# ANALYSIS AND DESIGN OF NOVEL ABSORPTION POWER CYCLE PLANTS

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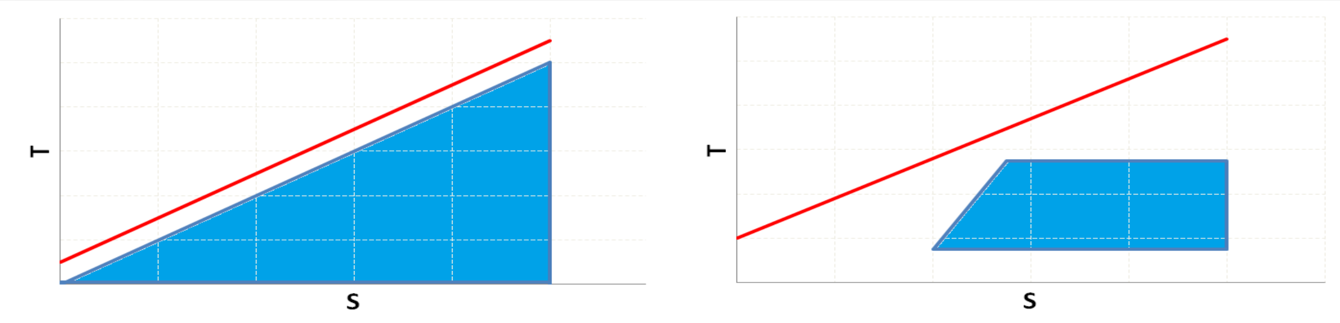
# Outline

- Waste heat recovery – features and issues
- Absorption power cycles
  - General principles
  - Thermodynamic models + results
  - Components design
- Future planned and intended work
- Conclusion

# Waste heat recovery options

- ORC
  - Industrial standard, robust, reliable
  - But
    - High irreversibility in heat exchangers
    - Negative effect growing with lowering heat source temperature
    - Result is very low efficiency, hardly economical application



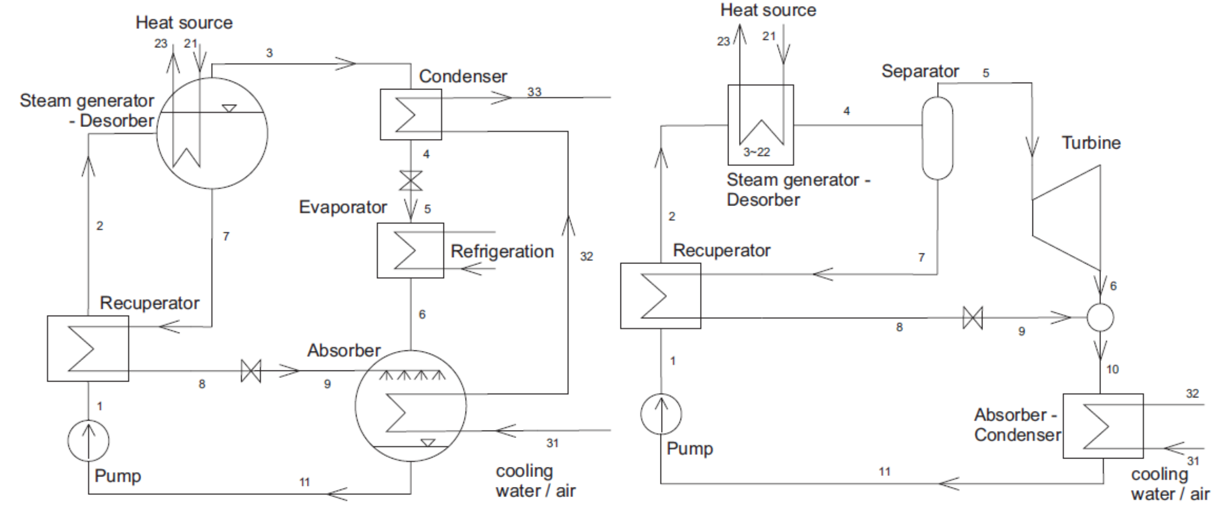
Ideal WHR cycle

Ideal Rankine cycle

# Waste heat recovery options

- Solutions?
  - Variable boiling point – use of (zeotropic) mixture as working fluid – lowering irreversibility by temperature match of hot and cold fluid due to temperature glide
  - Supercritical state of working fluid – no boiling point, specific fluid for specific temperature
  - Cascading of multiple cycles, multiple pressure systems
  - Trilateral cycle with expansion from saturated liquid
    - All mostly in research or only limited commercialization

# Absorption chiller cycle vs. Absorption power cycle

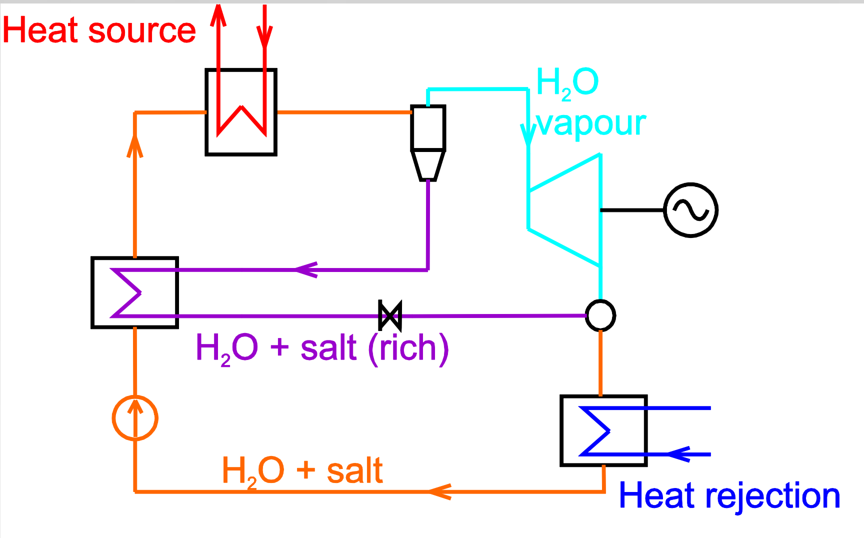


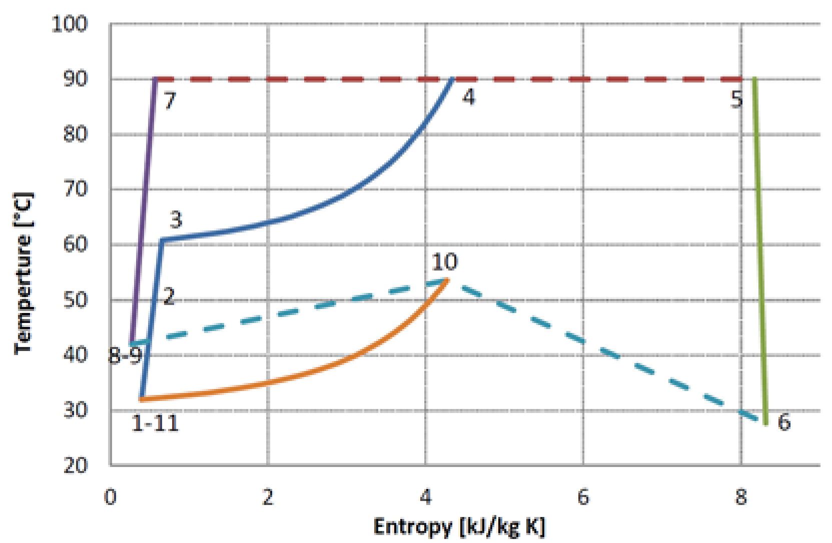
(a) Absorption cooling cycle (b) Low temperature absorption power cycle

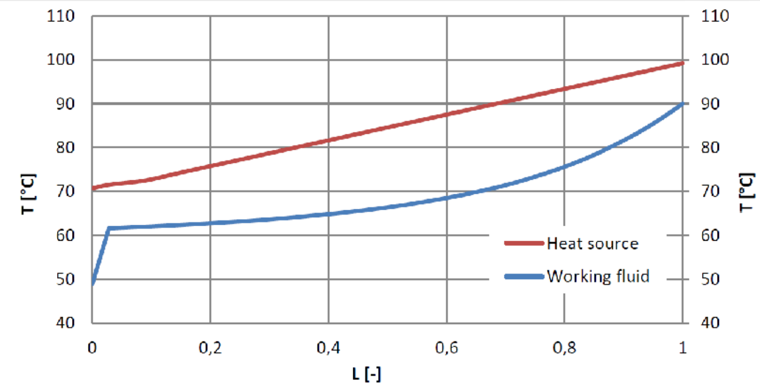
- Working fluids enabling temperature glide of boiling point
- Range of possible working fluids especially for cooling cycles
  - Cooling cycles – LiBr – H2O, NH3-H2O (commercial), other salts, ionic liquids – refrigerants mixtures
  - Power cycles – previous work limited to NH3-H2O, only few theoretical works about different working fluids, theoretically range should be same or larger than for cooling, should not be so limited by freezing problems

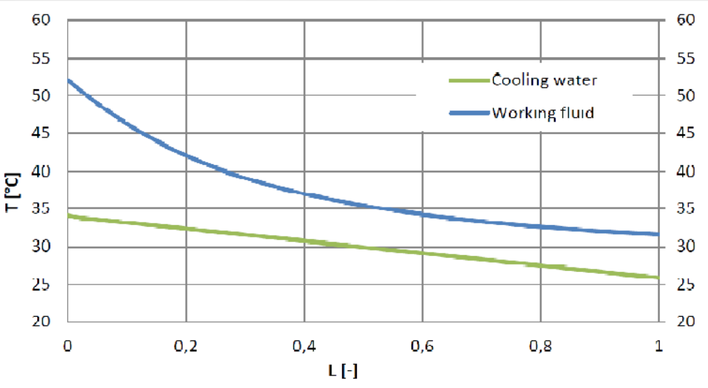
# LiBr solution absorption power cycle

## - operation principle









# LiBr absorption power cycle

## - features

- Once through counterflow HXs for high exergy efficiency
- Separator of liquid and vapour (Compared to typical chiller with pool boiling and solution circulation in absorber)
- Similarly to absorption cooling whole cycle under vacuum conditions
- Vapour is supposed to be free of LiBr and after separation is superheated
  - Low pressure allows high efficiency turbine (but bulky)
  - Working fluid handling mostly known from chillers

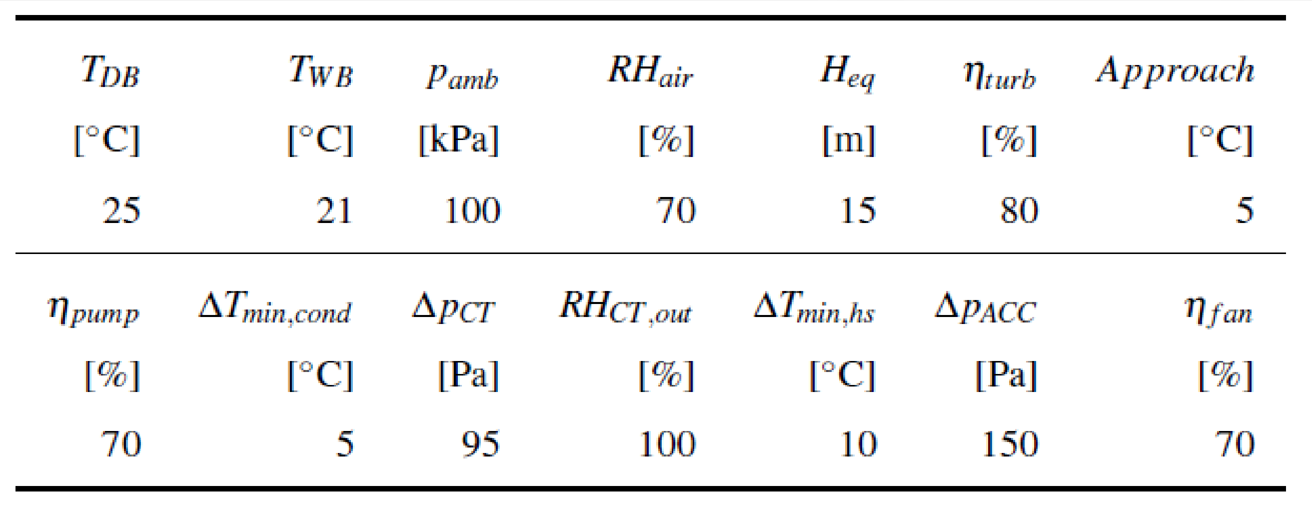
- Potential issues
  - Vacuum in whole working fluid area
  - Corrosion from the solution
  - Temperature glide HXs not proven

# Thermodynamic models

- Steady state based on heat and mass transfer
- Performance optimized for utilization efficiency
- Comparison made between
  - Kalina cycle (NH3-H2O)
  - Salt aqueous solution absorption cycles –LiBr, CaCl2, LiCl
  - Steam cycle
  - Organic Rankine cycles

# Thermodynamic models
## -assumptions & boundary conditions

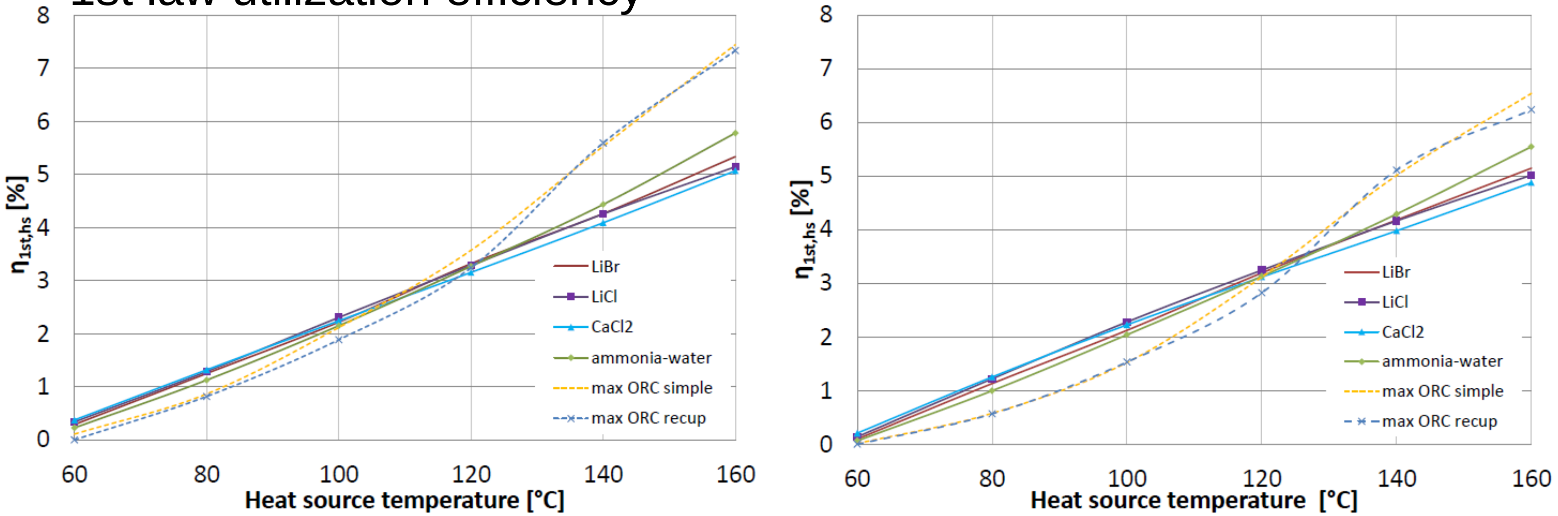
- Heat source is pressurized water, explored range 60-160°C
- Heat rejection by fan cooling tower or air cooled condenser
- Neglected pressure losses, condensate subcooling
- Working fluid in every node in thermodynamic equilibrium
- Experimental corelations of working fluid properties
- Other:



| $T_{DB}$ | $T_{WB}$ | $p_{amb}$ | $RH_{air}$ | $H_{eq}$ | $\eta_{turb}$ | $Approach$ |
|---|---|---|---|---|---|---|
| [°C] | [°C] | [kPa] | [%] | [m] | [%] | [°C] |
| 25 | 21 | 100 | 70 | 15 | 80 | 5 |
| $\eta_{pump}$ | $\Delta T_{min,cond}$ | $\Delta p_{CT}$ | $RH_{CT,out}$ | $\Delta T_{min,hs}$ | $\Delta p_{ACC}$ | $\eta_{fan}$ |
| [%] | [°C] | [Pa] | [%] | [°C] | [Pa] | [%] |
| 70 | 5 | 95 | 100 | 10 | 150 | 70 |

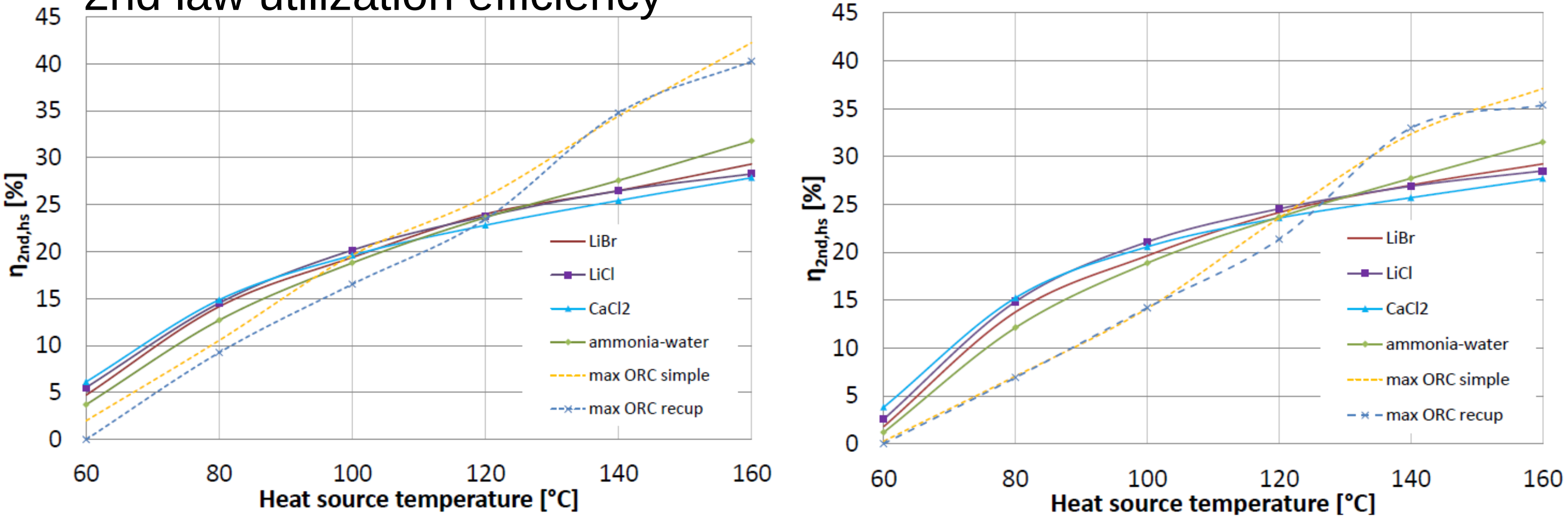
# Results of maximal efficiency points

## 1st law utilization efficiency



(a) cooling tower (b) air cooled condenser

## 2nd law utilization efficiency



(a) cooling tower (b) air cooled condenser

# Components design (LiBr APC)

- Pump
    - except for corrosion resistance minimal requirements
- Desorber
    - Heat exchanger of counterflow design
    - Heat transfer calculated from flow boiling corelations
    - Actual behaviour of temperature glide, especially for these application not well documented – under planning for experimental validation
- Separator
    - In first approach can be followed geothermal separator design
    - High requirement on droplets elimination – limit LiBr salt to turbine
    - High requirement on low pressure drop

# Components design (LiBr APC)

- Absorber
  - Heat exchanger of counterflow design
  - Complicated physical process of absorption
    - Absorption takes place at a film interface between vapour and liquid
    - Simultanious heat and mass transfer problem
    - Literature proposes several methods with limited success from experiments
    - For innitial design chosen constant mass transfer coefficient from temperature driving force, absorption over large concentration range will have to be validated experimentally
- Turbine
  - In principle a standard steam turbine
  - Steam paremeters allow use of single/multi - stage axial turbine, design includes most of losses
  - For detailed design will have to be solved seals / hermetic design
- Recuperative solution HX
  - Simple HX design, for given APC only small amount of recuperated heat

# Conceptual design results
# - 100°C heat sources

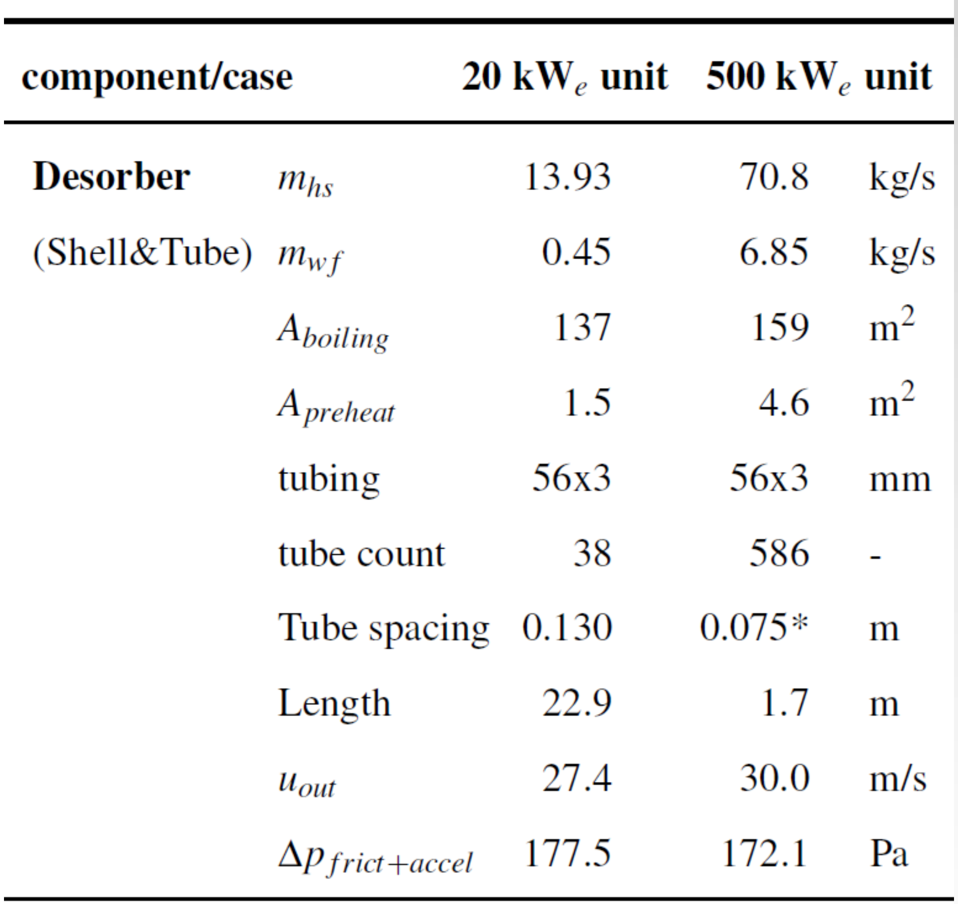
- **20 kW unit** with **hot air heat** source and **air cooled condensation**

| | | |
|---|---|---|
| Turbine inlet temperature | 90 | °C |
| Turbine inlet pressure | 12.54 | kPa |
| Turbine outlet temperature | 23.5 | °C |
| Turbine outlet pressure | 2.90 | kPa |
| Absorber inlet temperature | 56.3 | °C |
| Absorber outlet temperature | 32.8 | °C |

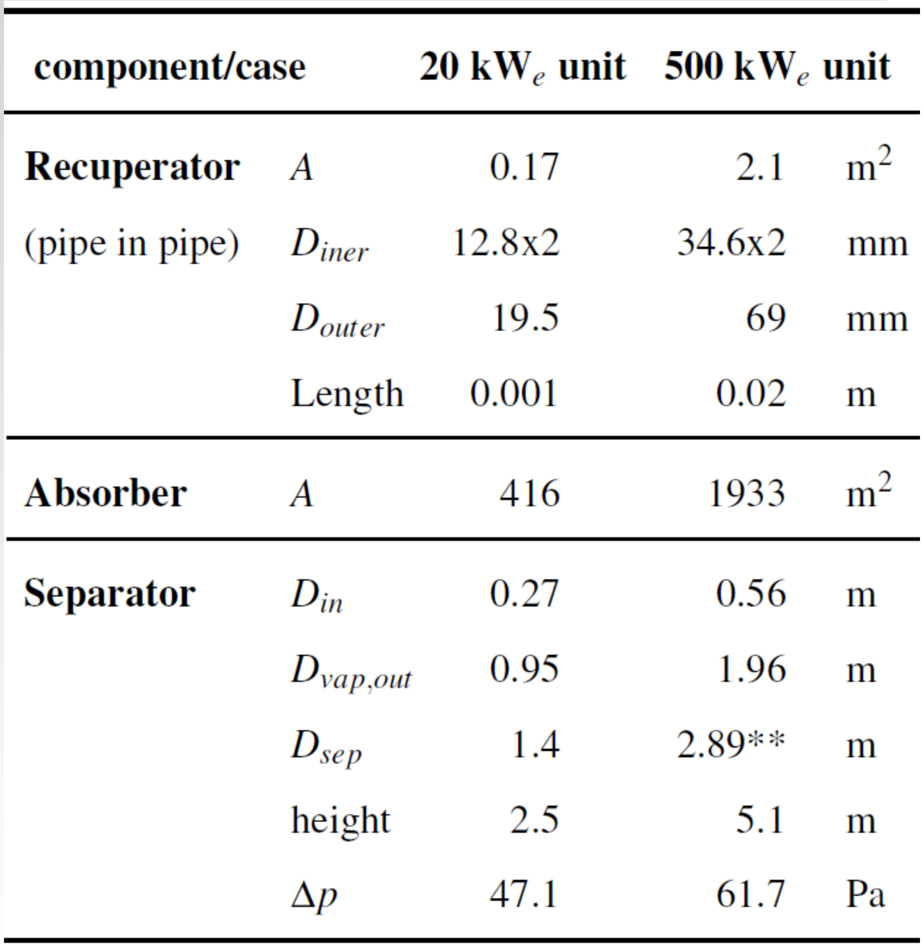
- **500 kW unit with hot water heat source and wet cooling tower**

| | | |
|---|---|---|
| Turbine inlet temperature | 90 | °C |
| Turbine inlet pressure | 16.44 | kPa |
| Turbine outlet temperature | 27.7 | °C |
| Turbine outlet pressure | 3.71 | kPa |
| Absorber inlet temperature | 53.5 | °C |
| Absorber outlet temperature | 32.0 | °C |

# Conceptual design results - 100°C heat sources



| component/case | | 20 kW$_e$ unit | 500 kW$_e$ unit | |
|---|---|---|---|---|
| **Desorber** | $m_{hs}$ | 13.93 | 70.8 | kg/s |
| (Shell&Tube) | $m_{wf}$ | 0.45 | 6.85 | kg/s |
| | $A_{boiling}$ | 137 | 159 | m$^2$ |
| | $A_{preheat}$ | 1.5 | 4.6 | m$^2$ |
| | tubing | 56x3 | 56x3 | mm |
| | tube count | 38 | 586 | - |
| | Tube spacing | 0.130 | 0.075* | m |
| | Length | 22.9 | 1.7 | m |
| | $u_{out}$ | 27.4 | 30.0 | m/s |
| | $\Delta p_{frict+accel}$ | 177.5 | 172.1 | Pa |

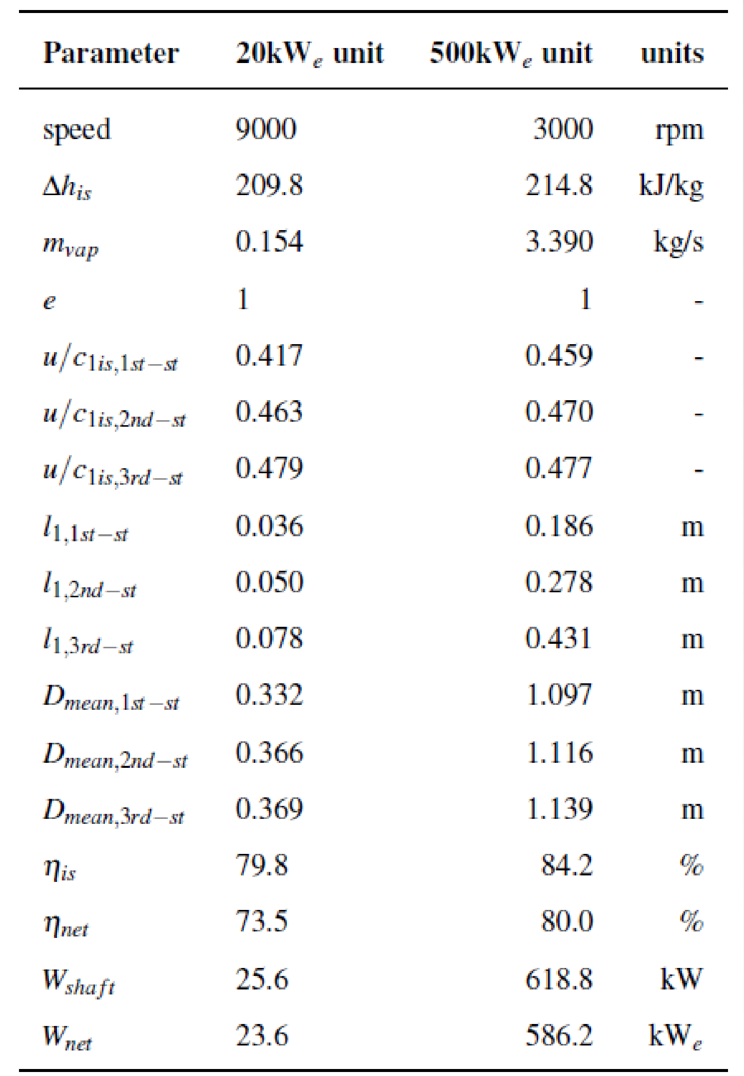


| component/case | | 20 kW$_e$ unit | 500 kW$_e$ unit | |
|---|---|---|---|---|
| **Recuperator** | $A$ | 0.17 | 2.1 | m$^2$ |
| (pipe in pipe) | $D_{iner}$ | 12.8x2 | 34.6x2 | mm |
| | $D_{outer}$ | 19.5 | 69 | mm |
| | Length | 0.001 | 0.02 | m |
| **Absorber** | $A$ | 416 | 1933 | m$^2$ |
| **Separator** | $D_{in}$ | 0.27 | 0.56 | m |
| | $D_{vap,out}$ | 0.95 | 1.96 | m |
| | $D_{sep}$ | 1.4 | 2.89** | m |
| | height | 2.5 | 5.1 | m |
| | $\Delta p$ | 47.1 | 61.7 | Pa |

* used baffles; ** 4 parallel unit to keep reasonable dimensions and pressure drop

# Conceptual design results
# - 100°C heat sources

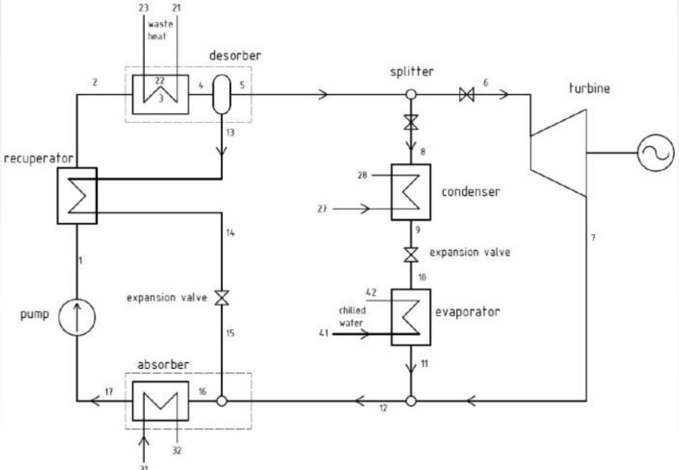
- Turbine highly efficient but bulky



| Parameter | 20kW$_e$ unit | 500kW$_e$ unit | units |
|---|---|---|---|
| speed | 9000 | 3000 | rpm |
| $\Delta h_{is}$ | 209.8 | 214.8 | kJ/kg |
| $m_{vap}$ | 0.154 | 3.390 | kg/s |
| $e$ | 1 | 1 | - |
| $u/c_{1is,1st-st}$ | 0.417 | 0.459 | - |
| $u/c_{1is,2nd-st}$ | 0.463 | 0.470 | - |
| $u/c_{1is,3rd-st}$ | 0.479 | 0.477 | - |
| $l_{1,1st-st}$ | 0.036 | 0.186 | m |
| $l_{1,2nd-st}$ | 0.050 | 0.278 | m |
| $l_{1,3rd-st}$ | 0.078 | 0.431 | m |
| $D_{mean,1st-st}$ | 0.332 | 1.097 | m |
| $D_{mean,2nd-st}$ | 0.366 | 1.116 | m |
| $D_{mean,3rd-st}$ | 0.369 | 1.139 | m |
| $\eta_{is}$ | 79.8 | 84.2 | % |
| $\eta_{net}$ | 73.5 | 80.0 | % |
| $W_{shaft}$ | 25.6 | 618.8 | kW |
| $W_{net}$ | 23.6 | 586.2 | kW$_e$ |

# Future work

- Detailed sizing and economic comparison with ORC
- Experimental validation
  - HXs – actual temperature profile
  - Steam separation – steam quality
- Investigation of alternative absorption pairs as working fluid
- Combined power and cooling cycle concept



# Conclusion

- LiBr (or generally salt solution) APC power cycle has potential for utilization of low temperature ~ 100°C heat sources
- Theoretically better than ORC and Kalina cycle
- Design methodology proposed
- Bulky but efficient device
- Experimental validations of several assumptions needed and already planned

# Questions?