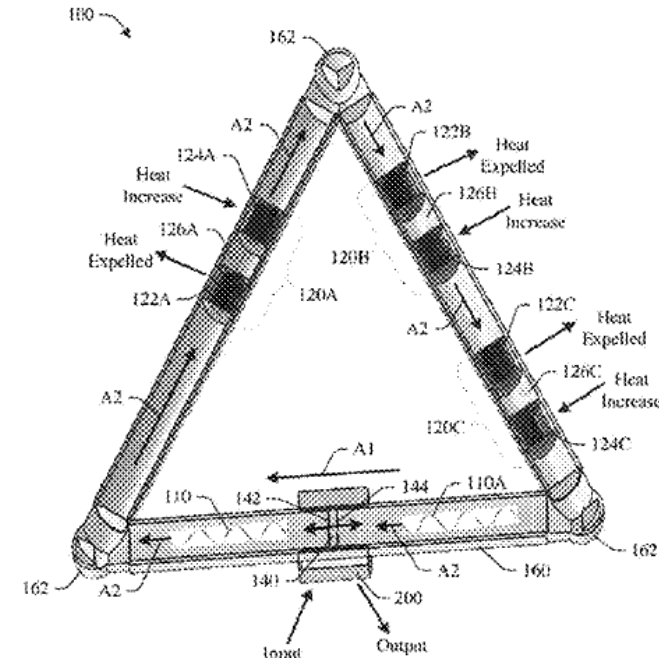
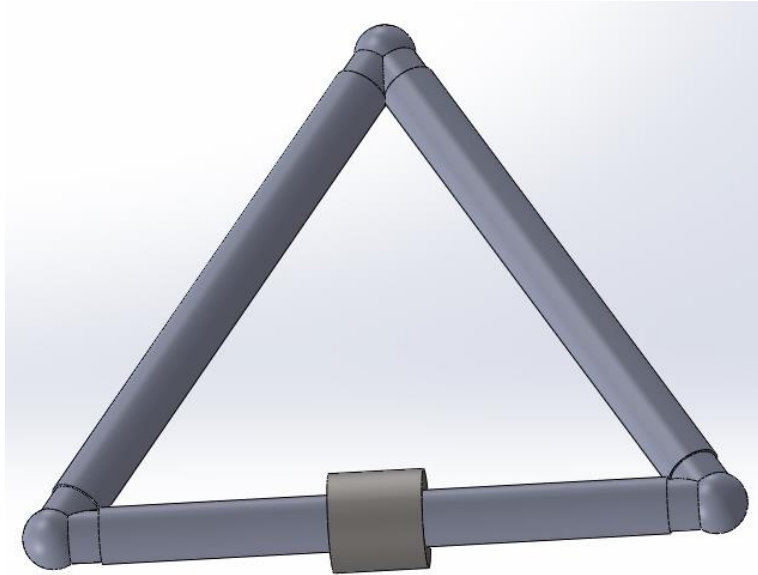


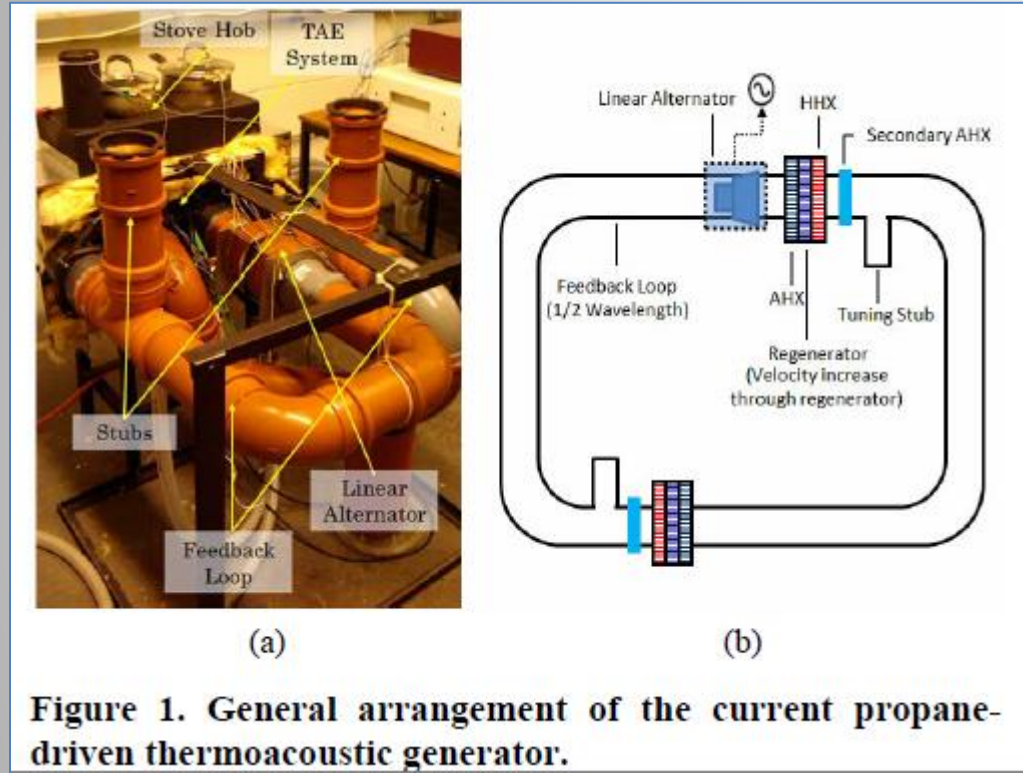


DELTA TRL STATUS AND DESIGN DETAILS

Rodger Dyson
NASA Glenn Research Center
Cleveland, OH

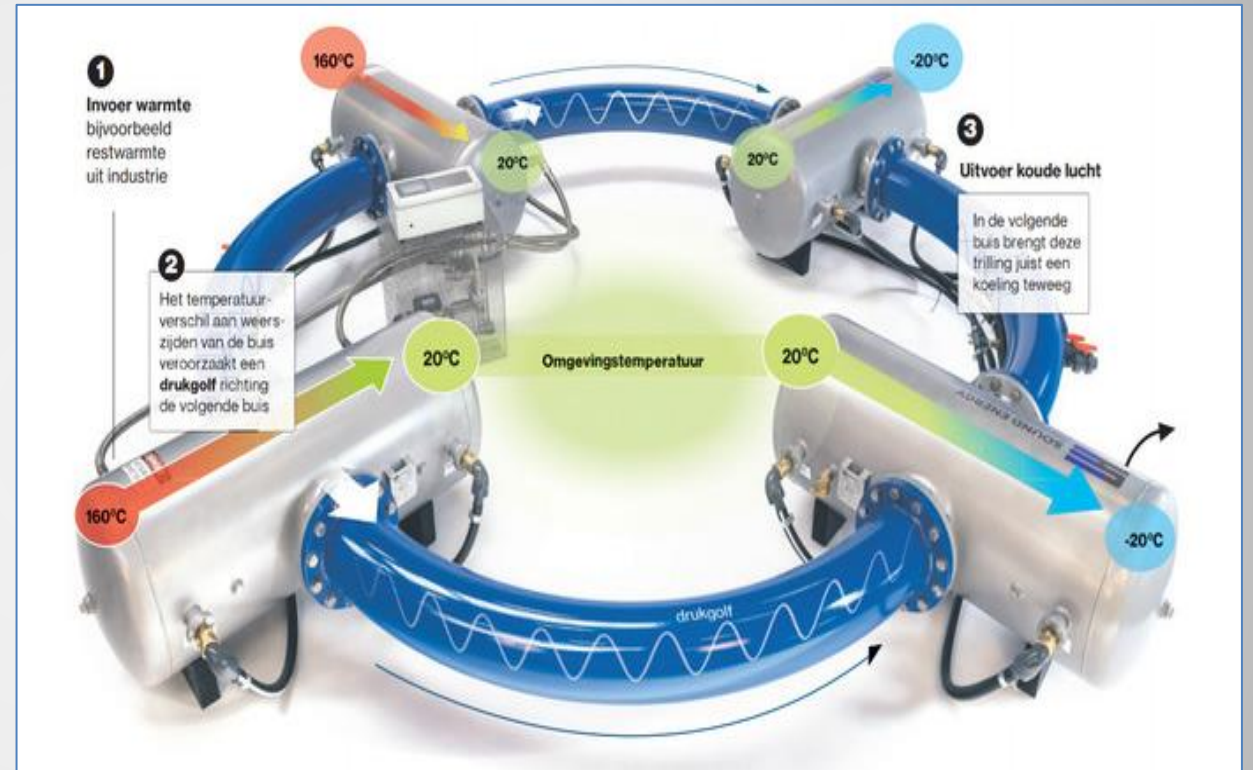
NASA DELTA Generator Technology Summary
Sept. 19, 2022

Related TRL 6 Operating Equipment Looped Design, Multi-Stage



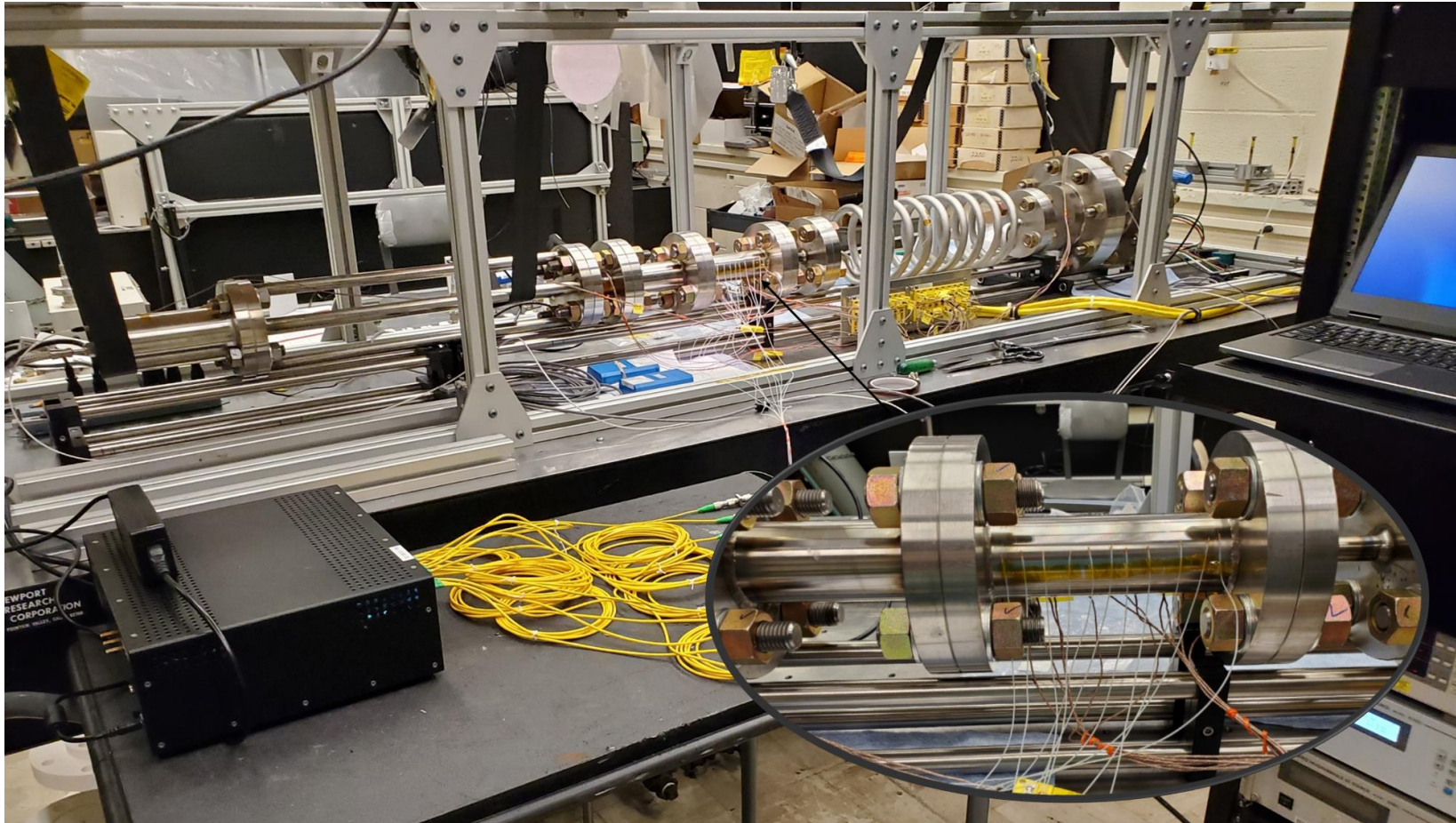
University of Nottingham

Engineering, 2012, 4, 894-902

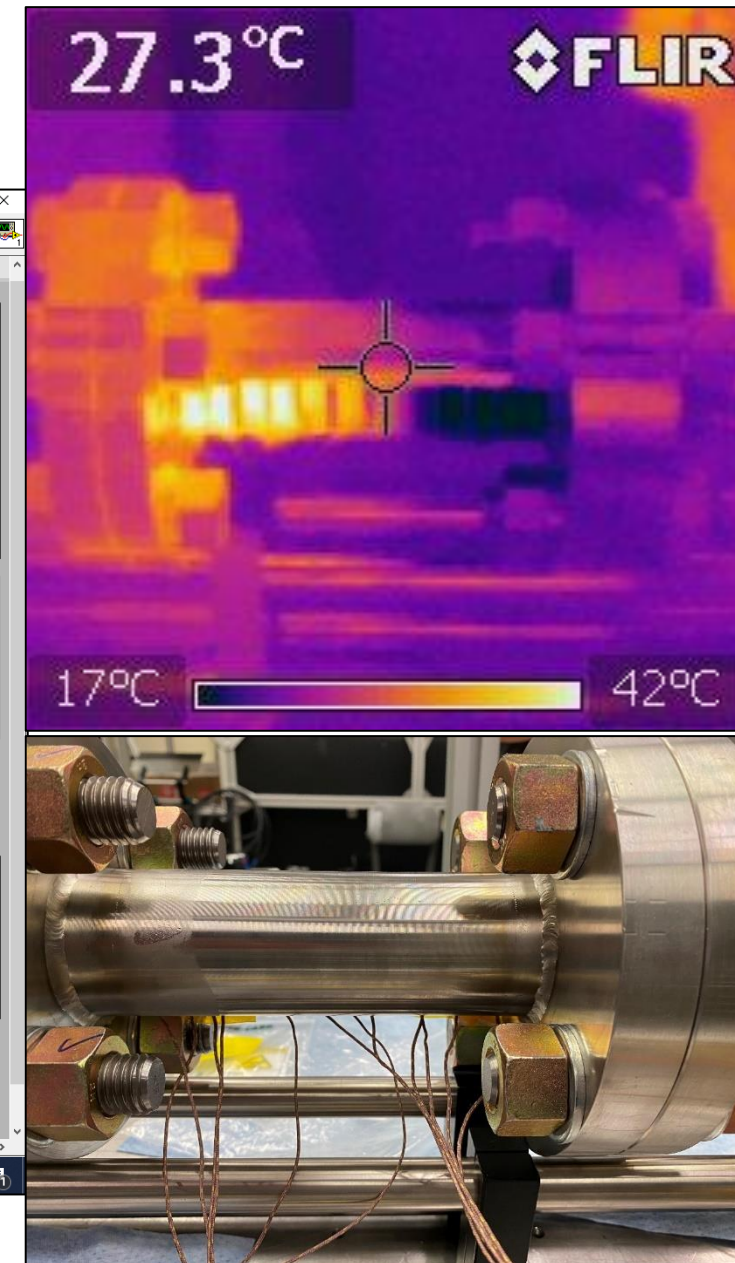
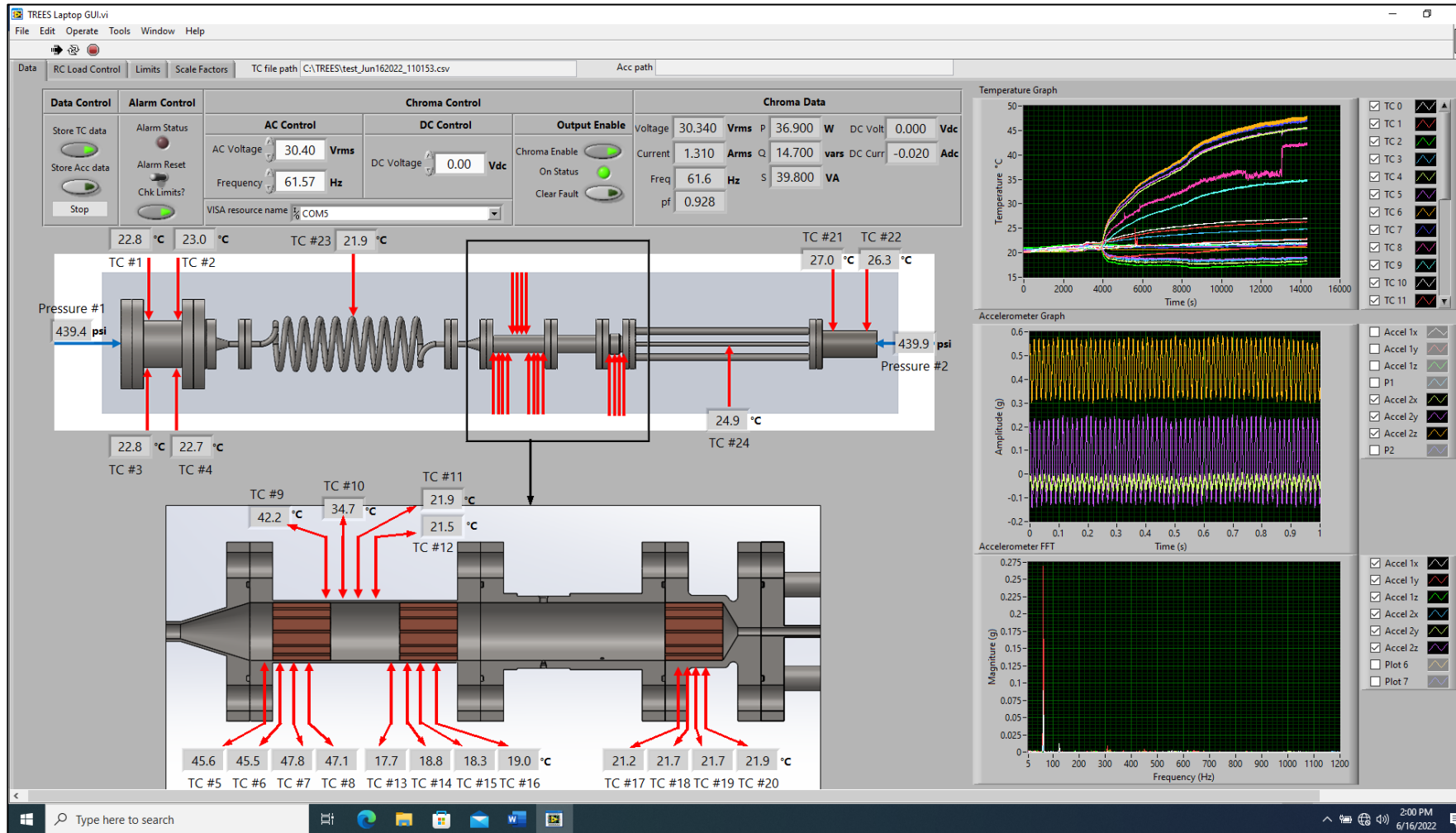


SoundEnergy in Netherlands

TRL-4 Thermoacoustic Demo – Single-Stage

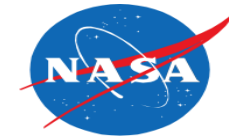


Reverse Thermoacoustic Result

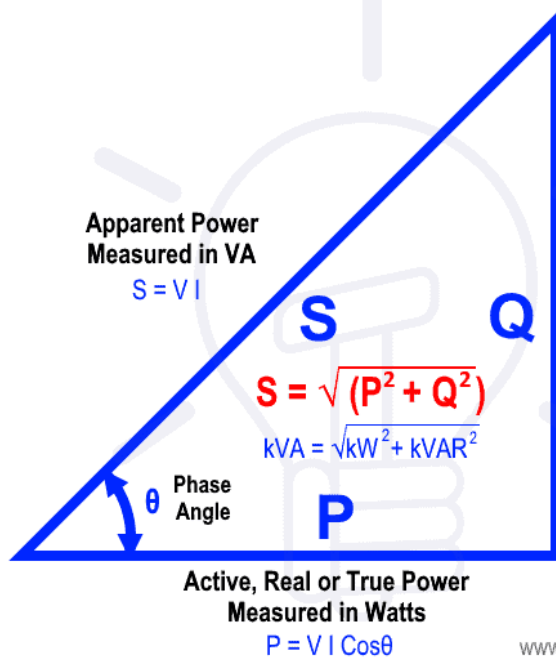


30.1 °C Temperature Difference with 90-degree bend, 33 °C when smooth

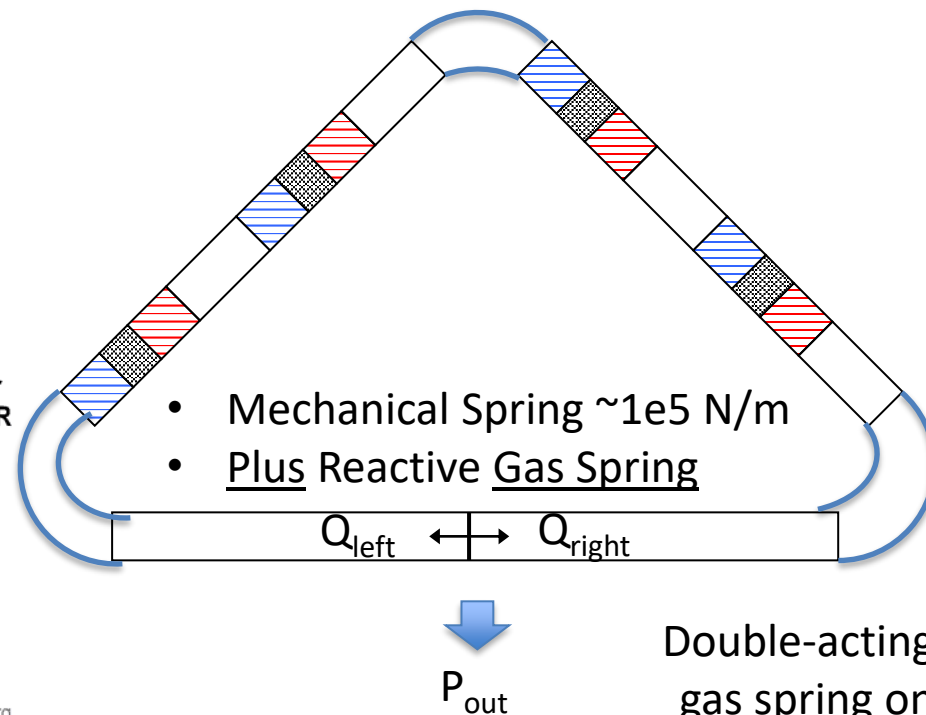
Reactive Pressure Power Gas Springs



Power Triangle

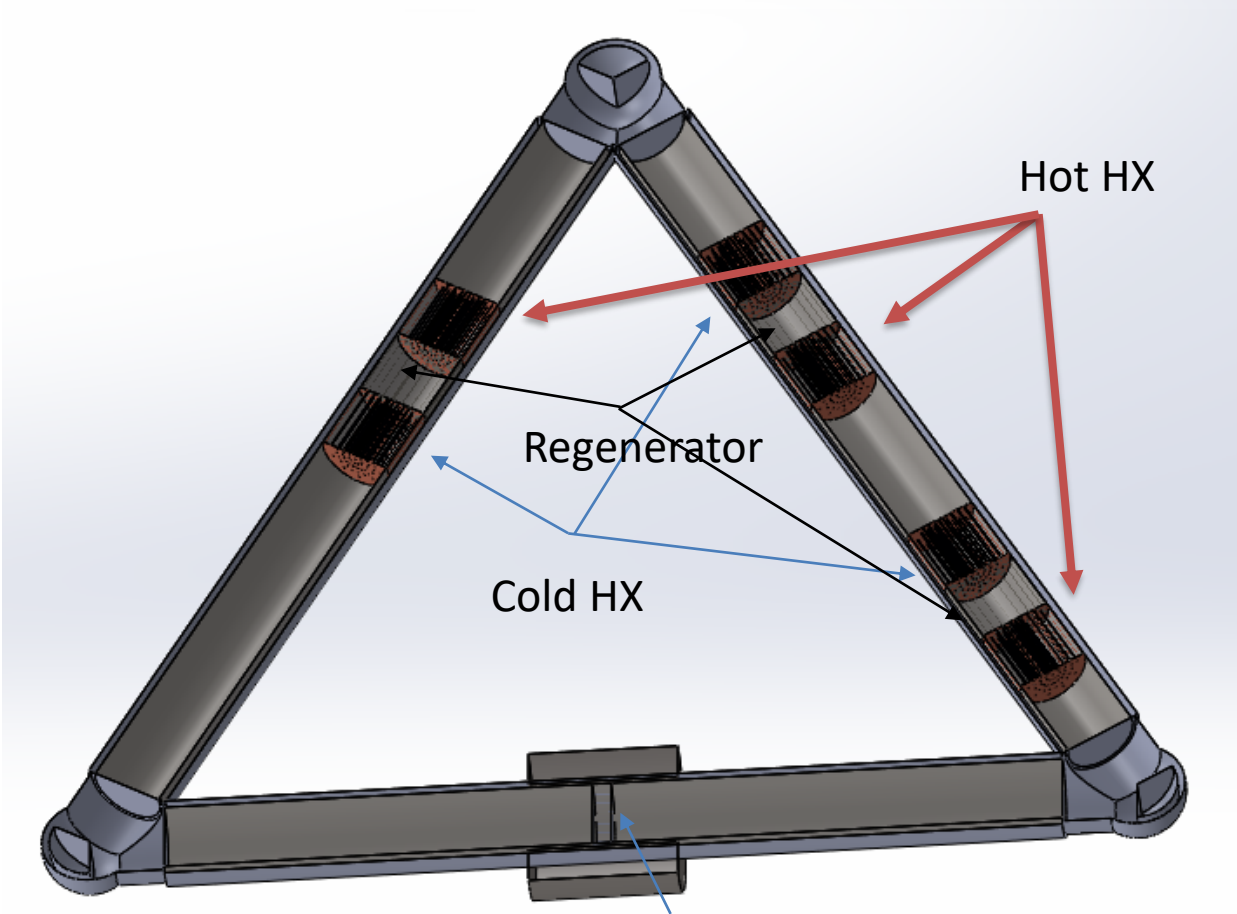


www.electricaltechnology.org

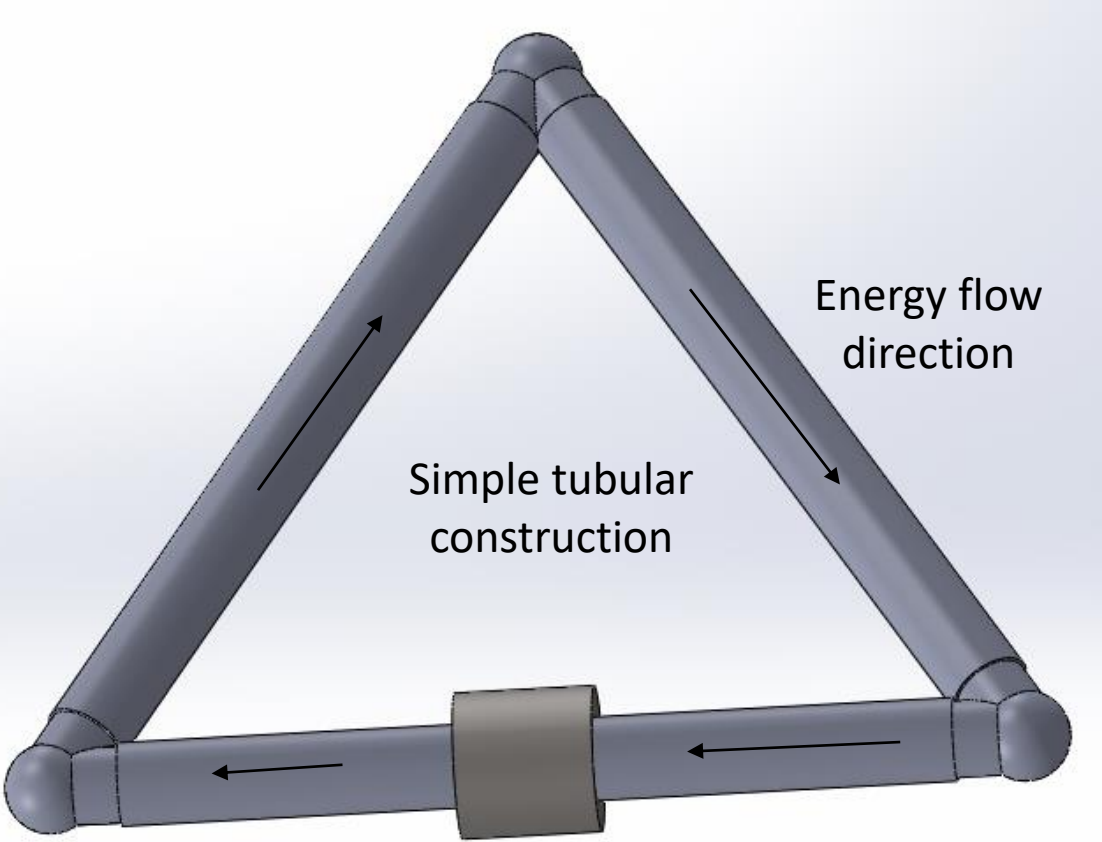


The moving piston can oscillate faster since it has both mechanical and gas spring stiffness in this configuration.

DELTA Converter Cross-Section



Double-Acting Push/Pull Piston

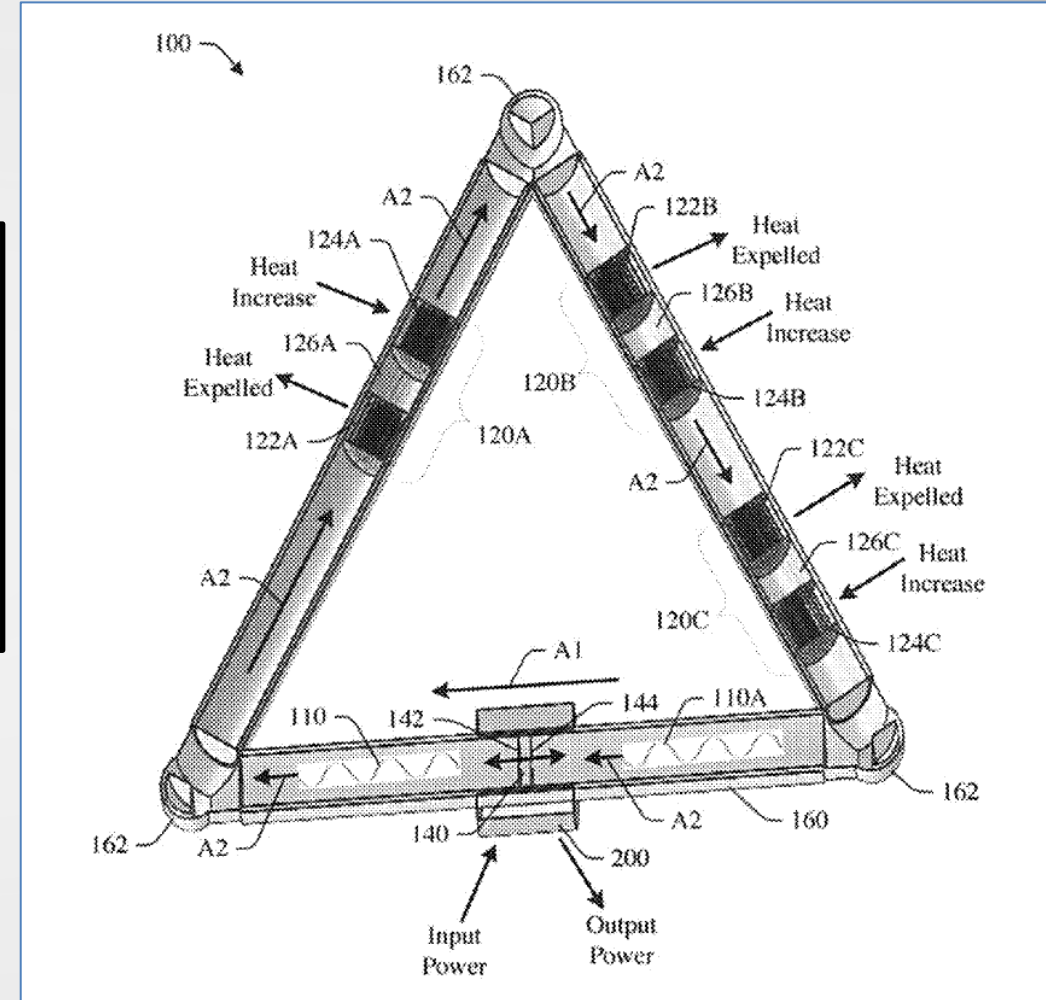


Alternator

DELTA Operation



- Double-Acting Push/Pull Single Piston
- Multiple Thermo-acoustic Stages
- DELTA or Toroidal Shaped Simple Tube Geometry
- No hot moving parts, no large springs, high frequency operation
- Multiple heat inputs, no electric feedback, easy control
- Low cost, high specific power, no maintenance



Governing DELTA Generator Equations and Modeling



Navier–Stokes Equations 3 – dimensional – unsteady



Coordinates: (x,y,z) Time : t Density: ρ Pressure: p Reynolds Number: Re
Velocity Components: (u,v,w) Stress: τ Heat Flux: q Prandtl Number: Pr

Continuity:
$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0$$

X – Momentum:
$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \frac{1}{Re_r} \left[\frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} \right]$$

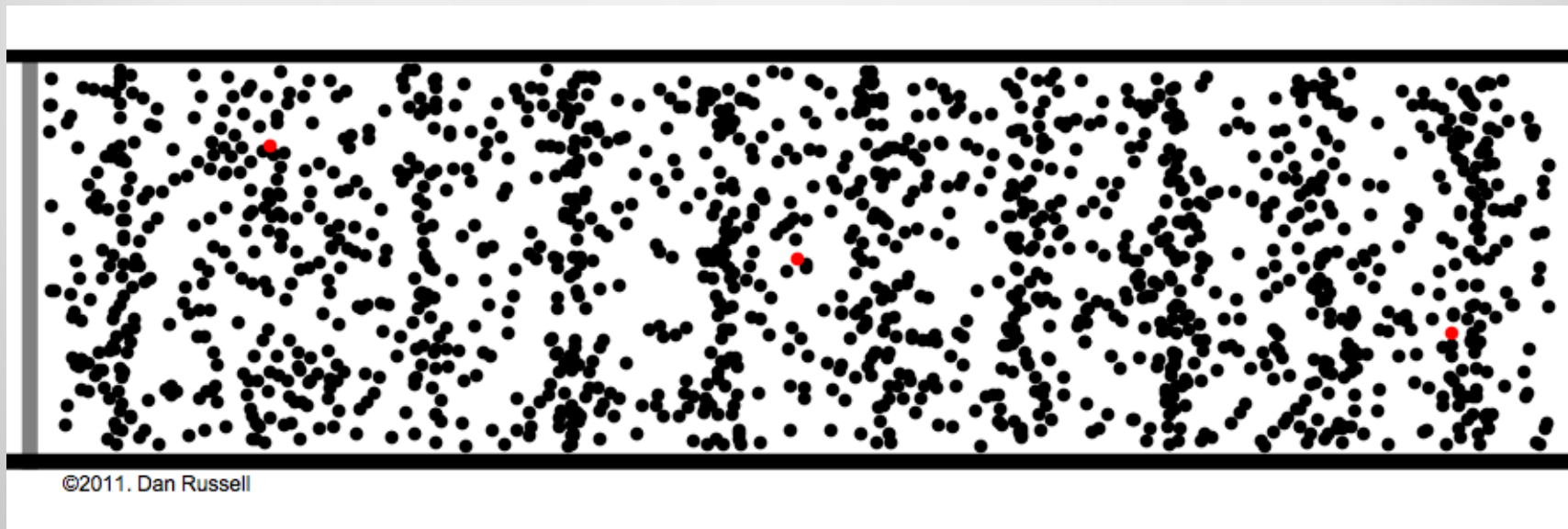
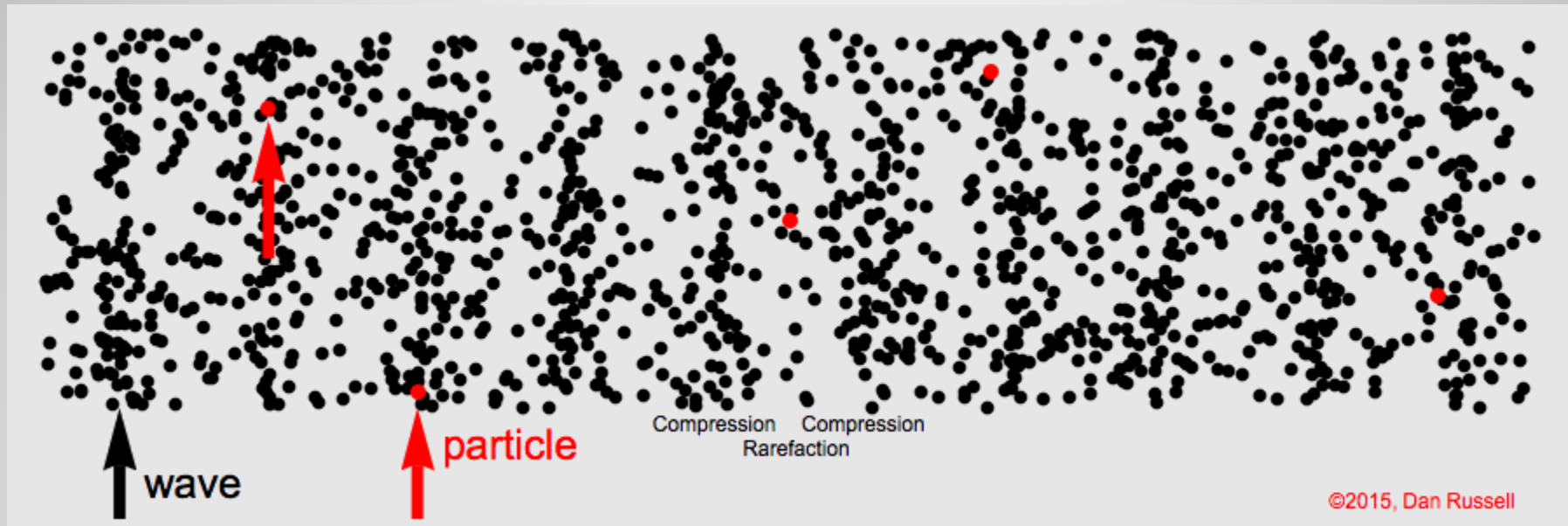
Y – Momentum:
$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} = -\frac{\partial p}{\partial y} + \frac{1}{Re_r} \left[\frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} \right]$$

Z – Momentum:
$$\frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw)}{\partial y} + \frac{\partial(\rho w^2)}{\partial z} = -\frac{\partial p}{\partial z} + \frac{1}{Re_r} \left[\frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} \right]$$

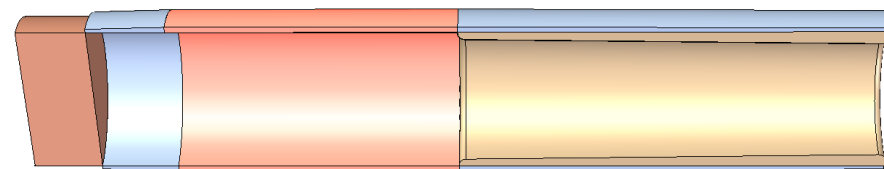
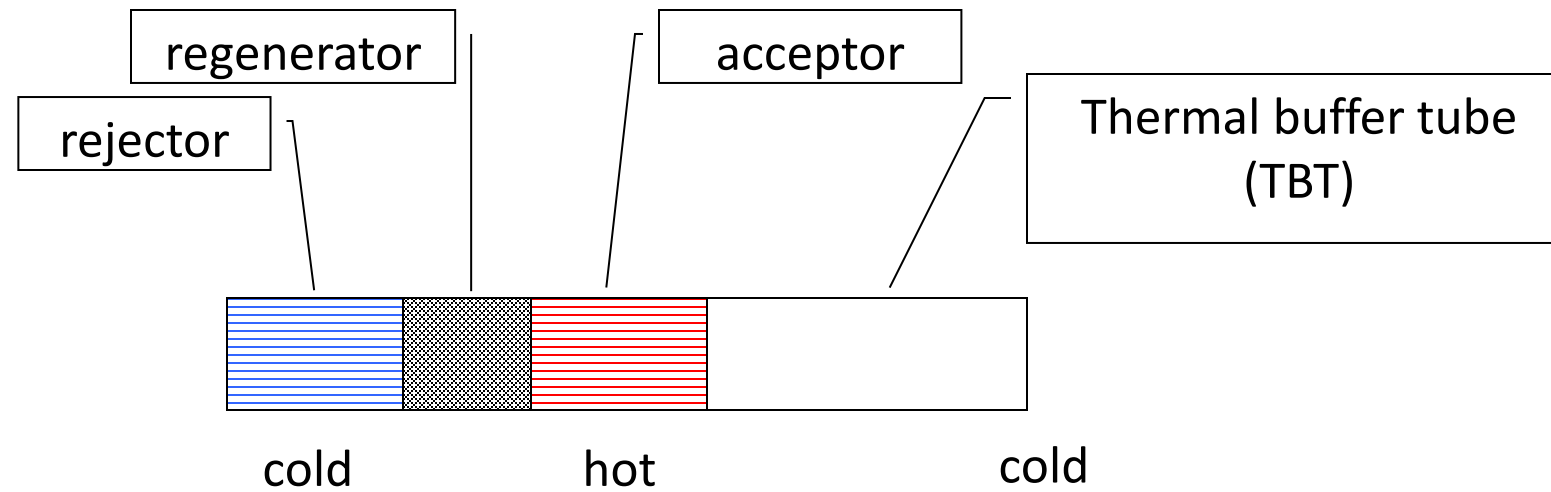
Total Energy – Et:
$$\begin{aligned} \frac{\partial(E_T)}{\partial t} + \frac{\partial(uE_T)}{\partial x} + \frac{\partial(vE_T)}{\partial y} + \frac{\partial(wE_T)}{\partial z} = & -\frac{\partial(up)}{\partial x} - \frac{\partial(vp)}{\partial y} - \frac{\partial(wp)}{\partial z} \\ & + \frac{1}{Re_r} \left[\frac{\partial}{\partial x}(u\tau_{xx} + v\tau_{xy} + w\tau_{xz}) + \frac{\partial}{\partial y}(u\tau_{xy} + v\tau_{yy} + w\tau_{yz}) + \frac{\partial}{\partial z}(u\tau_{xz} + v\tau_{yz} + w\tau_{zz}) \right] \\ & - \frac{1}{Re_r Pr_r} \left[\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} \right] \end{aligned}$$

- Represent all known physics in the engine
- Require specialized numerical resolution to combine hydrodynamics with acoustics
- COMSOL cannot solve system for example
- DELTAE frequency domain LANL
- SAGE time-periodic domain GRC/Gedeon
- Discontinuous Galerkin FE
- Compact Schemes
- Absorbing Boundary Layer
- Low Order Diffusion a Problem
- Space and Time Together Works with sinusoidal basis functions
- Gas Bearing Hydrodynamics with Fluent FV

Traveling Wave Basic Principles – Helium oscillates

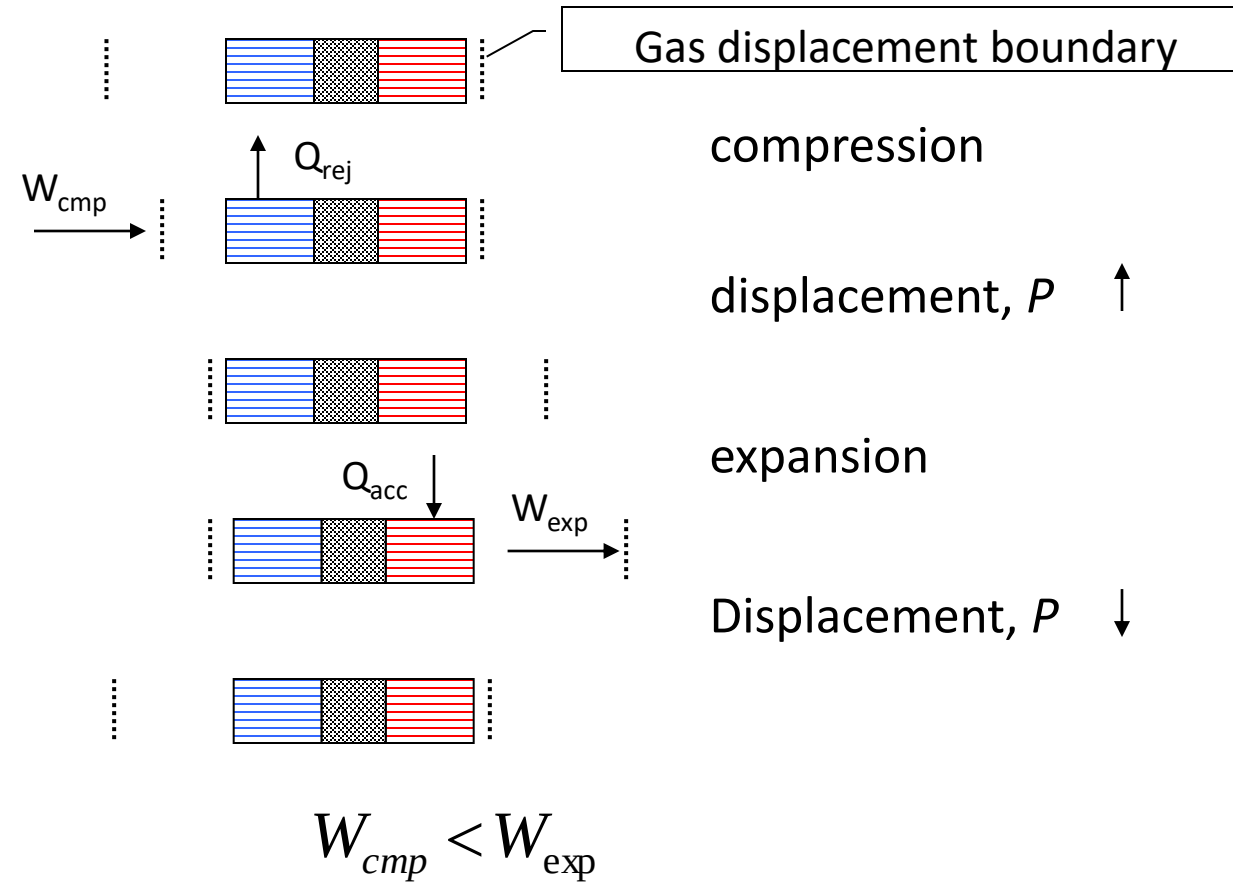


DELTA Stage Physics

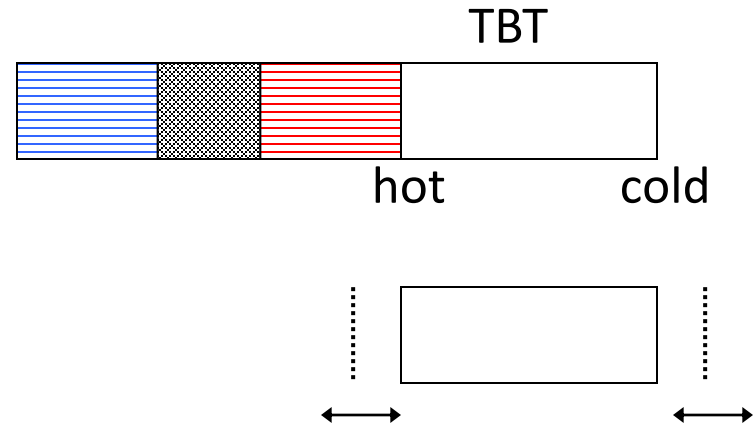


Simplified physical appearance

Thermodynamic Cycle

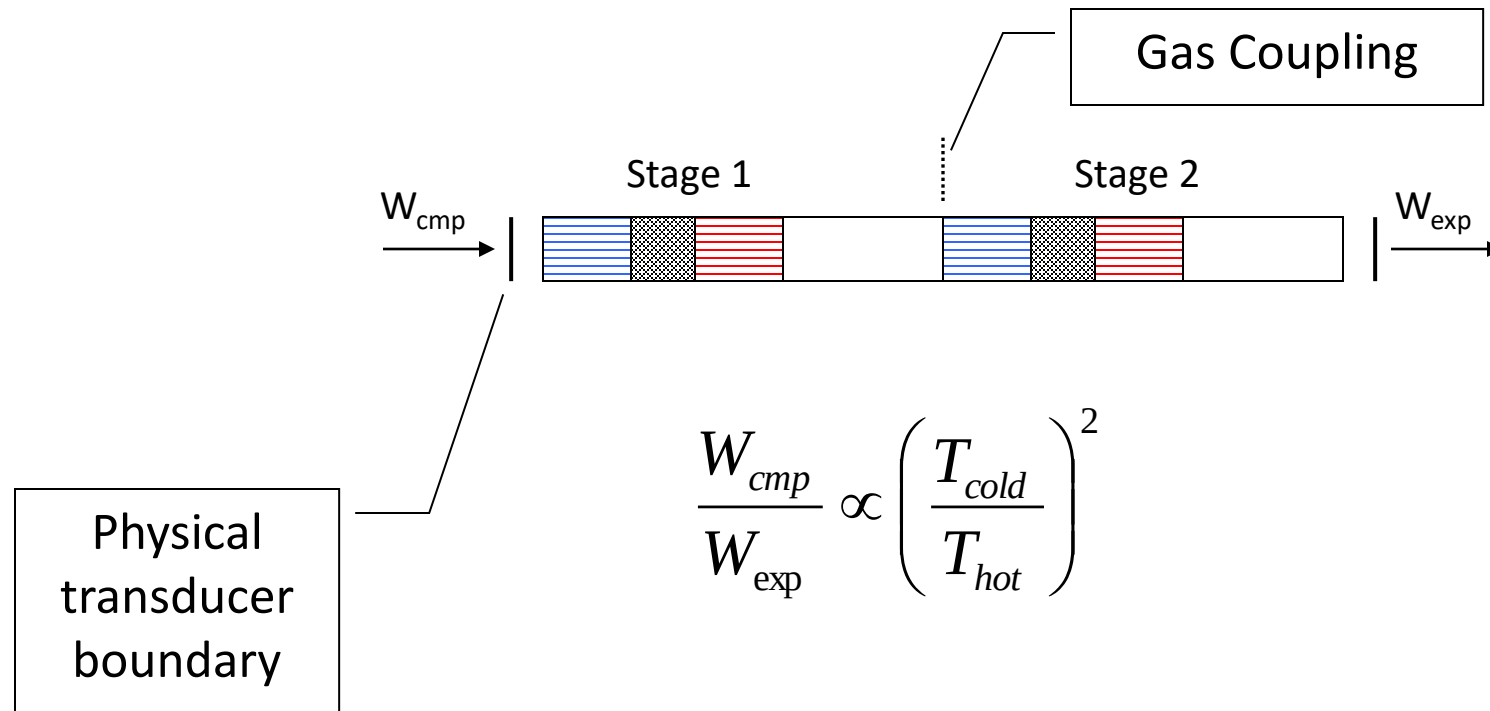


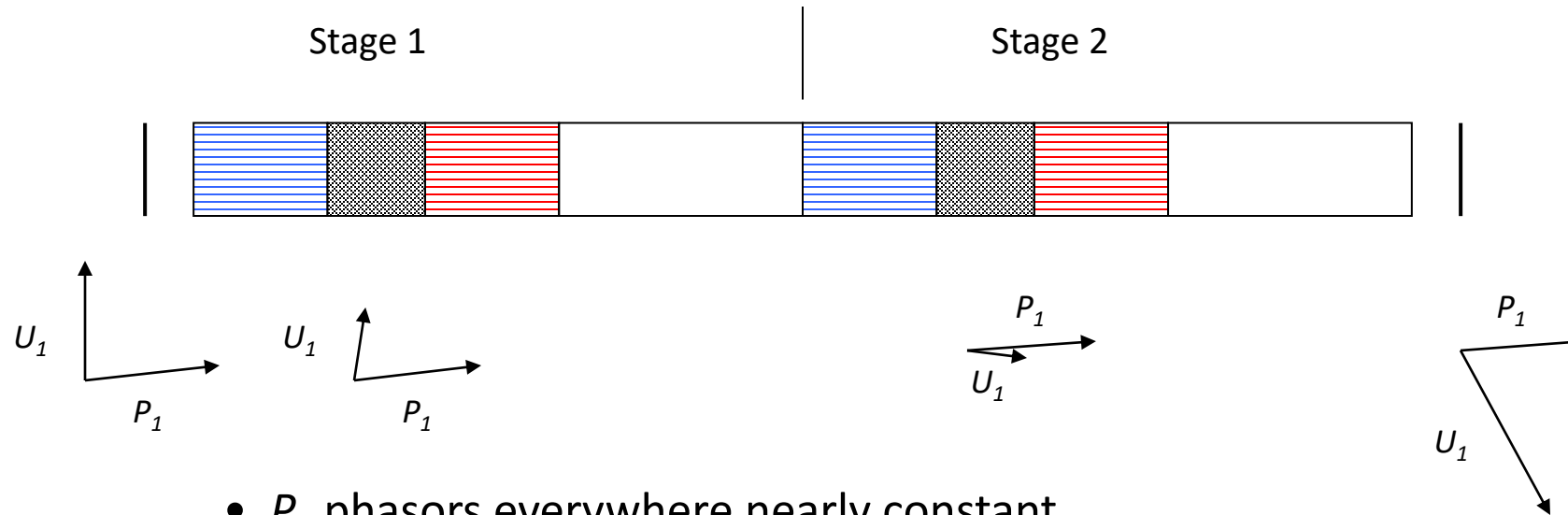
Thermal Buffer Tube/Pulse Tube



- Isolates hot from cold parts
- Transmits PV power, like a compliant displacer
- Adiabatic (ideally)
- Except for jets, streaming, turbulence, etc.

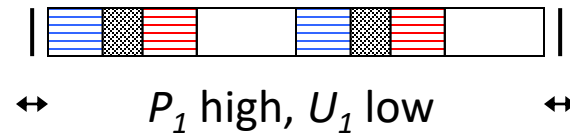
Two stage cascade



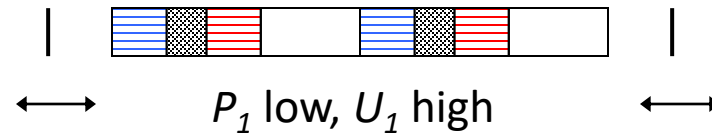


- P_1 phasors everywhere nearly constant
- U_1 phasors progressively lag due to volume (compliance)
- Ideally, P_1 and U_1 in phase in regenerators
- Gas inertia (inertance) can be used to counter U_1 lag
- E.g. Swift inter-stage inertance tube
- Modeling tools like Sage automatically account for distributed compliance and inertance

End Transducer Options



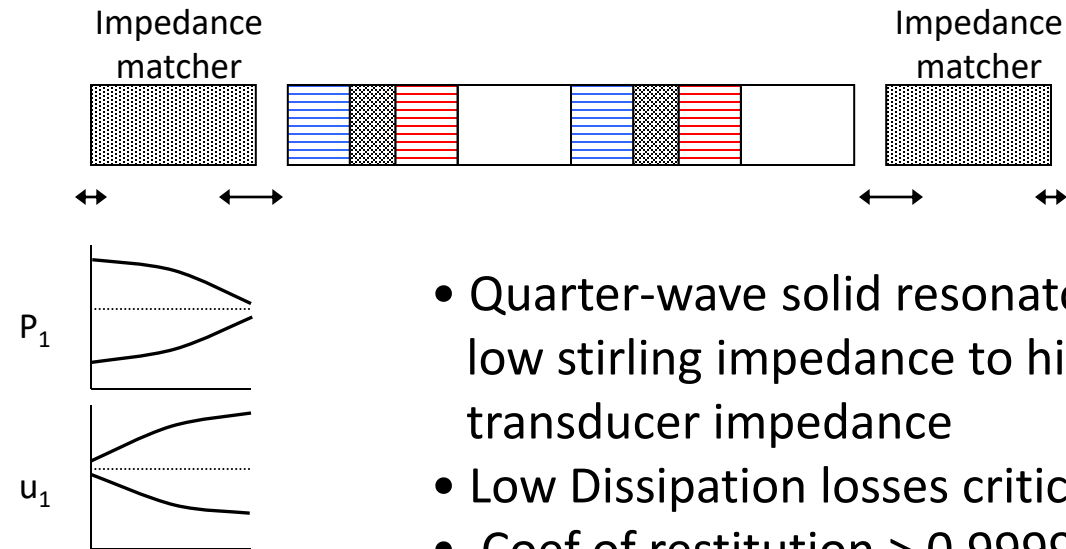
High Impedance
(Piezo or magnetostrictive)



Low Impedance
(Moving Magnet actuator)

Impedance is P_1 / U_1

High Impedance Matching



- Quarter-wave solid resonator converts low stirling impedance to high transducer impedance
- Low Dissipation losses critical
- Coef of restitution > 0.9999
- Three-dimensional effects?
- Piezo transducers prefer higher frequency than stirling thermodynamics allows

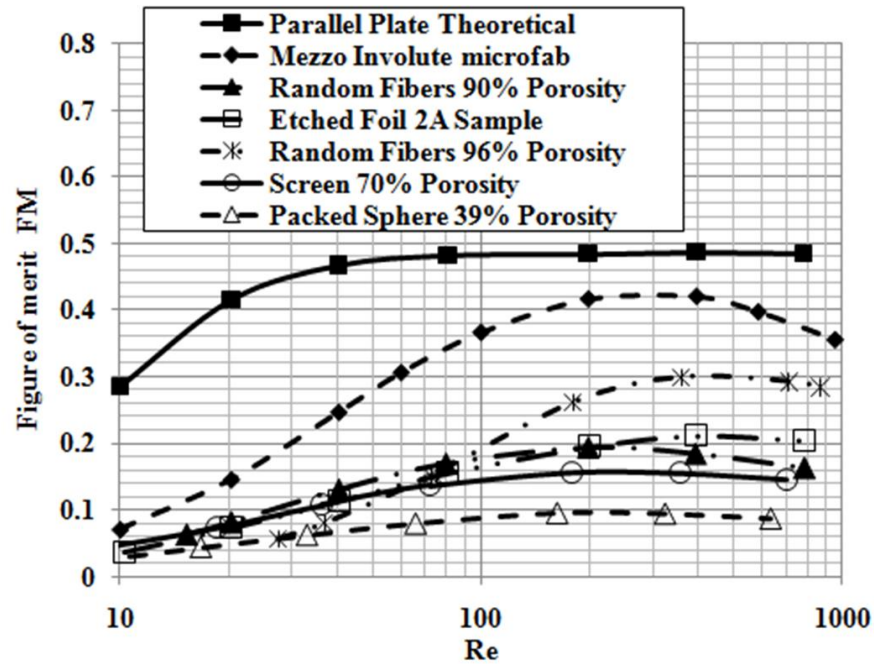
Low Impedance Matching



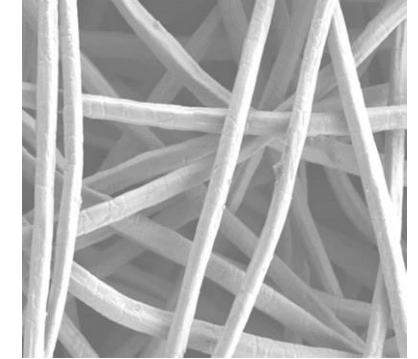
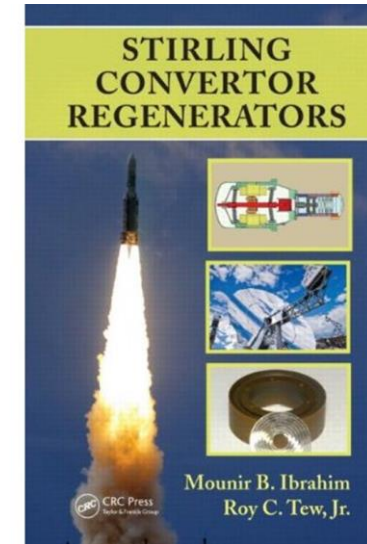
Qdrive linear motor

- Moving magnet linear transducers can intrinsically match stirling impedance
- But have relatively high reciprocating mass compared to piezo transducers
- Limiting maximum operating frequency without external springs unless reactive pressure spring is used as in DELTA

Regenerators



$$F_M = \frac{1}{f \left(\frac{R_e P_r}{4 N_u} + \frac{N_k}{R_e P_r} \right)}$$



f = Darcy friction factor

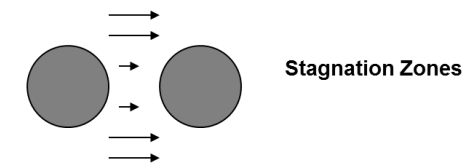
N_u = Nusselt Number, $h d/k$

N_k = effective gas conductivity due to thermal dispersion as a fraction of molecular conductivity

R_e = Reynolds number, $\rho u d/\mu$

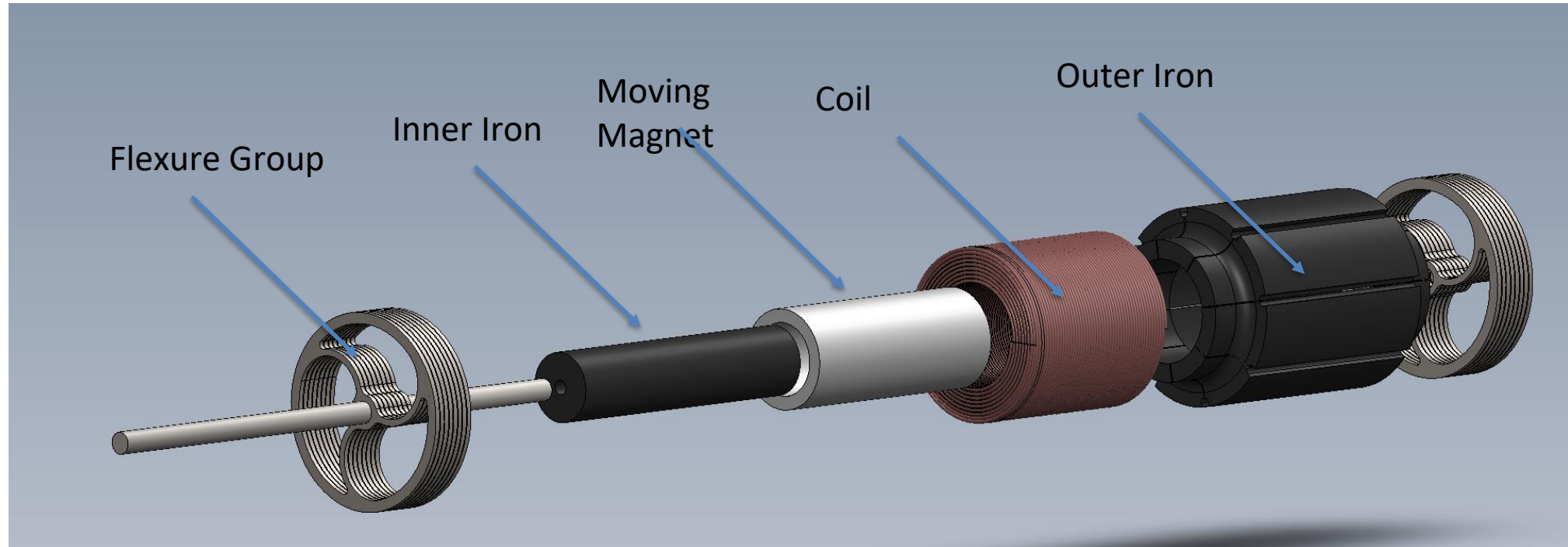
P_r = Prandtl number, $C_p \mu/k$

d = hydraulic diameter



- Wakes and eddies increase ΔP and thermal dispersion (axial conduction losses)
- Thermal dispersion was measured/simulated during DOE & NASA efforts
- Stagnation zones tend to decrease heat transfer
- Blowby at wall, wall-caused flow non-uniformities found to be potential random-fiber/wire screen regenerator losses

Linear Alternator Exploded View



Summary

- Similar basic configurations already demonstrated at low frequency
- Multi-stage design available but only sub-components tested
- Final step is assembling entire unit to operate at high frequency
 - Mass reduces since linear machine is operated at high frequency
 - No hot moving parts or maintenance required
 - Simple construction with mostly porous acoustic heat exchangers and waveguide tubes
 - Linear machine can be commercially purchased