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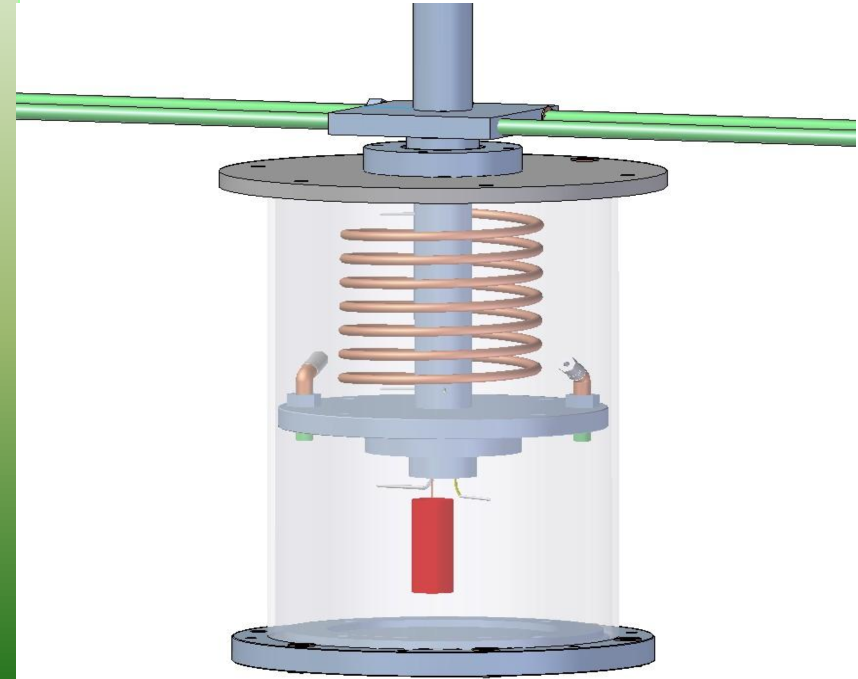

A SMALL SCALE TURBINE FOR THE ORGANIC RANKINE CYCLE

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The Start

- In small-scale and microscale CHP systems, organic working fluids are preferable because the fluid mechanics leads to high turbine efficiency in both full and partial load.

- Further development of existing technologies and implementation of new technologies are inevitably required in order to achieve higher electrical and CHP efficiencies under the constraint of a specific investment cost

  (Dong et al., Applied Thermal Engineering 29 (2009) 2119….)

The Kompaktdampfturbine (KDT) is an integrated powerplant contained in a cylinder of 20cm diameter and 30 cm of height:

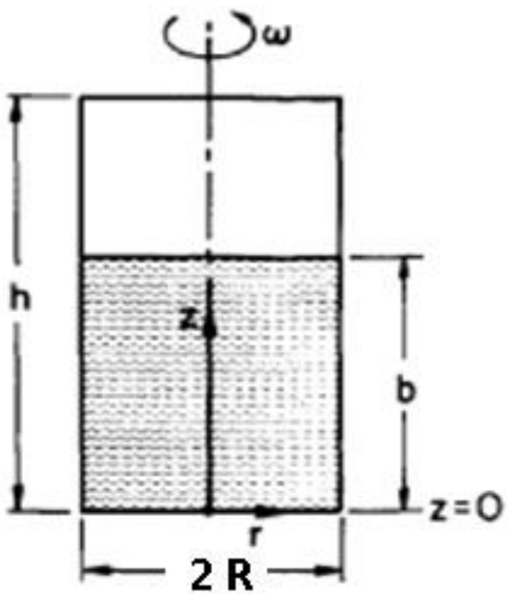
Evaporator, Condenser, Heat-Power-Coupling, Pump.

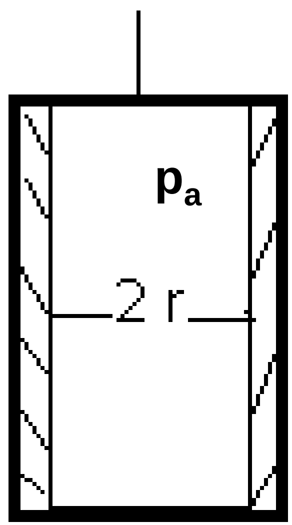
- **The list of parts is small**
- **The construction is simple – only rotating part**

Basic principle: Newtons bucket

- A cylinder partially filled with liquid set into rotation
- Surface of liquid quickly becomes an annulus
- Formulas in (Gerber, BRL Report 2462, 1975)

ω: Rotation frequency
p_a: gas pressure in cylinder
p_w : total pressure on wall
R : radius of cylinder
r: radius of liquid annulus
b: height of fluid at rest





$$r^2 = R^2 \left(1 - \frac{b}{h}\right)$$

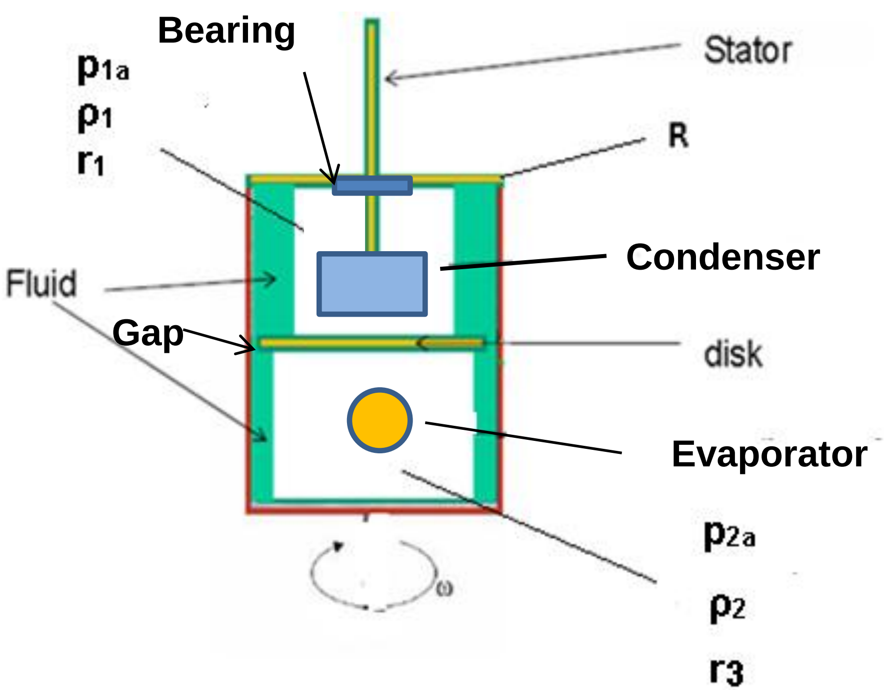
$$p_w = p_a + \frac{1}{2}\rho \ \omega^2 R^2 \frac{b}{h}$$

Centrifugal pressure

Balance of Pressure

- The cylinder ist rotating
- Different ambient (vapor) pressures in the two cavities $\mathbf{p_{1a}}$,$\mathbf{p_{2a}}$
- Different radii of the fluid annulus in the cavities

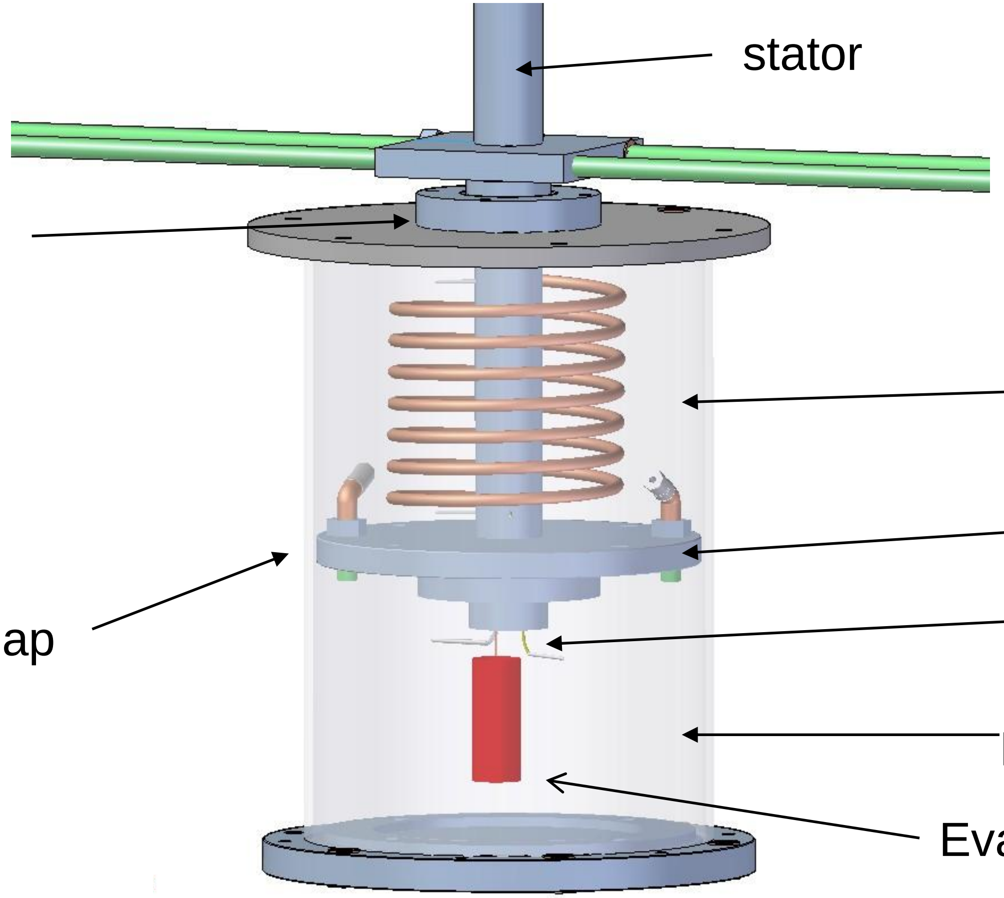
- The vapor pressures are balanced by the centrifugal pressures of the fluid



$$p_2 - p_1 = \frac{1}{2}\,\omega^2(\rho_1 R^2 - \rho_1 r_1{}^2 + \rho_2 r_3^2 - \rho_2 R^2)$$

r_i: distance fluid from rot-axis
ρ_i density of the liquid
p_i ambient pressure
R: inner Radius of the cylinder
ω: rotation frequency

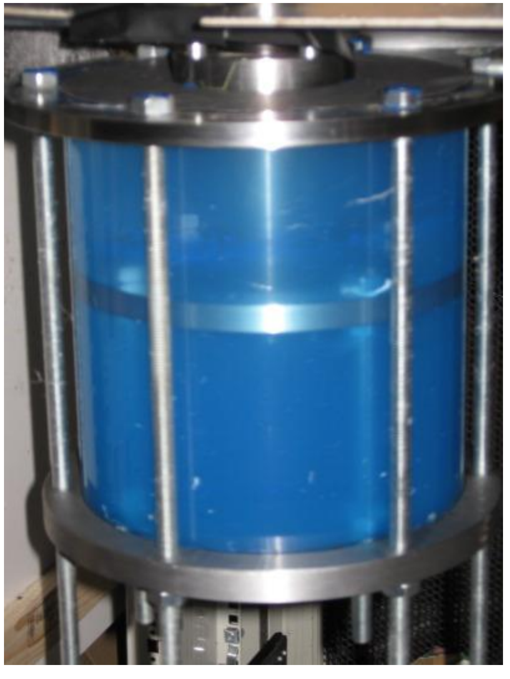
CAD-Design for experimental KDT



In this picture: no fluid in KDT

KDT: The First Experiment

- Cylinder partially filled with liquid divided by a disk into two cavities.
- Gap between rim of the plate and the cylinder



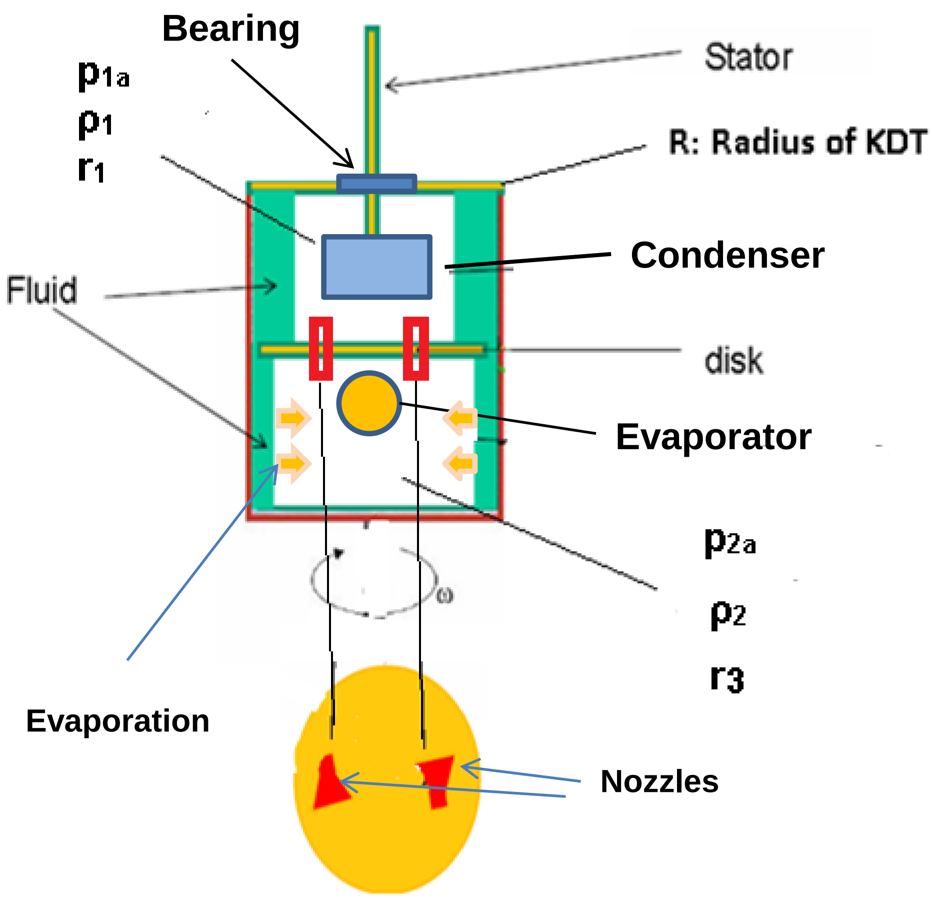
When rotating, the fluid covers the gap

The seal insulates the cavities

Different pressures in the cavities possible

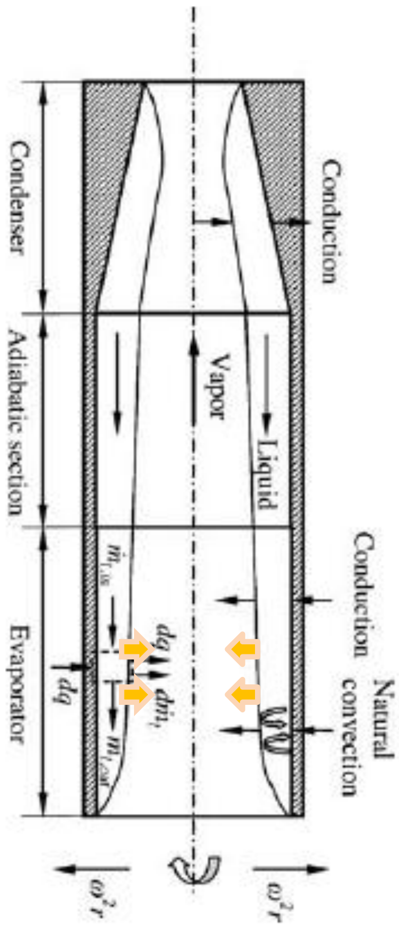
Rotating coloured oil at 2000 rpm

KDT and Propulsion



- Nozzles in the plate
- Heater in the lower cavity
- Cooler/condenser in the upper cavity.
- Massflow through the nozzles powers the cylinder
- After condensation centrifugal forces pump fluid back to the evaporator

KDT and Rotating Heat Pipe



Condenser

Evaporator

Song et. al. , Fluid Flow and heat transfer model for high-speed rotating heat pipes, International Journal of Mass and Heat Transfer 46 (2003) 4393.

- **The KDT is similar to a Rotating Heat Pipe (RHP) with <u>larger pressure difference</u>**

- Heat Pipes are devices making large heat transfers possible

- First Heat Pipe patent 1944

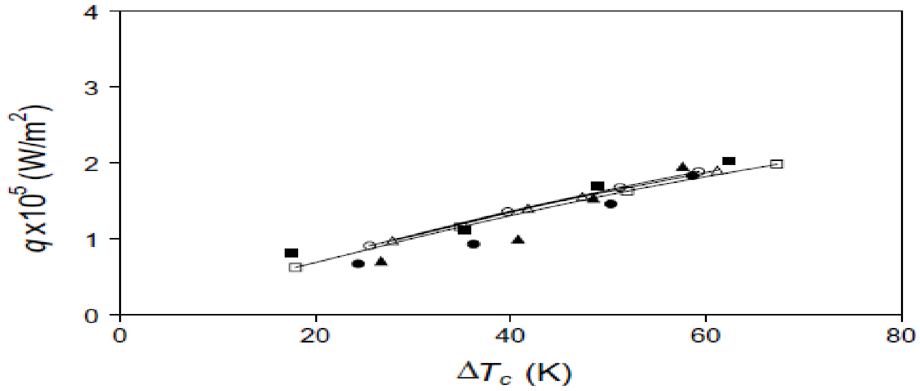
- Rotating Heat Pipes since 1969

- Heat Pipes are well researched

D. Reay, P. Kew, Heat Pipes: Theory, Design and Applications, Butterworth Heinemann (2006)

Results from RotatingHeatPipe research

- A complete model for high-speed rotating heat pipes with centrifugal accelerations up to 10 000g was developed (F. Song, Intl. Journal of Heat and Mass Transfer 46 (2003) 4393)
- Modified Nusselt model. Mixed and natural convection, film evaporation, nucleation suppressed
- Effect of fluid loading on heat transfer
- Model is in good agreement with experimental data (100-200kW/m^2)

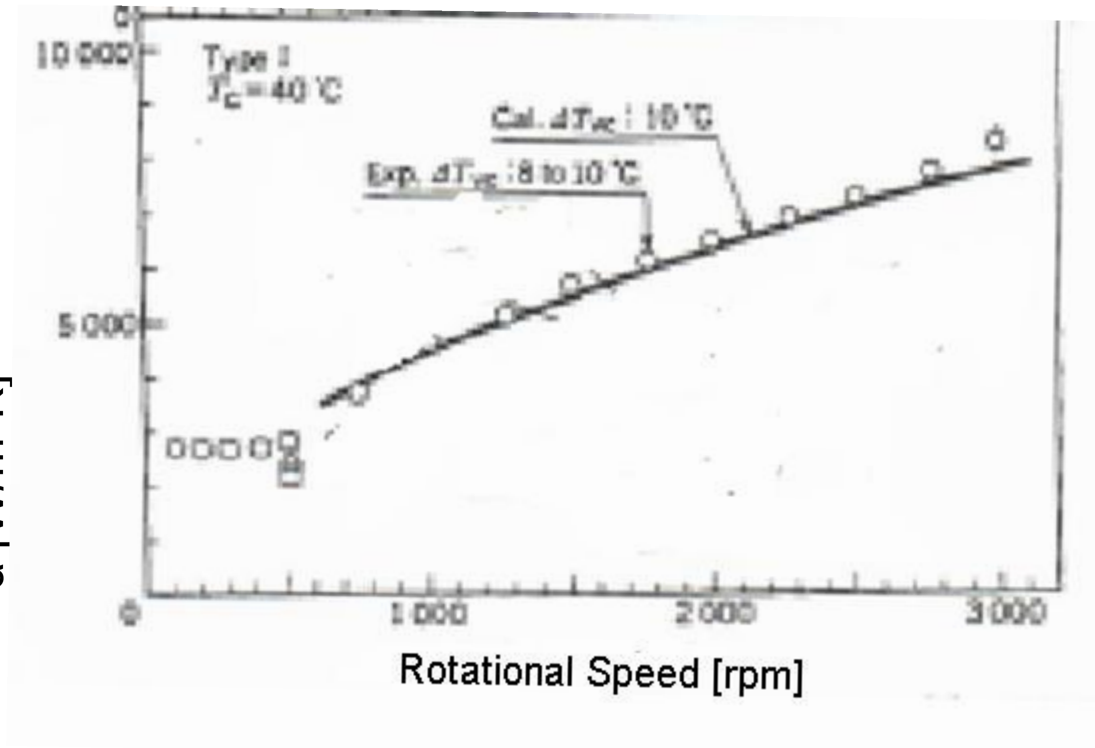


Data from:
R. Ponnappan, Q. He, J.E. Leland, Test results of a high speed rotating heat pipe, AIAA Paper No. 97-2543, 1997.

Extract from Song et al.
------ Songs model, experimental data from Ponnappan et al.: solid symbols
Open symbols Songs calculations

More results from RHP

Heat transfer coefficient for condensator α [W/m^{2}K]



Data measured for Methanol

Rotational speed, superheat temperature and heat transfer coefficient for condensation in a rotating heat pipe.

Extracted from Hashimoto et.al., Mitsubishi Heavy Industries, Technical Review Vol .33 No.2 (1996)

KDT Summary

- Newtons bucket gives the classical foundation: The fluid and the centrifugal forces seal the chambers
- Rotating Heat Pipes (RHP) are working and are well researched
- Heat transfer is calculated for hi-speed RHP
  - Accelarations: 3000g – 10000 g – comparable to KDT
  - Heat transfer is calculated at 100-200kW/m^2
  - Large heat transfer coefficients (α) have been measured

Indication: The KDT is able to transfer the necessary heat

…**but the calculations and experiments should be done with the ORC (e.g. Xylene, Siloxanes fluids, ...)**

Advantages KDT/Disadvantages

- An integrated power plant: Evaporation-Heat Power Transfer-Condensation – Pump
- Advantages of the rotating turbine
  - Very few rotating parts
  - No pump, no valves necessary
  - Simple and cheap to manufacture for mass production

- Disandvantages
  - Small mass flows -> compensated by ORC
  - Heat transfer criticial - ORC has worse thermal conductance than water –> compensated by fins and high rotatioanal speeds

Challenges / Next steps

The idea seems promising, **but** a number questions have to be answered

- Investigate friction losses of a rotating cylinder
  - Theory by: Dierich (Experiments in Fluids 25 (1998) 465)
    Theodorsen and Regier (NACA Report 723 (1944))
- Investigate friction losses of a rotating cylinder enclosed in a static cylinder
  - Theory by: Tillmann (Forsch. Ing. Wiss 27 (1961) 189)
- Build model to demonstrate the complete thermodynamic cycle with the laval nozzles
- System simulation (CFD)
- Choice of the right fluid
  - ORC, i.e. Xylene, Siloxanes…
- Improve on the turbine geometry
  - Second stage, Ljungström
- Design Heat Exchanger

- **The goal: Build a prototype with electrical efficiency of 10%**

Test Stand

Thank you very much!