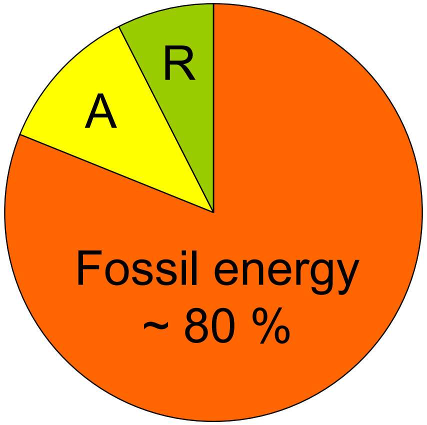
Modelica based simulation model of a Pulse Tube Engine

Stefan Moldenhauer and André Thess

TU Ilmenau (Germany)

Unused waste heat



Thermal
energy conversion

Problem: 30..60 % of waste heat

Usage ?

Large-scale

- Gas turbine combined cycle

Small-scale

- no practical solution!

Technologies for waste heat usage

Thermodynamic cycles

• Gas cycles (Stirling etc.)

⟶ low specific power output

• Organic–Rankine–Cycle (ORC)

⟶ complex systems, thermal instability of working fluids

Problem: accident-sensitive, cost-intensive, heavy

Thermoelectric materials

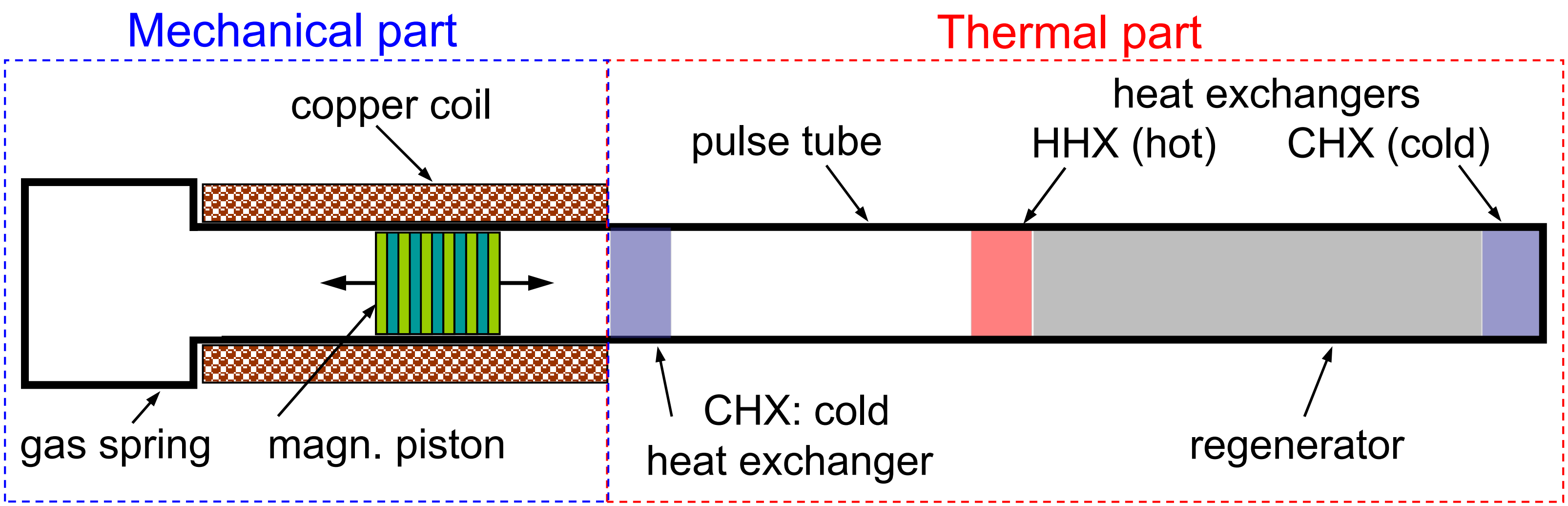
• Seebeck-Effect

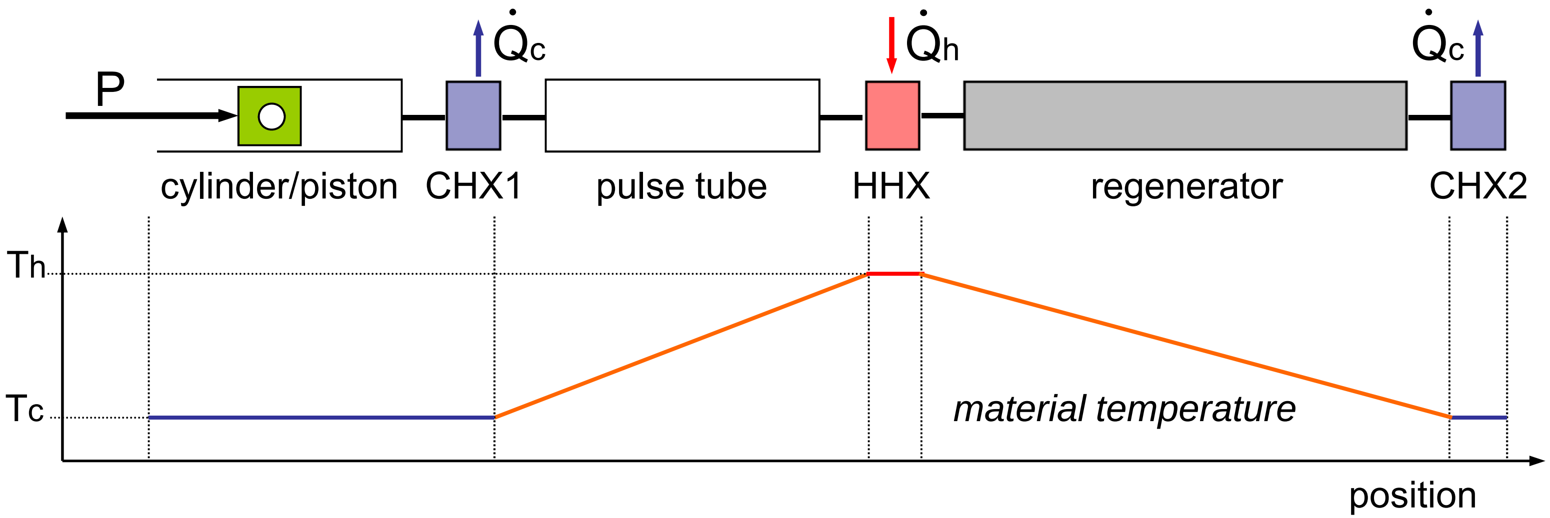
⟶ low thermal efficiency, expensive materials

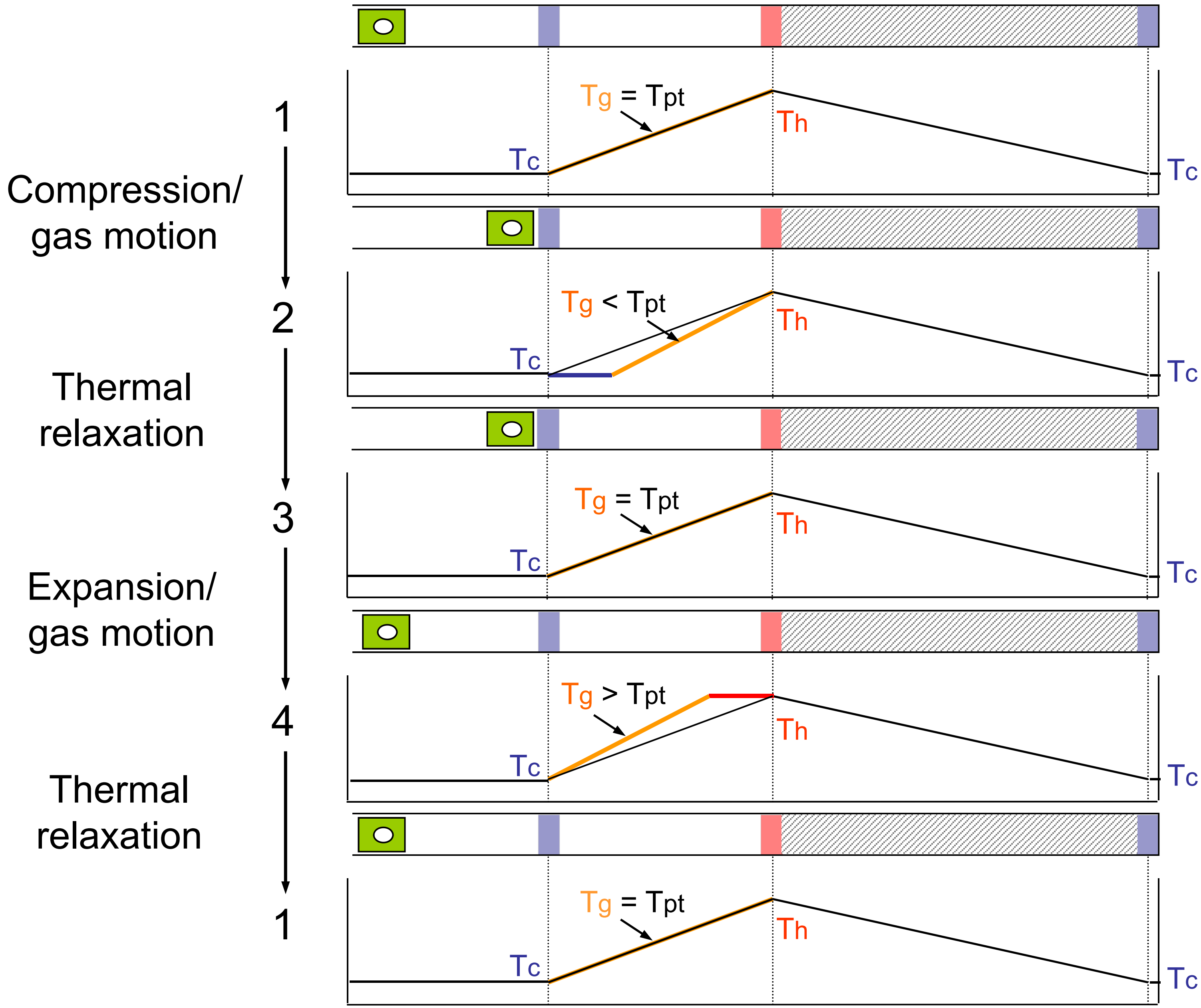
Problem: not profitable

Objective: Simple and efficient prime mover

Proposition: The Pulse Tube Engine (Hamaguchi 2005, Organ 2007)

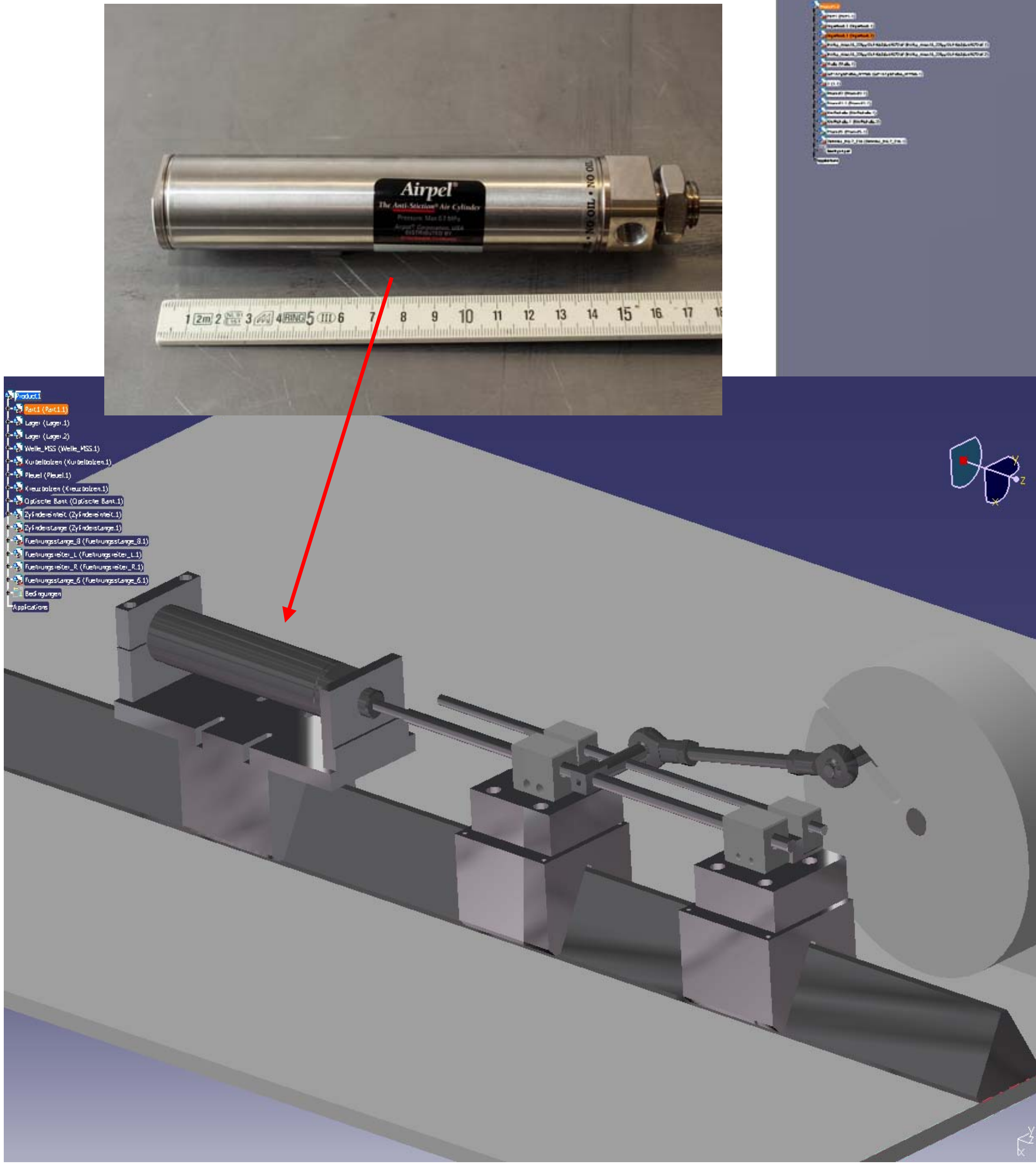




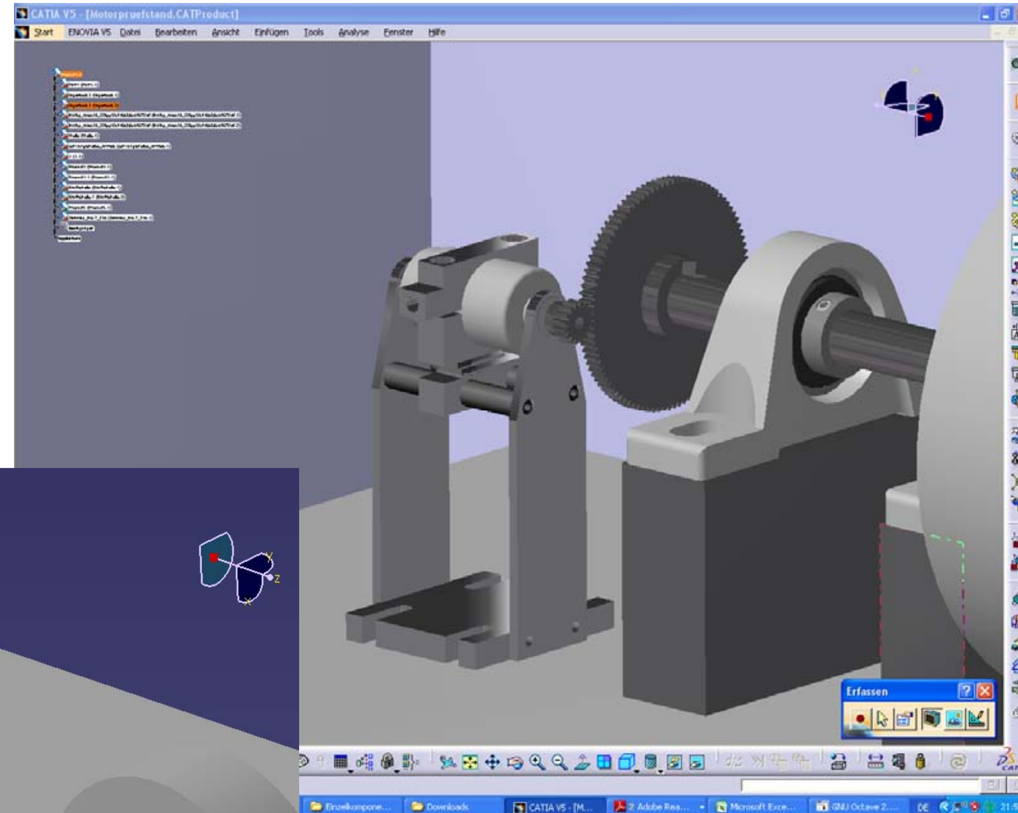


ILMENAU UNIVERSITY OF TECHNOLOGY
Dipl.-Phys. Stefan Moldenhauer
Institute of Thermodynamics and Fluid Mechanics
DBU
SimulationX Powered by ITI

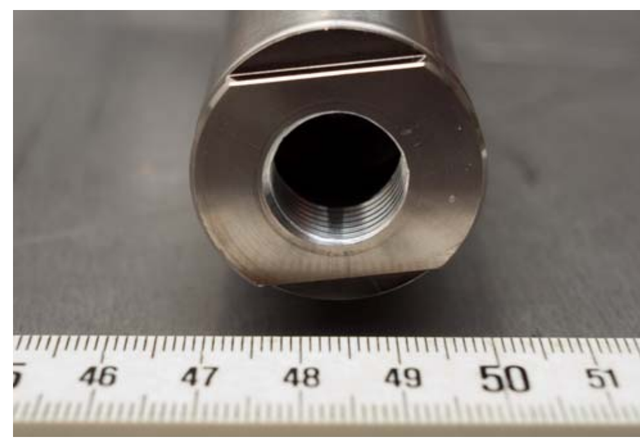
Experiment



Airpel
The Anti-Stiction Air Cylinder
NO OIL • NO OIL



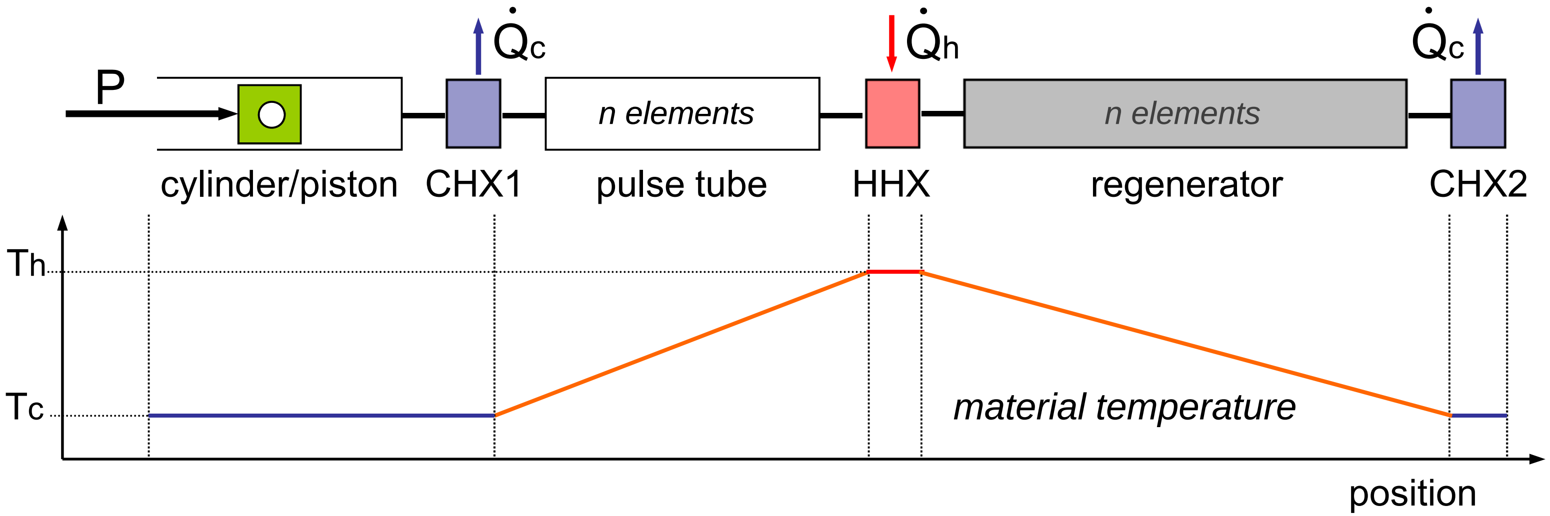
CATIA V5 - [Motorpruefstand.CATProduct]
Start ENOVIA V5 Datei Bearbeiten Ansicht Einfügen Tools Analyse Fenster Hilfe
Erfassen



46 47 48 49 50 51

Modelica based simulation model

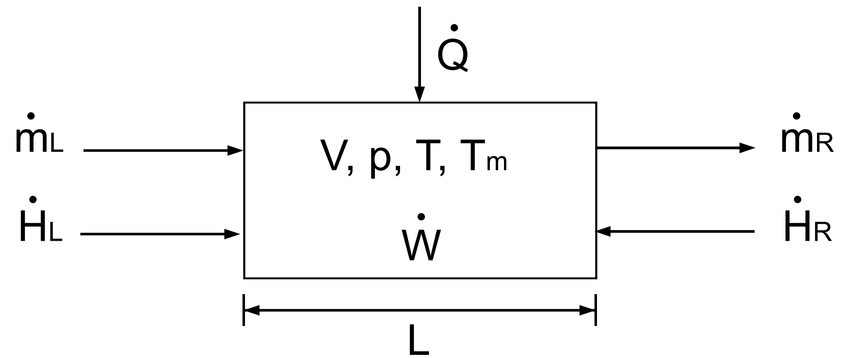
Step 1: **Segmenting in components**



Step 2: **Simplifications & assumptions**

- working fluid is a perfect gas
- one-dimensional flow
- no temporal change in material temperature
- experimental relations for heat transfer and friction

Step 3: **Balance for mass, energy and momentum**



$$\dot{Q} = \alpha\, A_w\, (T_m - T), \quad \dot{W} = -\,p\,\frac{dV}{dt}, \quad \dot{H} = \dot{m}\, c_p\, T$$

System of coupled differential equations

$$\frac{dp}{dt} = (\dot{m}_{in} - \dot{m}_{out})\,\frac{R\,T}{V} - \frac{p}{V}\,\frac{dV}{dt} + \frac{p}{T}\,\frac{dT}{dt}$$

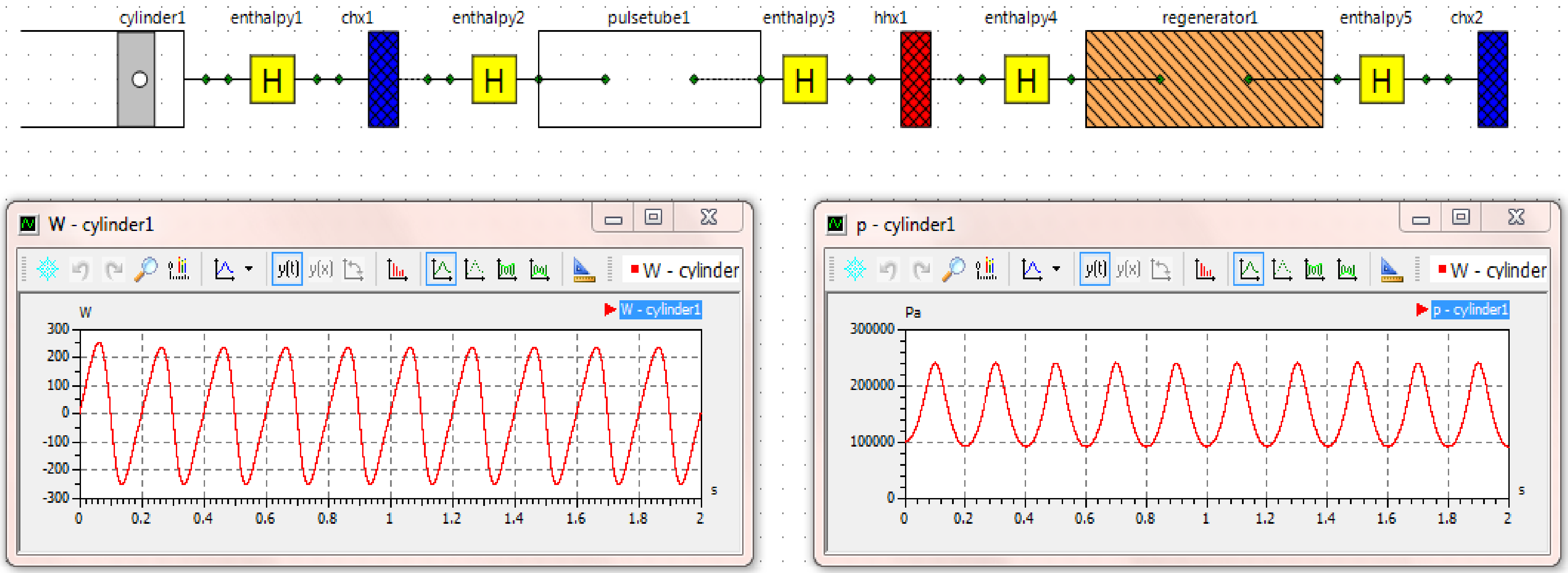
$$c_v\,\frac{p\,V}{R\,T}\,\frac{dT}{dt} = -\,c_v\,T\,(\dot{m}_{in} - \dot{m}_{out}) + \sum_i \left(\dot{Q}_i + \dot{W}_i + \dot{H}_i\right)$$

$$\frac{\partial \dot{m}}{\partial t} = -\,\frac{R\,T}{p\,A_g}\,\frac{\partial \dot{m}^2}{\partial x} - A_g\,\frac{\partial p}{\partial x} - \frac{2\,f_R\,|\dot{m}|\,\dot{m}}{\rho\,A_g^2\,d_h}$$

ILMENAU UNIVERSITY OF TECHNOLOGY
Dipl.-Phys. Stefan Moldenhauer
Institute of Thermodynamics and Fluid Mechanics

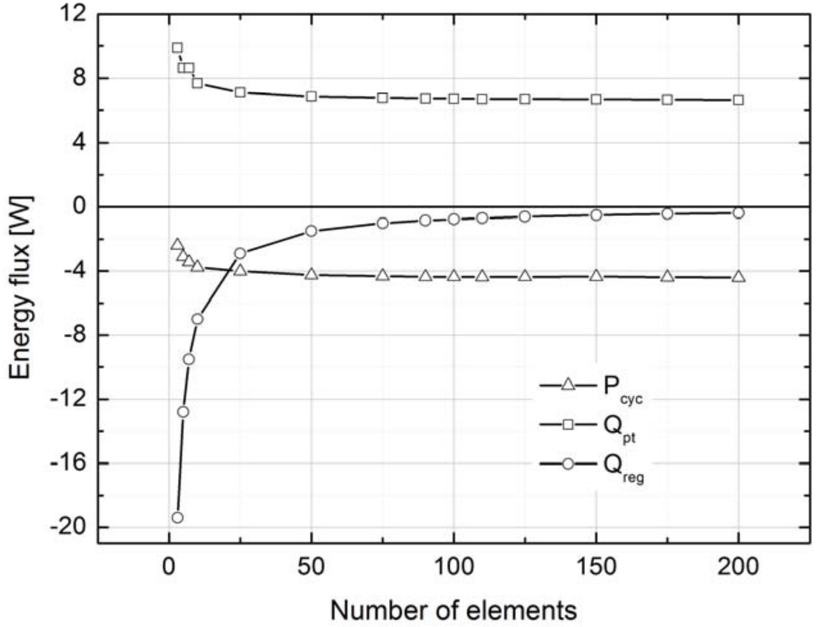
Step 4: Solving the system of differential equations

- numerical integration via implementation in Modelica
- environment: SimulationX 3.3 (ITI GmbH)

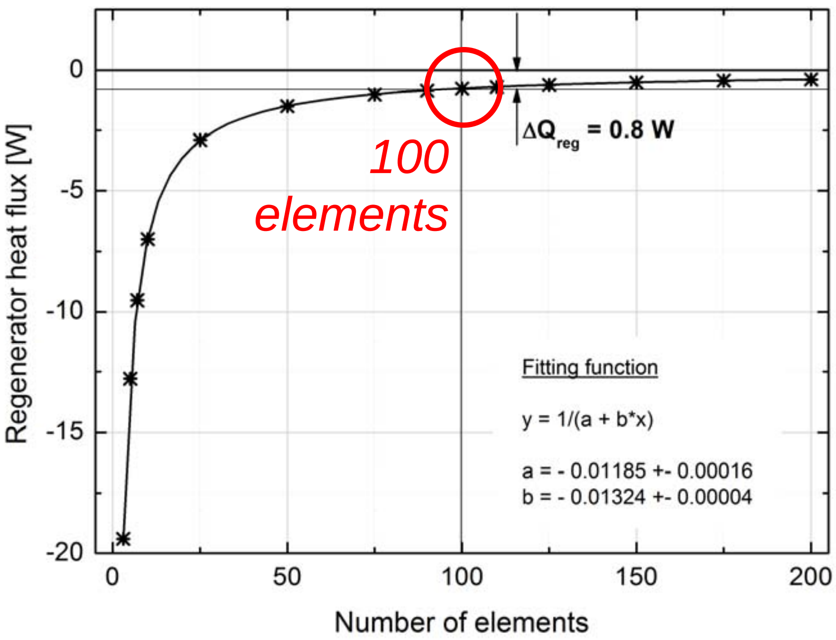


SimulationX representation of the Pulse Tube Engine

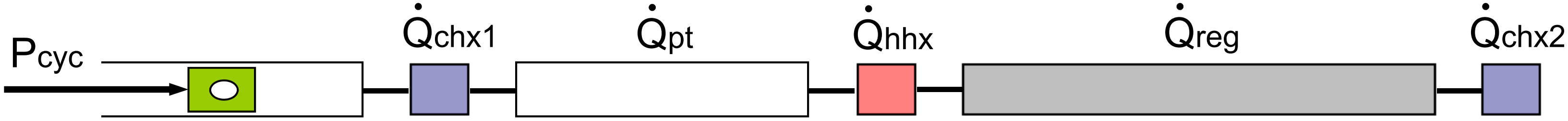
Step 5: **Defining the number of pulse tube / regenerator elements**

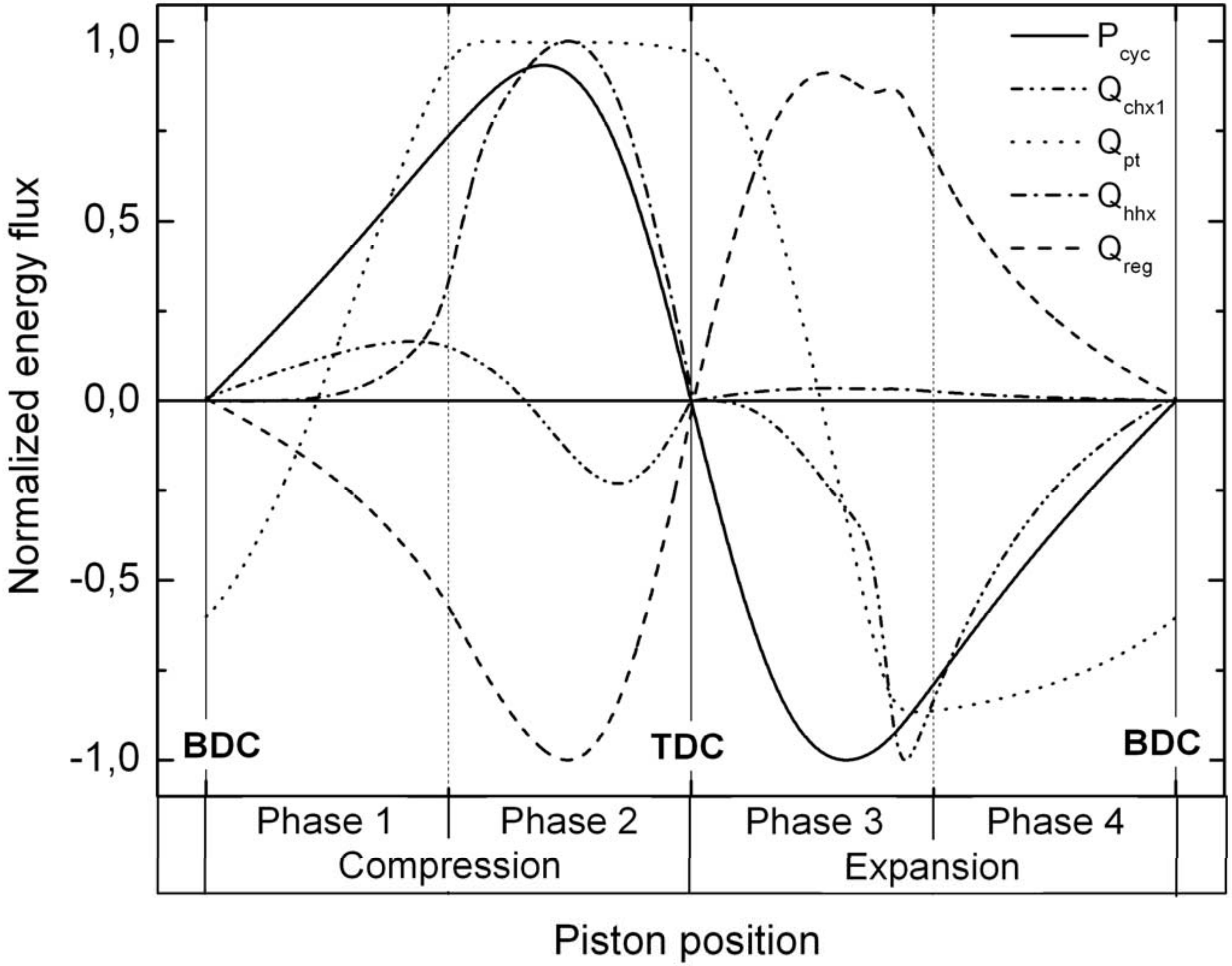


Model of an ideal regenerator

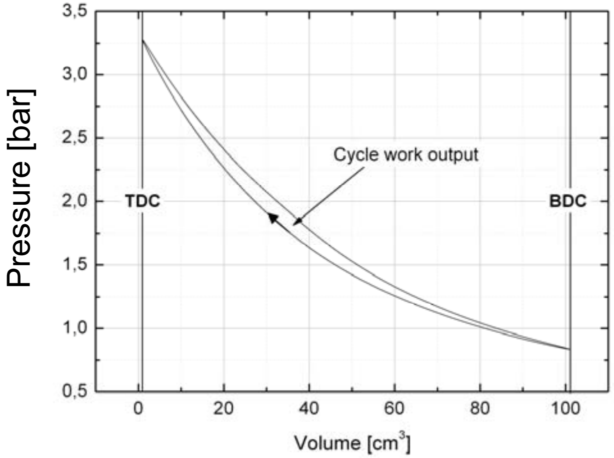


Results – Energy fluxes



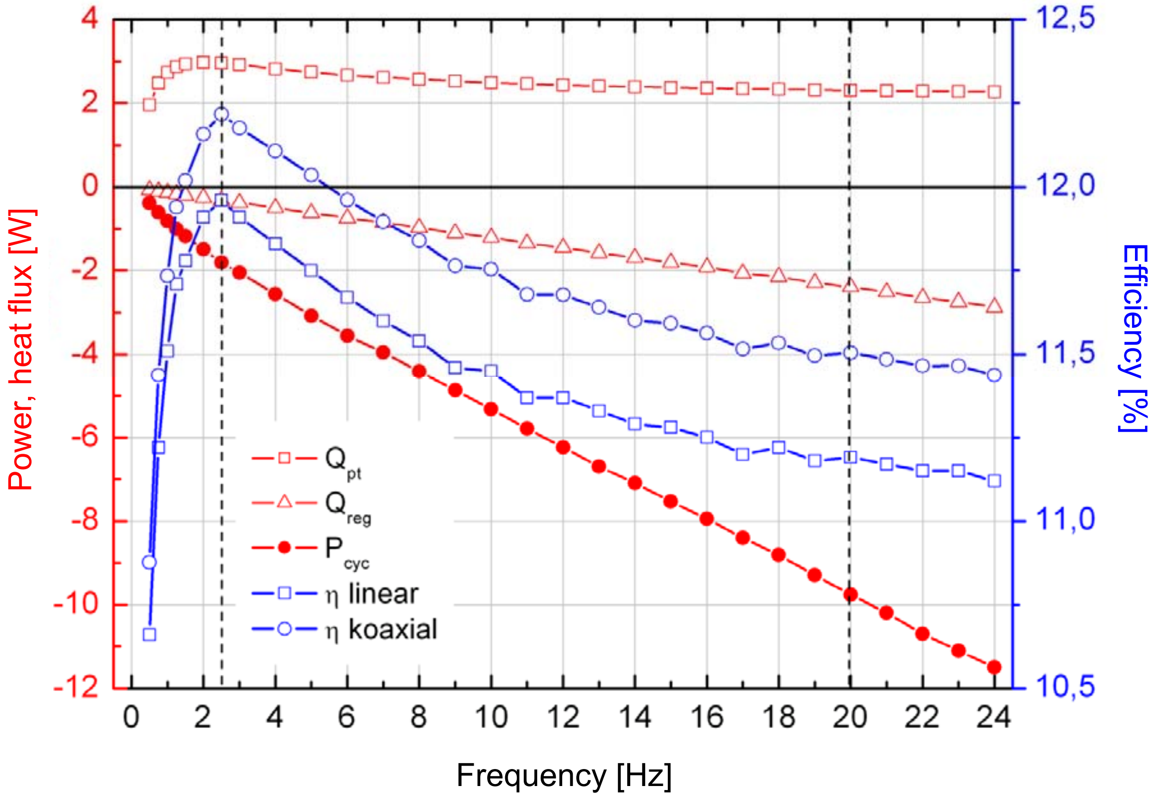


Performance of the Pulse Tube Engine



P_{out} = 3 W
η = 12%

@ f = 5 Hz

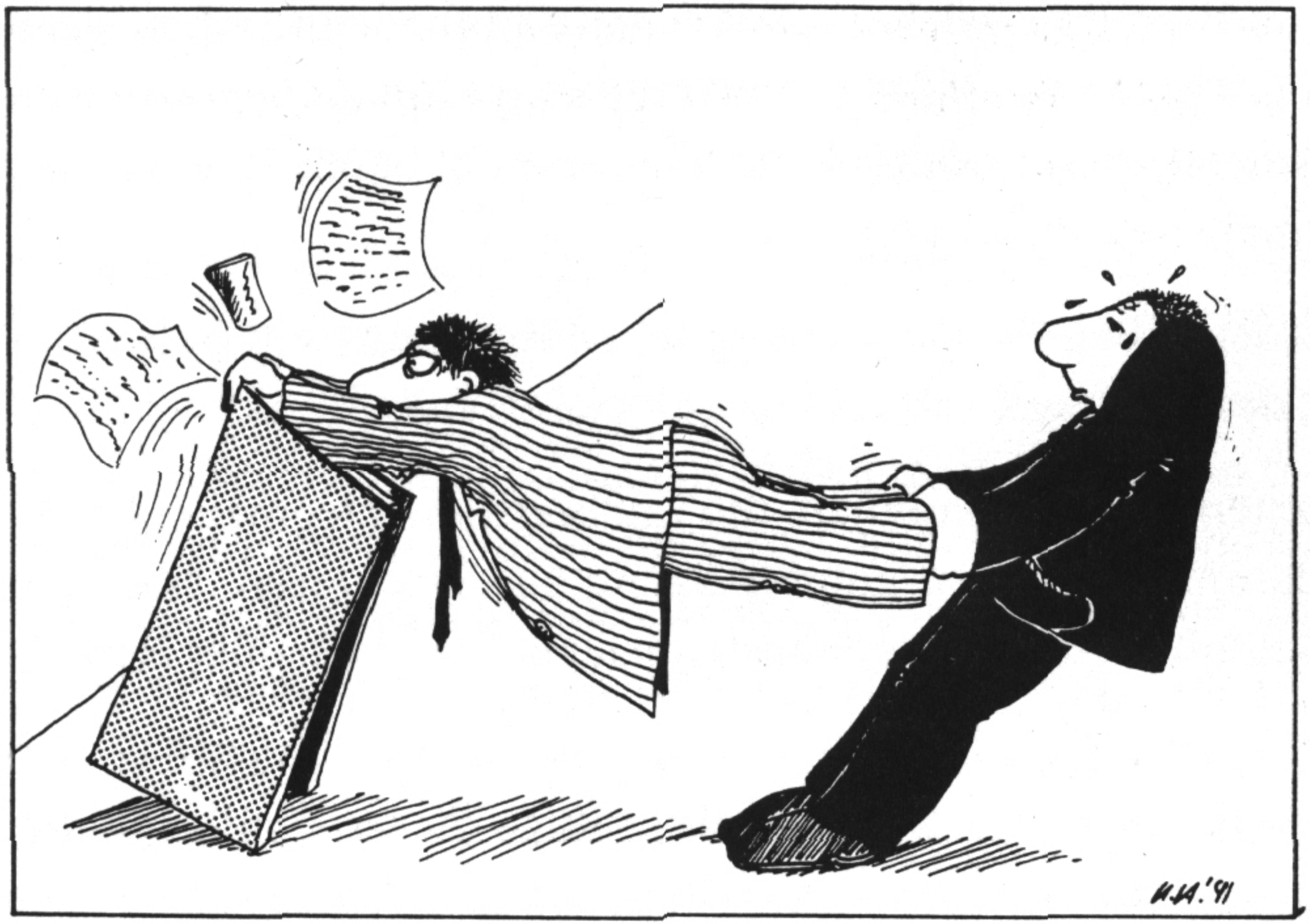


V_s = 100 cm³
p_{fill} = 1 bar
T_h = 600 K (waste heat)
T_c = 300 K (ambient)

Summary

- Pulse Tube Engine = simple prime mover
- only one moving component in the cold region
- SimulationX model allows to study physical properties
- model based optimization is possible

Possibility of a market for small pressurized engines!


U.A.'91