2                   8.6241E+04 A |p|     Pa
                 0.5000 b K+                               1.1132 B Ph(p)   deg
                 0.5000 c K-                           5.6920E-02 C |U|     m^3/s
                                                           -86.63 D Ph(U)   deg
                                                           116.00 E Htot    W
                                                           96.651 F Edot    W
   49 DUCT       resonat.
    Same 47d 2.8000E-03 a Area   m^2                   6.2068E+04 A |p|     Pa
    Same 47e     0.1720 b Perim  m                        0.43482 B Ph(p)   deg
                 0.1260 c Length m                     6.1403E-02 C |U|     m^3/s
    Same 47f 2.0000E-03 d Srough                           -86.83 D Ph(U)   deg
Master-Slave Links                                         116.00 E Htot    W
Optional Parameters                                        90.942 F Edot    W
stainless        Solid type
   50 DUCT       resonat.
    Same 49a 2.8000E-03 a Area   m^2                   2.1728E+04 A |p|     Pa
    Same 49b     0.1720 b Perim  m                        -3.5983 B Ph(p)   deg
                 0.1960 c Length m                     6.5348E-02 C |U|     m^3/s
```

```
    Same 47f 2.0000E-03 d Srough                   -87.071 D Ph(U)   deg
Master-Slave Links                                  116.00 E Htot    W
Optional Parameters                                 80.702 F Edot    W
stainless     Solid type
   51 DUCT         resonat.
    Same 49a 2.8000E-03 a Area    m^2           2.0220E+04 A |p|     Pa
    Same 49b     0.1720 b Perim   m                 -171.2 B Ph(p)   deg
                 0.1960 c Length  m             6.5417E-02 C |U|     m^3/s
    Same 47f 2.0000E-03 d Srough                   -87.259 D Ph(U)   deg
Master-Slave Links                                  116.00 E Htot    W
Optional Parameters                                 69.794 F Edot    W
stainless     Solid type
   52 DUCT         resonat.
    Same 49a 2.8000E-03 a Area    m^2           8.4915E+04 A |p|     Pa
    Same 49b     0.1720 b Perim   m                -176.25 B Ph(p)   deg
                 0.3220 c Length  m             5.7203E-02 C |U|     m^3/s
    Same 47f 2.0000E-03 d Srough                   -87.513 D Ph(U)   deg
Master-Slave Links                                  116.00 E Htot    W
Optional Parameters                                 53.757 F Edot    W
stainless     Solid type
   53 MINOR        Change Me
    Same 47d 2.8000E-03 a Area    m^2           8.4894E+04 A |p|     Pa
                 0.5000 b K+                       -177.44 B Ph(p)   deg
                 0.5000 c K-                    5.7203E-02 C |U|     m^3/s
                                                   -87.513 D Ph(U)   deg
                                                    116.00 E Htot    W
                                                    3.0982 F Edot    W
   54 CONE         cone
    Same 47d 2.8000E-03 a AreaI   m^2           9.0007E+04 A |p|     Pa
    Same 47e     0.1720 b PerimI  m                -177.46 B Ph(p)   deg
             4.5000E-02 c Length  m             5.3937E-02 C |U|     m^3/s
    Same  2a 7.1630E-03 d AreaF   m^2              -87.512 D Ph(U)   deg
    Same  2b     0.3000 e PerimF  m                 116.00 E Htot    W
    Same 47f 2.0000E-03 f Srough                    2.3031 F Edot    W
Master-Slave Links
Optional Parameters
stainless     Solid type
   55 DUCT         Change Me
    Same 58a 7.1630E-03 a Area    m^2           1.0073E+05 A |p|     Pa
                 0.3000 b Perim   m                -177.47 B Ph(p)   deg
                 0.1990 c Length  m             3.0610E-02 C |U|     m^3/s
             2.0000E-03 d Srough                   -87.517 D Ph(U)   deg
Master-Slave Links                                  116.00 E Htot    W
Optional Parameters                                 1.1862 F Edot    W
ideal         Solid type
   56 RPN          ChangeMe
                 0.0000 a G or T                    0.2410  A ChngeMe
0.44 55c -
   57 DUCT         Change Me
    Same 58a 7.1630E-03 a Area    m^2           1.0440E+05 A |p|     Pa
    Same 58b     0.3000 b Perim   m                -177.48 B Ph(p)   deg
                 0.1280 c Length  m             1.4522E-02 C |U|     m^3/s
             2.0000E-03 d Srough                   -87.522 D Ph(U)   deg
Master-Slave Links                                  116.00 E Htot    W
Optional Parameters                                0.59871 F Edot    W
ideal         Solid type
   58 DUCT         tube
    Same  2a 7.1630E-03 a Area    m^2           1.0545E+05 A |p|     Pa
```

```
    Same   2b      0.3000 b Perim  m                      -177.48 B Ph(p)   deg
                   0.1130 c Length m                   1.9689E-06 C |U|     m^3/s
    Same 47f 2.0000E-03 d Srough                          -177.48 D Ph(U)   deg
Master-Slave Links                                         116.00 E Htot    W
Optional Parameters                                       0.10381 F Edot    W
ideal        Solid type
   59 SURFACE      Change Me
    Same   2a 7.1630E-03 a Area    m^2                 1.0545E+05 A |p|     Pa
                                                          -177.48 B Ph(p)   deg
                                                       1.2949E-15 C |U|     m^3/s
                                                           91.065 D Ph(U)   deg
                                                           116.00 E Htot    W
ideal        Solid type                               -1.7354E-12 F Edot    W
   60 HARDEND      Change Me
Targ               0.0000 a R(1/z)                     1.0545E+05 A |p|     Pa
Targ               0.0000 b I(1/z)                        -177.48 B Ph(p)   deg
                                                       1.2949E-15 C |U|     m^3/s
                                                           91.065 D Ph(U)   deg
Possible targets                                           116.00 E Htot    W
                                                      -1.7354E-12 F Edot    W
                                                      -3.1785E-16 G R(1/z)
                                                      -1.2500E-14 H I(1/z)
   61 RPN          Acoustic Polwer
                   0.0000 a G or T                      152.72    A ChngeMe
34F 33F - 12F + 11F -
   62 RPN          Eta & Carnot
                   0.0000 a G or T                        0.24704 A ChngeMe
                                                          0.50859 B ChngeMe
1 34G 34H / - 45F 16e 39e + /
   63 RPN          Eta_r
                   0.0000 a G or T                        0.48573 A ChngeMe
62A 62B /
   64 RPN          Dr
                   0.0000 a G or T                        30.800  A ChngeMe
                                                          5.5498  B ChngeMe
60A 0a / 100 * 64A 64A *
   65 RPN          Dr Engine side
                   0.0000 a G or T                        34.303  A ChngeMe
                                                          5.8569  B ChngeMe
0d 0a / 100 * 65A 65A *
   66 RPN          ChangeMe
                   0.0000 a G or T                        83.918  A ChngeMe
45F 20F -
   67 RPN          Eta engines
                   0.0000 a G or T                        0.25582 A ChngeMe
                                                          0.24074 B ChngeMe
66A 39e / 20F 16e /
```

Appendix B4: Serial configuration with load

```
F:\series_load Two stage engine in series (multi stage) with external load
Minor losses are made zero to compare with parallel configuration
    0 BEGIN        0
                 1.9000E+06 a Mean P Pa
Gues                 64.839 b Freq   Hz
                     300.00 c TBeg   K
                 4.3700E+04 d |p|    Pa
                     0.0000 e Ph(p)  deg
                     0.0000 f |U|    m^3/s
                     0.0000 g Ph(U)  deg
Optional Parameters
nitrogen       Gas type
    1 SURFACE     Closed end
    Same   2a 7.1630E-03 a Area    m^2                4.3700E+04 A |p|     Pa
                                                          0.0000 B Ph(p)   deg
                                                      7.3030E-07 C |U|     m^3/s
                                                          180.00 D Ph(U)   deg
                                                          0.0000 E Htot    W
ideal            Solid type                          -1.5957E-02 F Edot    W
    2 DUCT        tube
                 7.1630E-03 a Area    m^2                4.3328E+04 A |p|     Pa
                     0.3000 b Perim   m                  1.1105E-03 B Ph(p)   deg
                     0.1130 c Length  m                  5.4055E-03 C |U|     m^3/s
                 2.0000E-03 d Srough                        -90.044 D Ph(U)   deg
Master-Slave Links                                           0.0000 E Htot    W
Optional Parameters                                     -9.1957E-02 F Edot    W
ideal            Solid type
    3 TBRANCH     split
Gues            -9.2184E+05 a Re(Zb) Pa-s/m^3          4.3328E+04 A |p|     Pa
Gues             7.8153E+06 b Im(Zb) Pa-s/m^3          1.1105E-03 B Ph(p)   deg
Master-Slave Links                                      5.5058E-03 C |U|     m^3/s
                                                           -96.726 D Ph(U)   deg
Optional Parameters                                        -13.972 E HtotBr  W
                                                           -13.972 F EdotBr  W
                                                            13.880 G EdotTr  W
      4 RPN         Larea
    Same   4A 4.6023E-03 a G or T                       4.6023E-03 A ChngeMe
2a 9a -
      5 DUCT        Change Me
    Same   4A 4.6023E-03 a Area    m^2                4.1533E+04 A |p|     Pa
                     0.4404 b Perim   m                   0.22475 B Ph(p)   deg
                     0.1280 c Length  m                9.3310E-03 C |U|     m^3/s
                 2.0000E-03 d Srough                       -93.952 D Ph(U)   deg
Master-Slave Links                                         -13.972 E Htot    W
Optional Parameters                                        -14.112 F Edot    W
stainless        Solid type
      6 SOFTEND     Change Me
                                                        4.1533E+04 A |p|     Pa
                                                           0.22475 B Ph(p)   deg
                                                        9.3310E-03 C |U|     m^3/s
                                                           -93.952 D Ph(U)   deg
                                                           -13.972 E Htot    W
Possible targets                                           -14.112 F Edot    W
                                                            -0.198 G Re(z)
                                                            2.7115 H Im(z)
                                                            300.00 I T       K
    7 DUCT        dummy duct
                     1.0000 a Area    m^2                4.3328E+04 A |p|     Pa
```

```
                      1.0000 b Perim   m                    1.1105E-03 B Ph(p)   deg
                      0.0000 c Length m                     6.4375E-04 C |U|     m^3/s
                      0.0000 d Srough                           5.5683 D Ph(U)   deg
Master-Slave Links                                              13.972 E Htot    W
Optional Parameters                                             13.880 F Edot    W
ideal          Solid type
  8 BEGIN
                  2.0000E+06 a Mean P Pa
    Same   0b         64.839 b Freq   Hz
                      300.00 c TBeg   K
    Same   7A 4.3328E+04 d |p|    Pa
    Same   7B 1.1105E-03 e Ph(p)  deg
    Same   7C 6.4375E-04 f |U|    m^3/s
    Same   7D     5.5683 g Ph(U)  deg
Optional Parameters
Sameas    0      nitrogen Gas type
    9 DUCT        10
              2.5607E-03 a Area   m^2      Mstr         4.3328E+04 A |p|     Pa
                 0.17937 b Perim  m        9a          -2.9234E-02 B Ph(p)   deg
              1.0000E-02 c Length m                     6.4813E-04 C |U|     m^3/s
              3.0000E-04 d Srough                          -8.7982 D Ph(U)   deg
Master-Slave Links                                          13.880 E Htot    W
Optional Parameters                                         13.877 F Edot    W
stainless      Solid type
   10 RPN         minor loss
                  0.0000 a G or T                              0.0000 A ChngeMe
0.212 rho * 9C * 9a / 9a / 10a *
   11 IMPEDANCE   Change Me
    Same 10A      0.0000 a Re(Zs) Pa-s/m^3                  4.3328E+04 A |p|     Pa
                  0.0000 b Im(Zs) Pa-s/m^3                 -2.9234E-02 B Ph(p)   deg
Master-Slave Links                                          6.4813E-04 C |U|     m^3/s
                                                               -8.7982 D Ph(U)   deg
                                                                13.880 E Htot    W
                                                                13.877 F Edot    W
   12 TX          Rhx1               9
    Same   9a 2.5607E-03 a Area   m^2                       4.3297E+04 A |p|     Pa
                  0.3460 b GasA/A                             -0.16655 B Ph(p)   deg
              1.5000E-02 c Length m                         6.6435E-04 C |U|     m^3/s
              1.0000E-03 d radius m                            -16.201 D Ph(U)   deg
Gues             -38.564 e HeatIn W                            -24.683 E Htot    W
Master-Slave Links                                              13.823 F Edot    W
Possible targets                                                300.00 G GasT    K
stainless      Solid type                                       283.04 H SolidT  K
   13 STKSCREEN   regen 1
    Same   9a 2.5607E-03 a Area   m^2                       4.2043E+04 A |p|     Pa
                  0.7866 b VolPor                              0.64786 B Ph(p)   deg
              1.5000E-02 c Length m                         1.0694E-03 C |U|     m^3/s
              2.7650E-05 d rh     m                            -34.679 D Ph(U)   deg
                  0.2000 e ksFrac                              -24.683 E Htot    W
Master-Slave Links                                              18.341 F Edot    W
                                                                300.00 G TBeg    K
stainless      Solid type                                       436.62 H TEnd    K
   14 RPN         Tc-Reg
                  297.70 a G or T                        300.00     A FreeT
13G
   15 RPN         temp.R1
                  627.93 a G or T                        436.62     A FreeT
13H
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```
    16 HX           hhx1
     Same   9a 2.5607E-03 a Area    m^2               4.2027E+04 A |p|     Pa
                   0.3800 b GasA/A                       0.61992 B Ph(p)   deg
               3.6000E-03 c Length m                  1.0818E-03 C |U|     m^3/s
               9.0000E-04 d y0      m                    -35.641 D Ph(U)   deg
 Gues              55.120 e HeatIn W                      30.437 E Htot    W
 Master-Slave Links                                       18.330 F Edot    W
 Possible targets                                         436.62 G GasT    K
 stainless     Solid type                                 478.67 H SolidT K
    17 STKDUCT     Change Me
     Same   9a 2.5607E-03 a Area    m^2               4.1675E+04 A |p|     Pa
     Same   9b    0.17937 b Perim   m                    0.30383 B Ph(p)   deg
     Same 18A 7.9400E-02 c Length m                   2.0695E-03 C |U|     m^3/s
               2.9500E-04 d WallA   m^2                  -64.573 D Ph(U)   deg
 Master-Slave Links                                       30.437 E Htot    W
                                                          18.308 F Edot    W
                                                          436.62 G TBeg    K
 stainless     Solid type                                 222.18 H TEnd    K
    18 RPN          cal. L-tbz
               2.5000E-02 a G or T                     7.9400E-02 A ChngeMe
 5c 9c - 12c - 13c - 16c - 19c -
    19 TX           Rhx1
     Same   9a 2.5607E-03 a Area    m^2               4.1533E+04 A |p|     Pa
                   0.3460 b GasA/A                       0.22475 B Ph(p)   deg
               5.0000E-03 c Length m                  2.0941E-03 C |U|     m^3/s
               1.0000E-03 d radius m                     -64.907 D Ph(U)   deg
 Gues              252.53 e HeatIn W                      282.97 E Htot    W
 Targ              300.00 f SolidT K                      18.288 F Edot    W
 Master-Slave Links                                       222.18 G GasT    K
 stainless     Solid type                                 300.00 H SolidT K
    20 RPN          ChangeMe
                   0.0000 a G or T                         0.0000 A ChngeMe
 0.212 rho * 19C * 19a / 19a / 20a *
    21 IMPEDANCE  minor loss
     Same 20A      0.0000 a Re(Zs) Pa-s/m^3           4.1533E+04 A |p|     Pa
                   0.0000 b Im(Zs) Pa-s/m^3              0.22475 B Ph(p)   deg
 Master-Slave Links                                   2.0941E-03 C |U|     m^3/s
                                                         -64.907 D Ph(U)   deg
                                                          282.97 E Htot    W
                                                          18.288 F Edot    W
    22 UNION        Rejoin
       6 a          SegNum                            4.1533E+04 A |p|     Pa
 Targ          1.0471E+05 b |p|Sft Pa                    0.22475 B Ph(p)   deg
 Targ              0.5499 c Ph(p)S deg                1.1208E-02 C |U|     m^3/s
 Possible targets                                        -88.747 D Ph(U)   deg
                                                          269.00 E Htot    W
                                                          4.1756 F Edot    W
                                                          222.18 G T       K
    23 RPN          power output
                   5.0000 a G or T                        4.1756  A FreeT
 22F
    24 RPN          COP1
                   0.1000 a G or T                     9.5636E-03 A ChngeMe
 22F 16G /
    25 DUCT         Room temp duct
               7.1630E-03 a Area    m^2               4.1336E+04 A |p|     Pa
     Same   2b     0.3000 b Perim   m                    0.22022 B Ph(p)   deg
               1.0000E-02 c Length m                  1.1640E-02 C |U|     m^3/s
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                 2.0000E-03 d Srough                        -88.787 D Ph(U)   deg
Master-Slave Links                                          269.00 E Htot    W
Optional Parameters                                         4.1702 F Edot    W
ideal            Solid type
   26 TBRANCH    split
Gues          -4.0886E+05 a Re(Zb) Pa-s/m^3            4.1336E+04 A |p|     Pa
Gues           3.5585E+06 b Im(Zb) Pa-s/m^3               0.22022 B Ph(p)   deg
Master-Slave Links                                     1.1540E-02 C |U|     m^3/s
                                                          -96.334 D Ph(U)   deg
Optional Parameters                                       -27.225 E HtotBr  W
                                                          -27.225 F EdotBr  W
                                                           31.395 G EdotTr  W

     27 RPN          Byp2-L
                     0.1000 a G or T                       0.1890  A ChngeMe
0.44 2c - 5c - 25c -
     28 RPN          Larea2
                 4.3800E-03 a G or T                    4.6023E-03 A ChngeMe
2a 33a -
     29 DUCT         Change Me
    Same 28A 4.6023E-03 a Area   m^2                   3.7889E+04 A |p|     Pa
                     0.5059 b Perim  m                    0.76966 B Ph(p)   deg
                     0.1000 c Length m                 1.4185E-02 C |U|     m^3/s
                 2.0000E-03 d Srough                      -95.072 D Ph(U)   deg
Master-Slave Links                                        -27.225 E Htot    W
Optional Parameters                                       -27.351 F Edot    W
stainless        Solid type
     30 SOFTEND      Change Me
                                                       3.7889E+04 A |p|     Pa
                                                          0.76966 B Ph(p)   deg
                                                       1.4185E-02 C |U|     m^3/s
                                                          -95.072 D Ph(U)   deg
                                                          -27.225 E Htot    W
Possible targets                                          -27.351 F Edot    W
                                                         -0.13576 G Re(z)
                                                           1.3269 H Im(z)
                                                           222.18 I T       K
   31 DUCT           dummy duct used to get input properties  23
                     1.0000 a Area   m^2               4.1336E+04 A |p|     Pa
                     1.0000 b Perim  m                    0.22022 B Ph(p)   deg
                     0.0000 c Length m                 1.5289E-03 C |U|     m^3/s
                     0.0000 d Srough                      -6.2927 D Ph(U)   deg
Master-Slave Links                                         296.22 E Htot    W
Optional Parameters                                        31.395 F Edot    W
ideal            Solid type
 32 BEGIN
    Same   0a 1.9000E+06 a Mean P Pa
    Same   0b     64.839 b Freq   Hz
                  300.00 c TBeg   K
    Same  31A 4.1336E+04 d |p|    Pa
    Same  31B    0.22022 e Ph(p)  deg
    Same  31C 1.5289E-03 f |U|    m^3/s
    Same  31D    -6.2927 g Ph(U)  deg
Optional Parameters
Sameas    0    nitrogen Gas type
   33 DUCT           10
                 2.5607E-03 a Area   m^2      Mstr      4.1327E+04 A |p|     Pa
                     0.1794 b Perim  m        33a          0.14858 B Ph(p)   deg
                 1.0000E-02 c Length m                 1.5554E-03 C |U|     m^3/s
```

```
               3.0000E-04 d Srough                      -12.244 D Ph(U)   deg
Master-Slave Links                                       31.395 E Htot    W
Optional Parameters                                      31.392 F Edot    W
stainless      Solid type
   34 RPN          minor loss
                   0.0000 a G or T                       0.0000 A ChngeMe
0.212 rho * 33C * 33a / 33a / 34a *
   35 IMPEDANCE   Change Me
    Same 34A       0.0000 a Re(Zs) Pa-s/m^3          4.1327E+04 A |p|     Pa
                   0.0000 b Im(Zs) Pa-s/m^3             0.14858 B Ph(p)   deg
Master-Slave Links                                   1.5554E-03 C |U|     m^3/s
                                                        -12.244 D Ph(U)   deg
                                                         31.395 E Htot    W
                                                         31.392 F Edot    W
   36 TX           Rhx1                 9
    Same 33a 2.5607E-03 a Area    m^2                4.1253E+04 A |p|     Pa
    Same 12b     0.3460 b GasA/A                       -0.17625 B Ph(p)   deg
    Same 12c 1.5000E-02 c Length m                   1.5737E-03 C |U|     m^3/s
    Same 12d 1.0000E-03 d radius m                      -15.345 D Ph(U)   deg
Gues            -79.317 e HeatIn W                      -47.921 E Htot    W
Master-Slave Links                                       31.328 F Edot    W
Possible targets                                         300.00 G GasT    K
stainless      Solid type                                284.99 H SolidT  K
   37 STKSCREEN  regen 2
    Same 33a 2.5607E-03 a Area    m^2                3.8151E+04 A |p|     Pa
    Same 13b     0.7866 b VolPor                         1.3650 B Ph(p)   deg
               1.3200E-02 c Length m                 2.3473E-03 C |U|     m^3/s
    Same 13d 2.7650E-05 d rh      m                     -23.208 D Ph(U)   deg
    Same 13e     0.2000 e ksFrac                        -47.921 E Htot    W
Master-Slave Links                                       40.720 F Edot    W
                                                         300.00 G TBeg    K
stainless      Solid type                                436.62 H TEnd    K
   38 RPN          Tc-reg2
                   301.40 a G or T                      300.00     A FreeT
37G
   39 RPN          temp.R2
TargSame 15A     436.62 a G or T                        436.62     A FreeT
37H
   40 HX           hhx1
    Same 33a 2.5607E-03 a Area    m^2                3.8125E+04 A |p|     Pa
    Same 16b     0.3800 b GasA/A                         1.2924 B Ph(p)   deg
    Same 16c 3.6000E-03 c Length m                   2.3556E-03 C |U|     m^3/s
    Same 16d 9.0000E-04 d y0      m                     -23.676 D Ph(U)   deg
Gues             99.847 e HeatIn W                       51.926 E Htot    W
Master-Slave Links                                       40.708 F Edot    W
Possible targets                                         436.62 G GasT    K
stainless      Solid type                                514.77 H SolidT  K
   41 STKDUCT     Change Me
    Same 33a 2.5607E-03 a Area    m^2                3.7889E+04 A |p|     Pa
    Same 33b     0.1794 b Perim   m                     0.76882 B Ph(p)   deg
    Same 42A 5.8200E-02 c Length m                   2.8287E-03 C |U|     m^3/s
               2.9500E-04 d WallA   m^2                  -39.85 D Ph(U)   deg
Master-Slave Links                                       51.926 E Htot    W
                                                         40.676 F Edot    W
                                                         436.62 G TBeg    K
stainless      Solid type                                300.00 H TEnd    K
   42 RPN          calc.of tbz length
               5.0000E-02 a G or T                   5.8200E-02 A ChngeMe
```

```
29c 33c - 36c - 37c - 40c - 0.0 -
   43 RPN          ChangeMe
Targ               300.00 a G or T                      300.00     A ChngeMe
41H
   44 IMPEDANCE  minor loss
    Same 43A       300.00 a Re(Zs) Pa-s/m^3           3.7889E+04 A |p|     Pa
                   0.0000 b Im(Zs) Pa-s/m^3              0.76966 B Ph(p)   deg
Master-Slave Links                                    2.8287E-03 C |U|     m^3/s
                                                          -39.85 D Ph(U)   deg
                                                          51.926 E Htot    W
                                                          40.675 F Edot    W
   45 UNION        Rejoin
     30 a          SegNum                             3.7889E+04 A |p|     Pa
Targ           9.8327E+04 b |p|Sft Pa                    0.76966 B Ph(p)   deg
Targ               0.7405 c Ph(p)S deg                1.5968E-02 C |U|     m^3/s
Possible targets                                         -86.706 D Ph(U)   deg
                                               P          24.701 E Htot    W
                                                          13.324 F Edot    W
                                                          300.00 G T       K
   46 DUCT         tube
               7.1630E-03 a Area   m^2                3.6178E+04 A |p|     Pa
                   0.3000 b Perim  m                     0.66532 B Ph(p)   deg
               8.0000E-02 c Length m                  1.9220E-02 C |U|     m^3/s
               2.0000E-03 d Srough                       -87.148 D Ph(U)   deg
Master-Slave Links                                        24.701 E Htot    W
Optional Parameters                                       13.265 F Edot    W
ideal          Solid type
   47 CONE         cone
               7.1630E-03 a AreaI  m^2                3.4273E+04 A |p|     Pa
                   0.3000 b PerimI m                     0.55557 B Ph(p)   deg
               4.5000E-02 c Length m                  2.0334E-02 C |U|     m^3/s
               2.3543E-03 d AreaF  m^2                   -87.272 D Ph(U)   deg
                   0.1720 e PerimF m                      24.701 E Htot    W
               2.0000E-03 f Srough                        13.206 F Edot    W
Master-Slave Links
Optional Parameters
stainless      Solid type
   48 DUCT         resonat.
    Same 47d 2.3543E-03 a Area   m^2                  2.4725E+04 A |p|     Pa
    Same 47e     0.1720 b Perim  m                      -0.16288 B Ph(p)   deg
                 0.1230 c Length m                    2.1645E-02 C |U|     m^3/s
    Same 47f 2.0000E-03 d Srough                         -87.429 D Ph(U)   deg
Master-Slave Links                                        24.701 E Htot    W
Optional Parameters                                       12.763 F Edot    W
stainless      Solid type
   49 DUCT         resonat.
    Same 48a 2.3543E-03 a Area   m^2                      8260.1 A |p|     Pa
    Same 48b     0.1720 b Perim  m                       -4.9192 B Ph(p)   deg
                 0.2000 c Length m                    2.2839E-02 C |U|     m^3/s
    Same 47f 2.0000E-03 d Srough                         -87.641 D Ph(U)   deg
Master-Slave Links                                        24.701 E Htot    W
Optional Parameters                                       11.951 F Edot    W
stainless      Solid type
   50 DUCT         resonat.
    Same 48a 2.3543E-03 a Area   m^2                      8798.6 A |p|     Pa
    Same 48b     0.1720 b Perim  m                       -171.48 B Ph(p)   deg
                 0.2000 c Length m                    2.2819E-02 C |U|     m^3/s
    Same 47f 2.0000E-03 d Srough                         -87.822 D Ph(U)   deg
```

```
Master-Slave Links                                        24.701 E Htot    W
Optional Parameters                                       11.094 F Edot    W
stainless      Solid type
    51 DUCT          resonat.
     Same 48a 2.3543E-03 a Area   m^2              3.4305E+04 A |p|     Pa
     Same 48b     0.1720 b Perim  m                   -176.48 B Ph(p)   deg
                  0.3170 c Length m                2.0326E-02 C |U|     m^3/s
     Same 47f 2.0000E-03 d Srough                     -88.098 D Ph(U)   deg
Master-Slave Links                                        24.701 E Htot    W
Optional Parameters                                       9.8652 F Edot    W
stainless      Solid type
    52 CONE          cone
     Same 47d 2.3543E-03 a AreaI  m^2              3.6209E+04 A |p|     Pa
     Same 47e     0.1720 b PerimI m                   -176.57 B Ph(p)   deg
              4.5000E-02 c Length m                1.9211E-02 C |U|     m^3/s
     Same  2a 7.1630E-03 d AreaF  m^2                 -88.185 D Ph(U)   deg
     Same  2b     0.3000 e PerimF m                    24.701 E Htot    W
     Same 47f 2.0000E-03 f Srough                      9.8060 F Edot    W
Master-Slave Links
Optional Parameters
stainless      Solid type
    53 RPN           ChangeMe
                  0.0000 a G or T                      0.1130  A ChngeMe
0.44 55c - 54c -
    54 DUCT          Change Me
     Same  2a 7.1630E-03 a Area   m^2              3.9861E+04 A |p|     Pa
                  0.3000 b Perim  m                   -176.76 B Ph(p)   deg
                  0.1990 c Length m          P     1.0871E-02 C |U|     m^3/s
              2.0000E-03 d Srough                      -89.32 D Ph(U)   deg
Master-Slave Links                                        24.701 E Htot    W
Optional Parameters                                       9.6659 F Edot    W
ideal          Solid type
    55 DUCT          Change Me
     Same  2a 7.1630E-03 a Area   m^2              4.1110E+04 A |p|     Pa
     Same  2b     0.3000 b Perim  m                   -176.87 B Ph(p)   deg
                  0.1280 c Length m          P     5.1826E-03 C |U|     m^3/s
              2.0000E-03 d Srough                     -92.032 D Ph(U)   deg
Master-Slave Links                                        24.701 E Htot    W
Optional Parameters                                       9.5851 F Edot    W
ideal          Solid type
    56 RPN           ChangeMe
                  0.0000 a G or T    P              8.0795E-02 A ChngeMe
54F 55F -
    57 DUCT          tube
     Same  2a 7.1630E-03 a Area   m^2              4.1467E+04 A |p|     Pa
     Same  2b     0.3000 b Perim  m                   -176.96 B Ph(p)   deg
     Same 53A     0.1130 c Length m                4.6020E-04 C |U|     m^3/s
     Same 47f 2.0000E-03 d Srough                     -172.81 D Ph(U)   deg
Master-Slave Links                                        24.701 E Htot    W
Optional Parameters                                       9.5166 F Edot    W
ideal          Solid type
    58 SURFACE       Change Me
     Same  2a 7.1630E-03 a Area   m^2        P     4.1467E+04 A |p|     Pa
                                             P        -176.96 B Ph(p)   deg
                                                   4.5951E-04 C |U|     m^3/s
                                                      -172.81 D Ph(U)   deg
                                                       24.701 E Htot    W
ideal          Solid type                              9.5023 F Edot    W
```

```
    59 IMPEDANCE  Change Me
     OPlt      9.0000E+07 a Re(Zs) Pa-s/m^3          3000.2 A |p|    Pa
                   0.0000 b Im(Zs) Pa-s/m^3          97.241 B Ph(p)  deg
Master-Slave Links                               4.5951E-04 C |U|    m^3/s
                                                    -172.81 D Ph(U)  deg
                                                     24.701 E Htot   W
                                                 5.9852E-04 F Edot   W

    60 COMPLIANCE Change Me
               5.7000E-02 a SurfAr m^2               3000.2 A |p|    Pa
               1.0000E-03 b Volume m^3               97.241 B Ph(p)  deg
Master-Slave Links                               3.2018E-14 C |U|    m^3/s
                                                    -24.788 D Ph(U)  deg
                                                     24.701 E Htot   W
ideal          Solid type                       -2.5473E-11 F Edot   W
    61 HARDEND     Change Me
Targ                   0.0000 a R(1/z)      P        3000.2 A |p|    Pa
Targ                   0.0000 b I(1/z)      P        97.241 B Ph(p)  deg
                                                 3.2018E-14 C |U|    m^3/s
                                                    -24.788 D Ph(U)  deg
Possible targets                                     24.701 E Htot   W
                                                -2.5473E-11 F Edot   W
                                                -5.9536E-12 G R(1/z)
                                                -9.5171E-12 H I(1/z)

    62 RPN         Carnot
                   0.0000 a G or T               8.5979E-02 A ChngeMe
                                                     0.3129  B ChngeMe
1 13G 13H / - 45F 16e 40e + /
    63 RPN         ChangeMe
                   0.0000 a G or T               8.5979E-02 A ChngeMe
                                                     0.3129  B ChngeMe
1 37G 37H / - 45F 16e 40e + /
    64 RPN         ChangeMe
                   0.0000 a G or T                  0.27478 A ChngeMe
63A 63B /
    65 RPN         Drive Ratio
Targ           2.3000E-02 a G or T               2.3000E-02 A ChngeMe
0d 0a /
    66 RPN         ChangeMe
                   0.0000 a G or T                   9.1483  A ChngeMe
45F 22F -
    67 RPN         ChangeMe
                   0.0000 a G or T               7.5755E-02 A ChngeMe
                                                 9.1623E-02 B ChngeMe
66A 40e / 22F 16e /
```

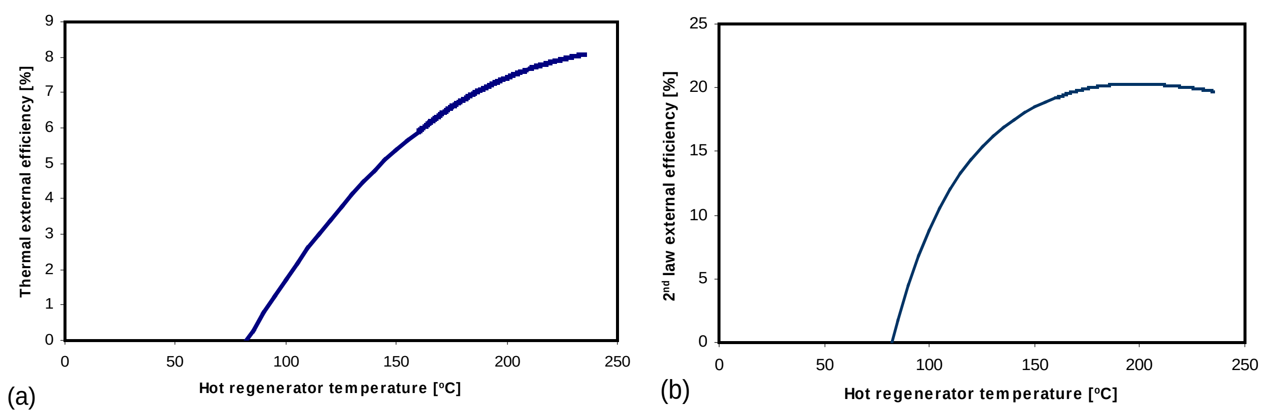


Figure B1 (a) Thermal and (b) second law efficiency of the load power in the DeltaEC simulation of the serial configuration.

Appendix C: Apparatuses dictionary

Driver

Generation of sound is done by a heat driven engine, mechanical pistons, or a speaker. The heat driven engine also can crate a temperature gradient from acoustic energy and will be discussed in S2.2.2. In order to optimize the driver different components are added to the system.

Linear motor
Acoustic waves can be created by acoustic power in speakers, or by piston displacement. Pistons have a better efficiency in converting electricity into mechanical acoustic power, which gives this technology currently the upper edge in thermoacoustic cooling or heating with electricity.

Driver/Load

Stack
The stack is an effective surface area for the transformation of acoustic energy into thermal energy, and vice versa. The stack can be a prime mover, or a heat pump/refrigerator. All stacks are permeable in the axial direction. The word stack is used for interactions with a standing wave.
A mathematical determination can be made whether a stack is a motor or a consumer of acoustic energy by observing the critical temperature gradient. When the temperature gradient within the stack or regenerator is higher than the critical gradient then acoustic power is produced. Acoustic power can be transferred into a temperature gradient until it reaches the critical value.
There is a theoretical critical temperature for a hypothetical system without viscous losses, when the heat introduced by the pressure wave equals the heat extracted by the same wave. The critical temperature determines whether the system is an acoustic driver, or an absorber of acoustic energy. In reality there are viscous losses, which results in two critical temperatures with a comparable deviation from this critical temperature. When the temperature is between these values, the acoustic effect is ineffective, and acoustic energy is used to transport heat from the hot to the cold side.
Swift (1988) derived a critical temperature gradient.

$$\frac{\partial T}{\partial x}_{crit} = \frac{T_m \beta \omega}{\rho_m c_p} \frac{p_a}{x_a} \qquad \text{(C1)}$$

Where T_m is the average temperature of the stack, x_a the length of the stack, all constants taken from the working fluid.

Swift (1988) further derived a relationship between design choices, and the attainable heat flux.

$$\dot{Q} \sim \Pi \delta_T T_m \beta p_a u_a \left(\frac{\Delta T}{\Delta T_c} - 1 \right) \qquad \text{(C2)}$$

With Π the perimeter of the cross section of the stack.

Regenerator
The regenerator is explained in detail in chapter 2, it is an apparatus similar to the stack. The regenerator transfers heat into acoustic energy, or visa versa. The acoustic energy being in this case a traveling wave.
Because the regenerator has favorable conditions, concerning the equal phase of pressure, and volumetric flow, it can constantly exchange heat with the medium. The ratio between viscous, and thermal boundary layer is not important anymore.
What is important is the thermal penetration depth. The pressure drop within the regenerator must be as low as possible while the surface area remains high. Ideally the hydraulic diameter shouldn't

exceed twice the thermal penetration depth.

$$\delta_{T,penetration} = \sqrt{\frac{2k_{regen}}{\rho_{regen} c_{p,regen} \omega}} \qquad \text{(C3)}$$

Jet Pump

Section 2.3.1 states why direct current in the traveling wave loop in unfavorable. The torus is asymmetrical, and so is the friction and the time-delay in different ends of the torus. This would result in a direct current beside the alternating current to compensate the friction and time delay effects. A Jet pump could be introduced to prevent this. The most simple jet pump can be a narrow cone geometry. The cone shape introduces a pressure loss, which is in theory equally asymmetric in the opposite direction of the torus, Backhaus and Swift (2000) concluded the theoretical required pressure drop in the jet pump can be expressed by:

$$\Delta \overline{p}_{jetpump} = \frac{R}{2\rho_m} \operatorname{Re}\left(\rho_a \overline{U}_a\right) \qquad \text{(C4)}$$

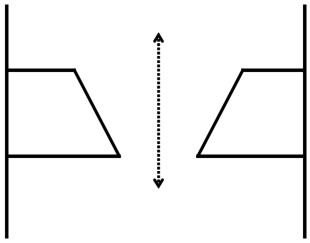


Figure C1 Jet pump

They designed a jet pump with a different flow loss in different directions, this principle can be expressed:

$$\Delta \overline{p}_{jetpump} = \frac{\rho_m \left(U_{a,jetpump}\right)^2}{8A^2} \left(K_{s,expansion} - K_{s,compression} + \left(\frac{A_s}{A_b}\right)^2 \left(K_{b,compression} - K_{b,expansion}\right) \right) \qquad \text{(C5)}$$

Where K is the friction constant while b and s represent the wide, and the small side.

Membrane

The jet pump operates by the introduction of unwanted pressure losses, and would in theory only completely block Gedeon streaming (section 2.3.1) at one specific condition, which is often slightly different in reality than in practice. A membrane can transfer impulse while it is impenetrable for the working fluid. The inelastic losses are small and the heat conduction through the membrane is also small.

Heat exchangers

In literature heat exchangers are explained, and tested extensively. What is important in the thermoacoustic system is the temperature difference, and temperature gradient over the stack/ regenerator $\Delta T = \left(T_h - T_c\right)$, and $\partial T / \partial x_a$.

Piezoelectric elements

A piezoelectric element can convert acoustic energy into electricity. In the test setup a load is applied to the acoustic resonator, which causes the same damping as a piezoelectric element would. If a setup is used for the production of electrical power the load power is very important.

Distribution

Resonator

Acoustic waves travel in the radial direction of a spherical coordinate system. This would lead to the dispersion of energy, and a reduction of the energy density in an acoustic wave. In order to prevent a reduction of energy density the sound wave is contained within a tube of impermeable material.

The resonator can only operate a standing wave due to the boundary conditions, nevertheless this could be useful in dominating the frequency of the system. The resonator is also the shell that determines the system boundary. It should always be structurally stronger than the medium that transports acoustic waves.

Extensions

Because the standing wave has unfavorable conditions for energy transfer, the regenerator is not placed within the oscillator, but in an extension where no borders dictate a standing wave. Such a configuration can have many shapes. Most commonly known are the torus, and the axial configuration. In the experiments we will use a coaxial configurations. Toruses have proven to generate better efficiencies. This is mostly due to the impracticality of thermal insulation in a coaxial configuration.

Feedback channel as a control for system impedance

The feedback channel is a small connection of the medium to different sides of the regenerator. This creates a loop in the system that corrupts the boundary layers that cause standing waves, thus creating a traveling wave. Because of the analogy between electrical and acoustical systems, the acoustic impedance is often represented as a coil.

In an electrical circuit the impedance is expressed as Z, in ohm, being the resistance in a circuit that is in operation under an alternating current. The resistance consists of a real, and an imaginary part. The real part is caused by viscous friction and the imaginary part by phase effects.

Compliance/ Capacitance

The compliance is a volume that can accumulate energy (pressure times volume). A volume in an acoustic wave will behave similarly to a capacitor in an electrical circuit with alternating current.

Sound Transport Medium

The acoustic wave needs to be transported through the system, This happens by a medium also called the working fluid. The medium could be a solid, liquid or gas; in this sense the term fluid is not correct. Nevertheless it is common to use gases and liquids. It undergoes the process of compression and expansion, thus it transports the heat.

From acoustics the relation between specific compressibility γ, and the speed of sound a is given by:

$$\gamma - 1 = \frac{T_m \beta^2 a^2}{c_p} \qquad \text{(C6)}$$

β is the isentropic expansion coefficient and T_m is the average temperature of the medium.

Flow straightener

In order to reduce the Rayleigh streaming, a friction barrier is placed at the exit of the thermal buffer tube. This will reduce the flow of highly buoyant hot fluids leaving, and cold fluids entering the thermal buffer tube.

Appendix C1: Two microphone method

The acoustic power is the power contents of an acoustic wave. As stated earlier the 2 microphone method predicts the acoustic energy transported through a cross sectional area. The velocity, the mean pressure, and the pressure difference could be derived from just two pressure sensors, as long as pressure amplitude, phase, and overall pressure can be separated.
The determination of acoustic energy in this matter was developed by Fusco et al. (1992). It is based upon the principle that the volume flow is a result of the pressure difference between two points.
Two general equations were used by Fusco et al. concerning viscous losses and the complex wave number which is the coefficient of p'' and was assigned Y.

$$i\omega\rho u = -\frac{\mathrm{d}\,p'}{\mathrm{d}\,x} + \mu\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u}{\partial r}\right)$$

$$Y^2 = \frac{\omega}{a^2}\left(\frac{1+(\gamma-1)f_T}{1-f_v}\right) \qquad \text{(C7)}$$

Then he used the statements for the derivative of pressure in an acoustic wave to determine

$$p'\left(\frac{-\Delta x}{2}\right) = p'_A = Ae^{-ik\Delta x/2} + Be^{ik\Delta x/2}$$

$$p'\left(\frac{\Delta x}{2}\right) = p'_B = Ae^{ik\Delta x/2} + Be^{-ik\Delta x/2}$$

$$p'(x=0) = A + B + (p'_A + p'_B)\frac{\sin(k\Delta x/2)}{\sin(k\Delta x)}$$

$$\frac{\mathrm{d}\,p'(x=0)}{\mathrm{d}\,x} = ik(A-B) = k(p'_A - p'_B)\frac{\cos(k\Delta x/2)}{\sin(k\Delta x)} \qquad \text{(C8)}$$

$$\dot{W}_{2mic} = \frac{-\pi r}{2\omega\rho_m}\mathrm{Im}\left((p'_A + p'_B)\frac{\sin(k\Delta x/2)}{\sin(k\Delta x)}k(p'_A - p'_B)\frac{\cos(k\Delta x/2)}{\sin(k\Delta x)}(1-f_v)\right)$$

$$k \simeq \frac{\omega}{C_m}\left(1+\frac{(\gamma-1)f_T}{2}+\frac{f_v}{2}\right) \simeq \frac{\omega}{C_m}\left(1+\frac{(1-i)}{2}\left(1+\frac{\gamma-1}{\sqrt{\mathrm{Pr}}}\right)\frac{\delta_v}{r}\right)$$

$$\dot{W}_{2mic} = \frac{-\pi r}{2\rho_m C_m \sin(\omega\Delta x/C_m)}\left(\mathrm{Im}(p'_A\,p'_B) - \frac{\delta_v}{2r}\left(\mathrm{Im}(p'_A\,p'_B)\left(1-\frac{\gamma-1}{\sqrt{\mathrm{Pr}}}+\left(1+\frac{\gamma-1}{\sqrt{\mathrm{Pt}}}\right)\frac{\omega\Delta x}{C_m}\frac{\cos\left(\frac{\omega\Delta x}{C_m}\right)}{\sin\left(\frac{\omega\Delta x}{C_m}\right)}\right)\right.\right.$$

$$\left.\left.+\frac{1}{2}\left(p'^2_A - p'^2_B\right)\left(1-\frac{\gamma-1}{\sqrt{\mathrm{Pr}}}+\left(1+\frac{\gamma-1}{\sqrt{\mathrm{Pr}}}\right)\frac{\omega\Delta x}{C_m}\frac{1}{\sin\left(\frac{\omega\Delta x}{C_m}\right)}\right)\right)\right)$$

Re() is the real part of (), and Im() is the imaginary part of ()

$$\frac{\omega\Delta x}{C_m}\frac{\cos\left(\frac{\omega\Delta x}{C_m}\right)}{\sin\left(\frac{\omega\Delta x}{C_m}\right)} \simeq 1, \text{ and } \quad \frac{\omega\Delta x}{C_m\sin\left(\frac{\omega\Delta x}{C_m}\right)} \simeq 1$$

So equation C8 could be rewritten as

$$\dot{W}_{2mic} = \frac{-\pi r}{2\rho_m C_m \sin(\omega\Delta x / C_m)}\left(\mathrm{Im}(p'_A\, p'_B)\left(1-\frac{\delta_v}{r}\right)+\frac{\delta_v}{2r}\left(p'^{\,2}_A - p'^{\,2}_B\right)\right)$$

$$\dot{W}_{2mic} = \frac{-\pi r}{2\rho_m C_m \sin(\omega\Delta x / C_m)}\left(\left(|p'_A||p'_B|\sin\varphi\right)\left(1-\frac{\delta_v}{r}\right)+\frac{\delta_v}{2r}\left(p'^{\,2}_A - p'^{\,2}_B\right)\right) \quad \text{(C9)}$$

A more simple approach is used for a non viscous medium:

$$\dot{W} = \overline{p(t)U(t)} = \mathrm{Re}(\overline{p_a} U_a)/2$$

$$i\omega\rho U = -\frac{\mathrm{d}\,p}{\mathrm{d}\,x}$$

$$p = \frac{p_1 + p_2}{2}$$

$$\frac{\mathrm{d}\,p}{\mathrm{d}\,x} = \frac{p_1 - p_2}{\Delta x} \quad \text{(C10)}$$

$$\frac{\dot{W}_{2mic}}{A_{cs}} = \mathrm{Re}\left(\frac{i}{\omega\rho}\frac{p_1 - p_2}{\Delta x}\frac{\overline{p_1}+\overline{p_2}}{2}\right)\frac{1}{2} = \frac{1}{4\omega\rho\Delta x}\mathrm{Im}\left(\overline{p_1}+\overline{p_2}\right)\left(p_1 - p_2\right) = \frac{|p_1||p_2|\sin\phi}{2\omega\Delta x}$$

$$\dot{W}_{2mic} = \frac{A_{cs}|p_1||p_2|\sin\phi}{2\omega\Delta x}$$

For a viscous medium the derived equation 3.6 of Fusco et al. 1992 was further simplified by Backhaus and Swift (2002)

$$i\omega\rho u(x,y) = -\frac{\mathrm{d}\,p}{\mathrm{d}\,x} + \mu\frac{\partial^2 u(x,y)}{\partial y^2}$$

For $r \gg \delta_v$ it holds that:

$$u = \frac{i}{\omega\rho}\left(1 - e^{(-1+i)\frac{y}{\delta_v}}\right)\frac{\mathrm{d}\,p}{\mathrm{d}\,x} \quad \text{(C11)}$$

The volumetric velocity is the average flow speed over the cross sectional area

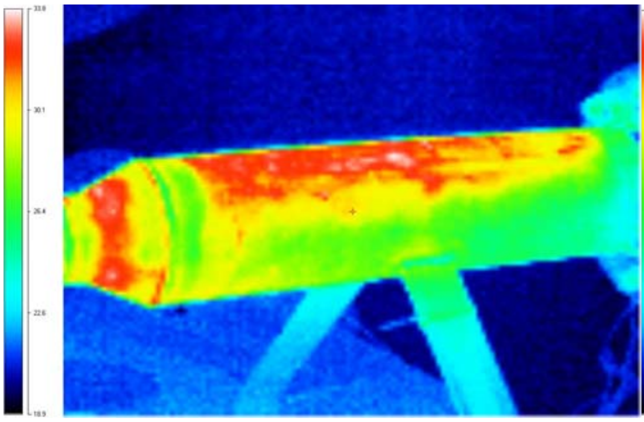
$$U = \frac{iA}{\omega\rho}\left(1-(1-i)\frac{\delta_v}{2r}\right)\frac{\mathrm{d}\,p}{\mathrm{d}\,x}$$

$$p \cong \frac{(p_2 + p_3)}{2}, \quad \frac{\mathrm{d}\,p}{\mathrm{d}\,x} \cong \frac{(p_2 - p_3)}{\Delta x}$$

$$\dot{W}_{2mic} = \frac{A_{cs}}{2\omega\Delta x}\left(1-\frac{\delta_v}{r}\right)|p_1||p_2|\sin\phi + \frac{\delta_v}{2r}\left(|p_1|^2 - |p_2|^2\right)$$

Where A_{cs} is the cross sectional area, and Δx is the distance between the two microphones, ρ is the density of the medium, and ω is the frequency of the acoustic wave, r is the radius of the cross sectional area, while δ_v is the viscous penetration depth, and Φ is the phase difference between p_1, and p_2.

Appendix D1 Heat Images Serial configuration.



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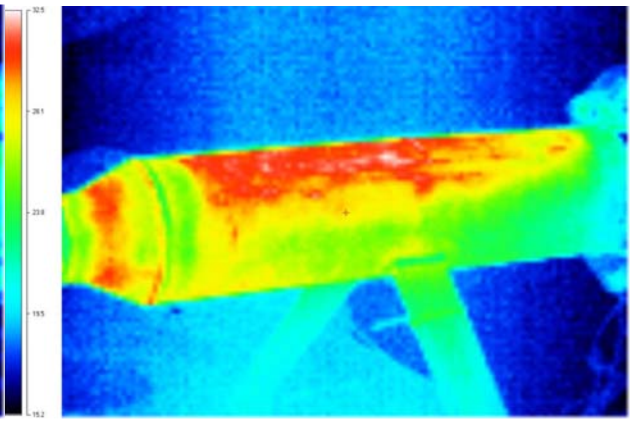

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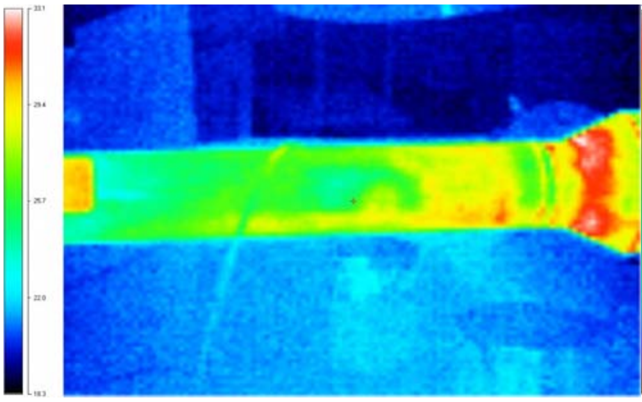

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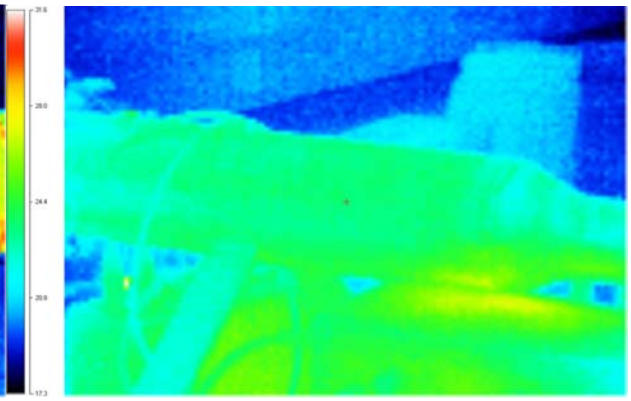
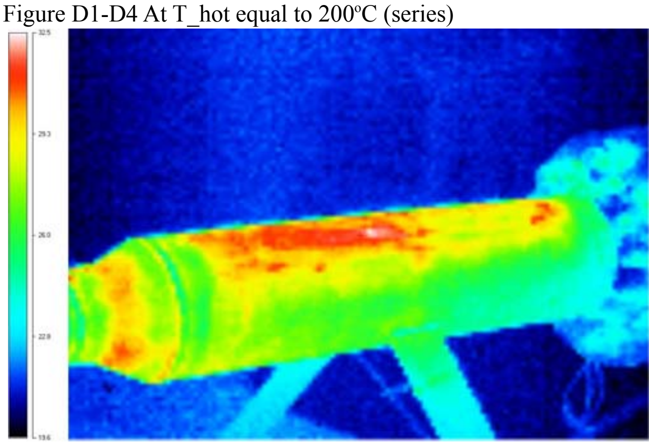


D4

Figure D1-D4 At T_hot equal to 200ºC (series)



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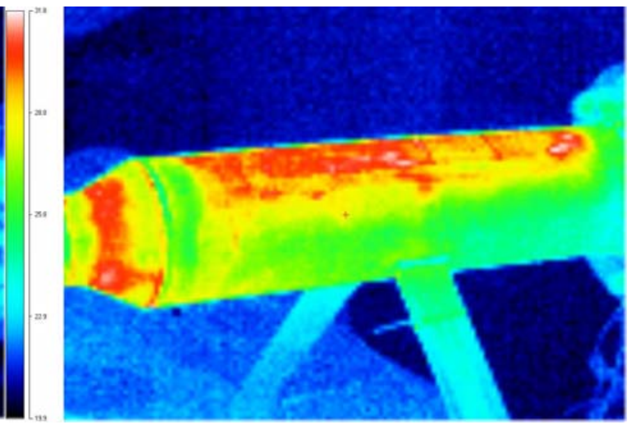
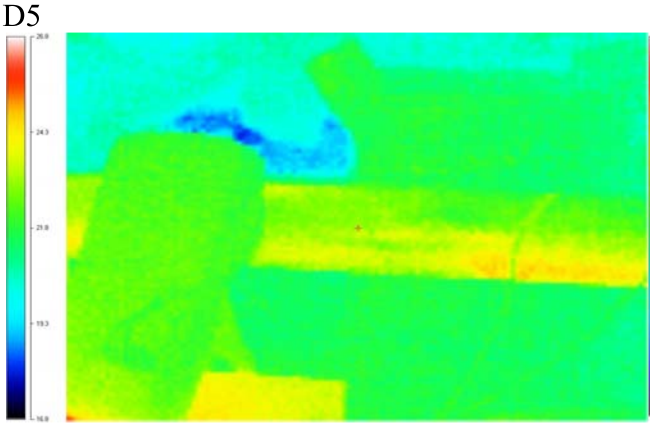
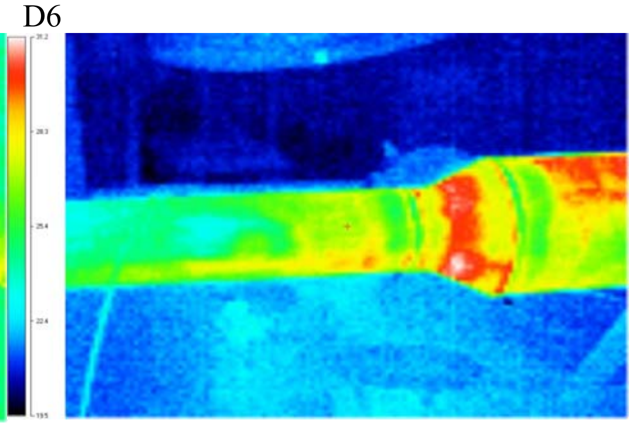


D6

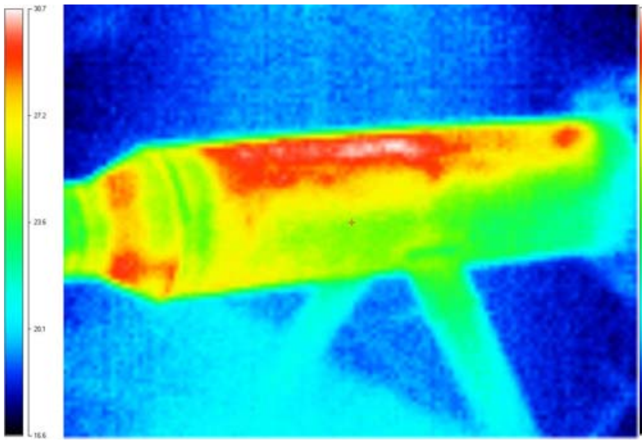


D7

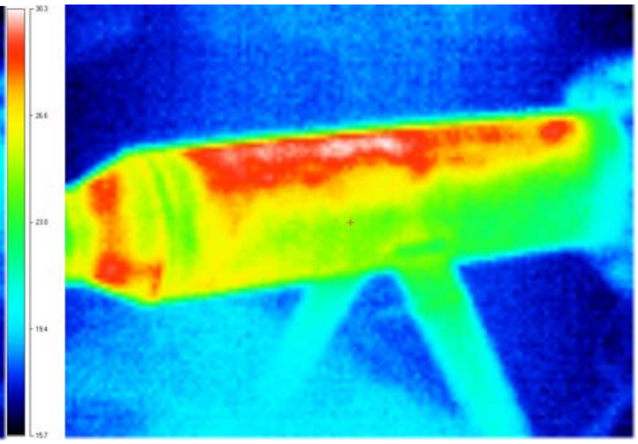


D8

Figure D5-D8 At T_hot equal to 160ºC (series)



D9



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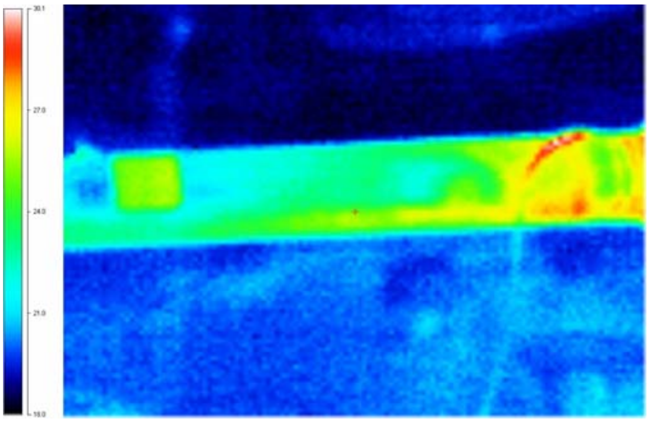
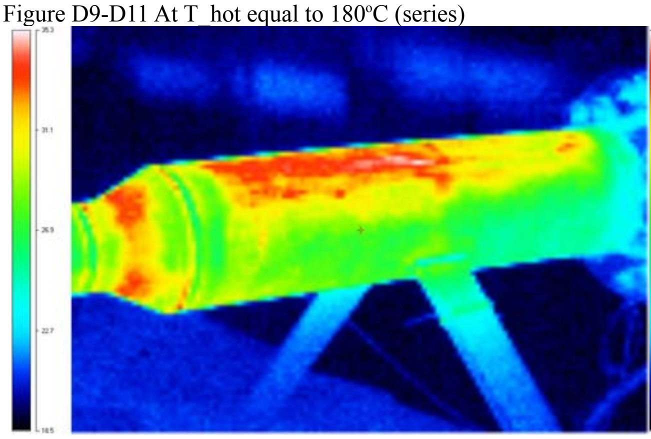


D11

Figure D9-D11 At T_hot equal to 180ºC (series)



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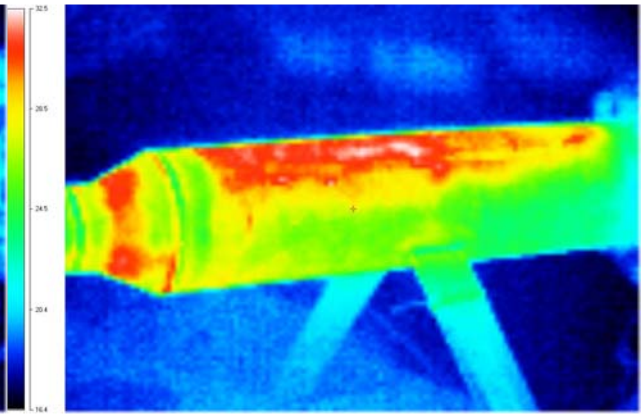
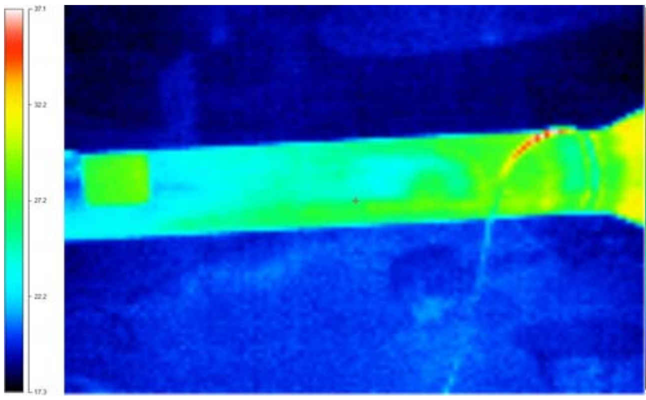
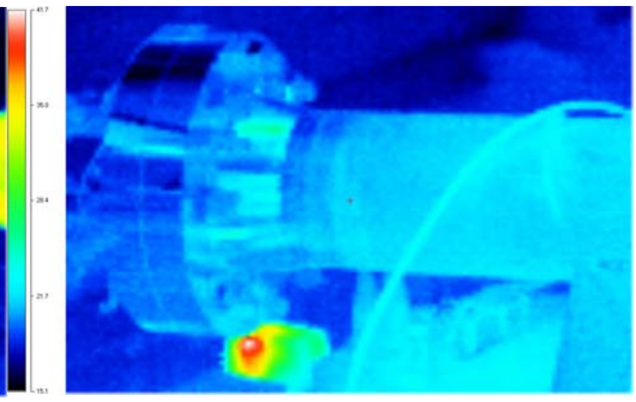


D13



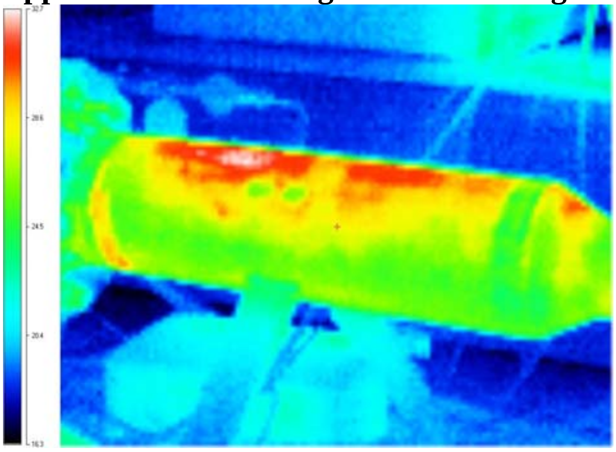
D14

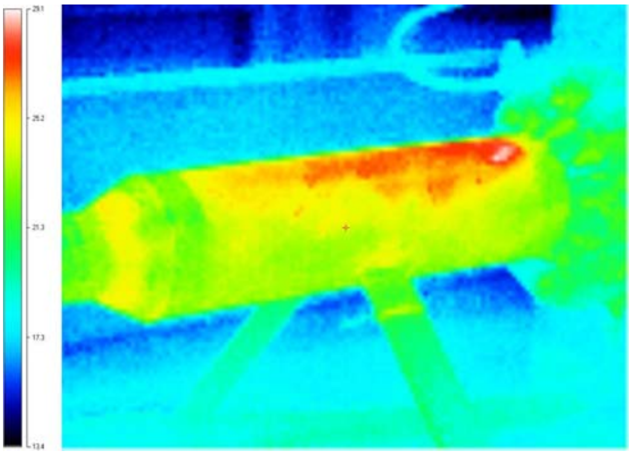


D15

Figure D12-D15 At T_hot equal to 220ºC (series)

Appendix D2 Heat Images Parallel configuration.


D16


D17

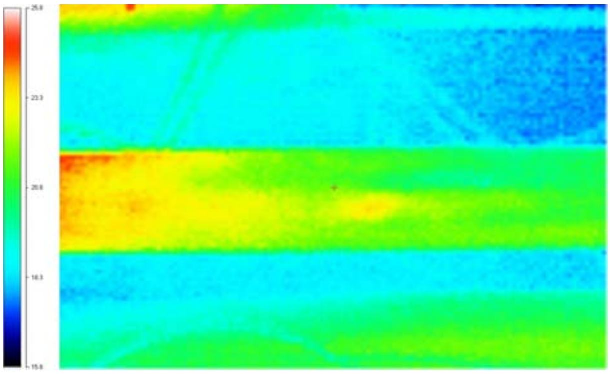
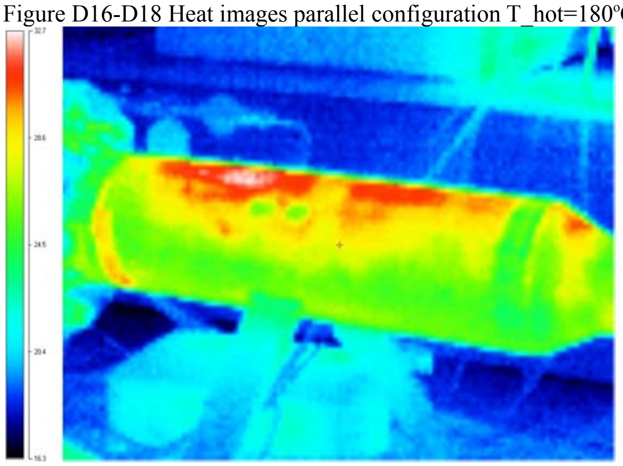
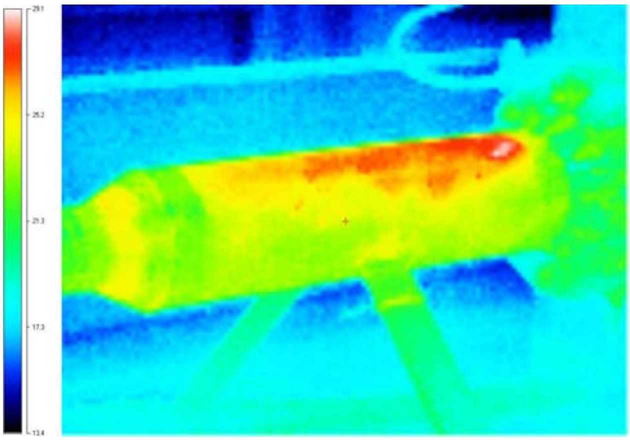

D18

Figure D16-D18 Heat images parallel configuration T_hot=180ºC


D19


D20

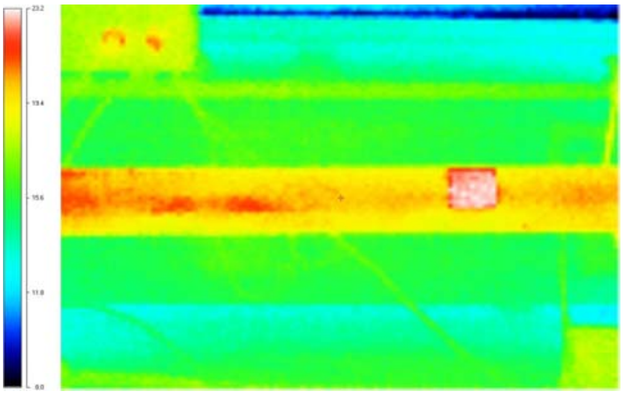
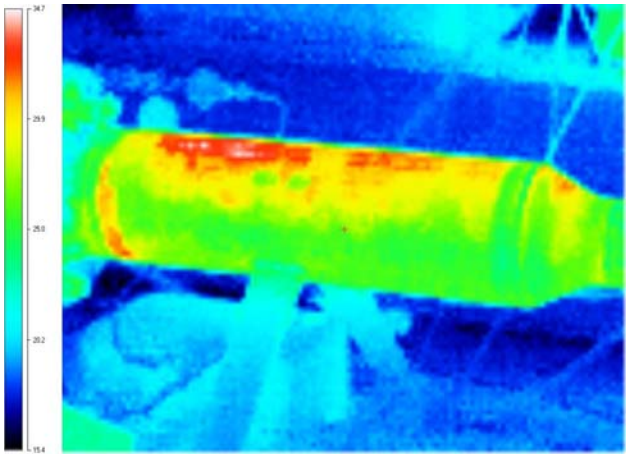
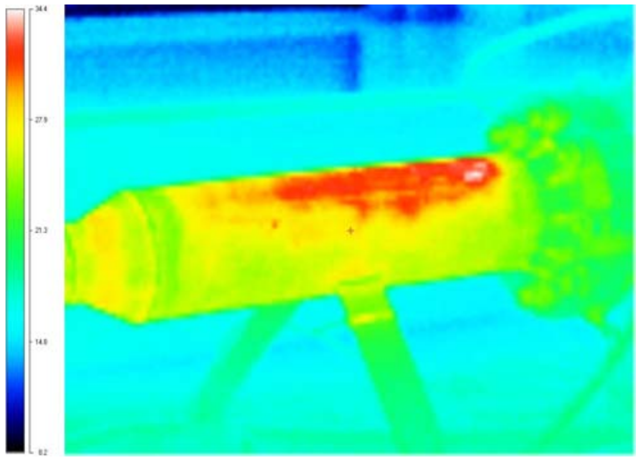

D21

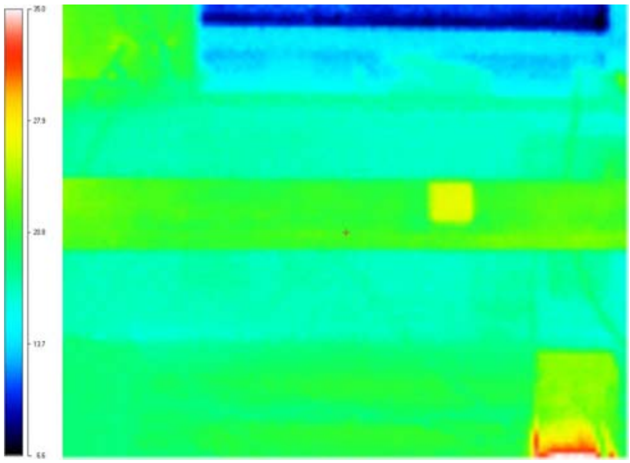
Figure D19-D21 Heat images parallel configuration T_hot=200ºC



D22



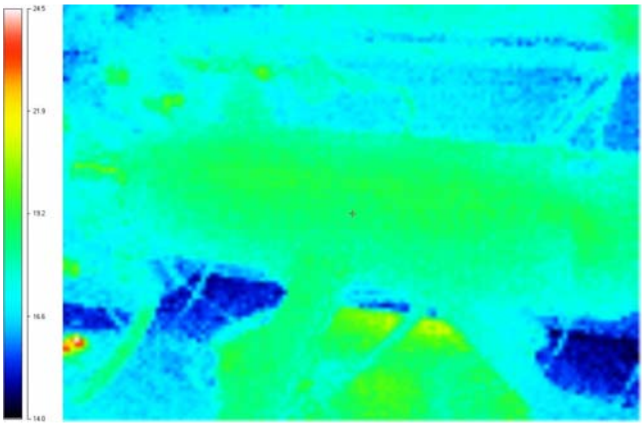
D23



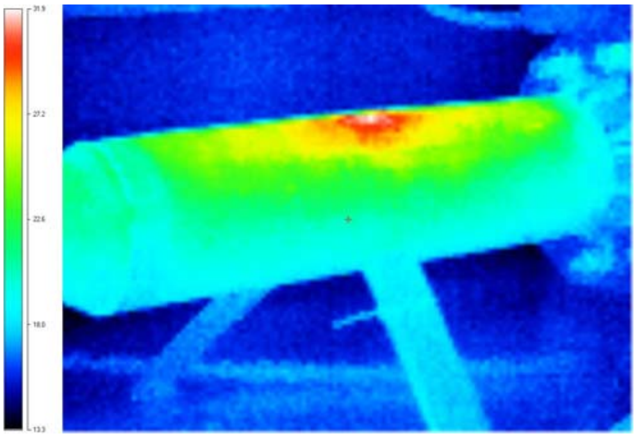
D24

Figure D22-D24 Heat images parallel configuration T_hot=220ºC

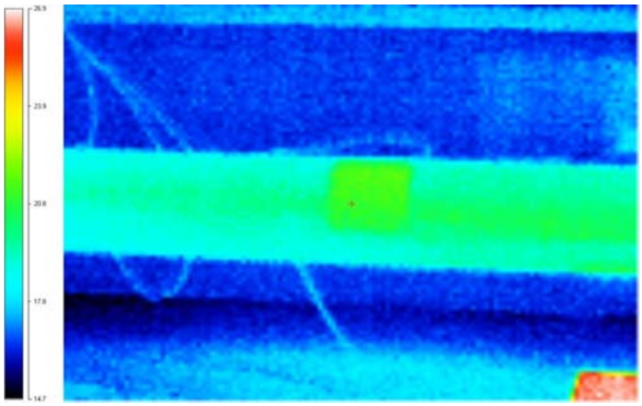
D3 Validation static Heat Images



D25

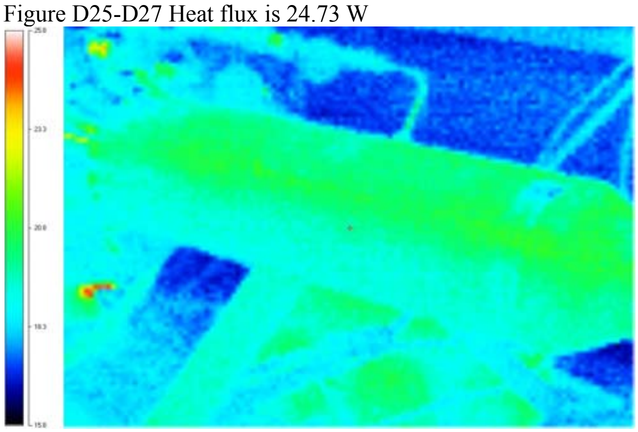


D26

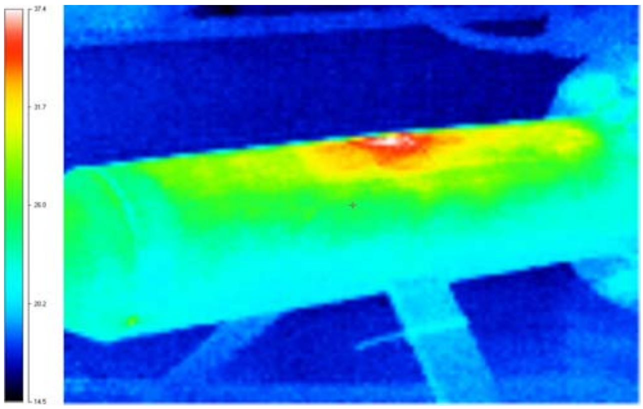


D27

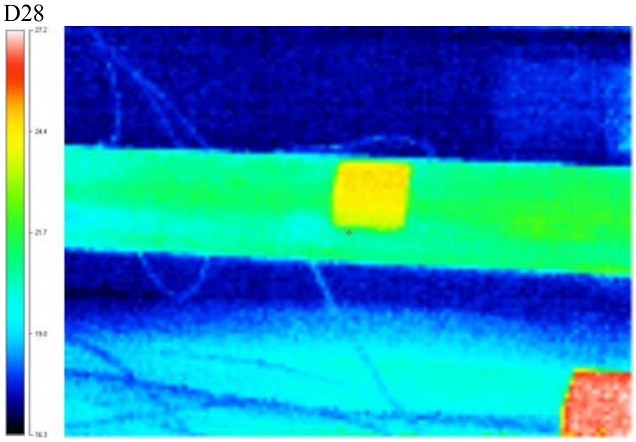
Figure D25-D27 Heat flux is 24.73 W



D28



D29



D30

Figure D28-D30 Heat Flux is 31.15 W