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Conversion Cycles with Supercritical Fluids for Nuclear Plants

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Objectives

The goal of this study is to check possibilities of designing power cycles in the range of lower temperatures with higher efficiency.
There are indications that it might be possible to design conversion cycles with maximum temperature between 100 and 200 ℃ with better efficiency.
Supercritical fluids are the candidate optimal media for these cycles.
The principle is to include certain parts with accelerated flow into the conversion cycle.

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CO2 cycles

The CO2 cycles supposed advantages:

• very small dimensions of the equipment
• low content of media, useful for start-up, shut down
• few problems with corrosion, erosion

The CO2 cycles disadvantages:

• high operational pressure, so problems with sealing etc.
• high temperature heat input
• no verification in full scale
• no significant growth of efficiency in comparison with steam cycles

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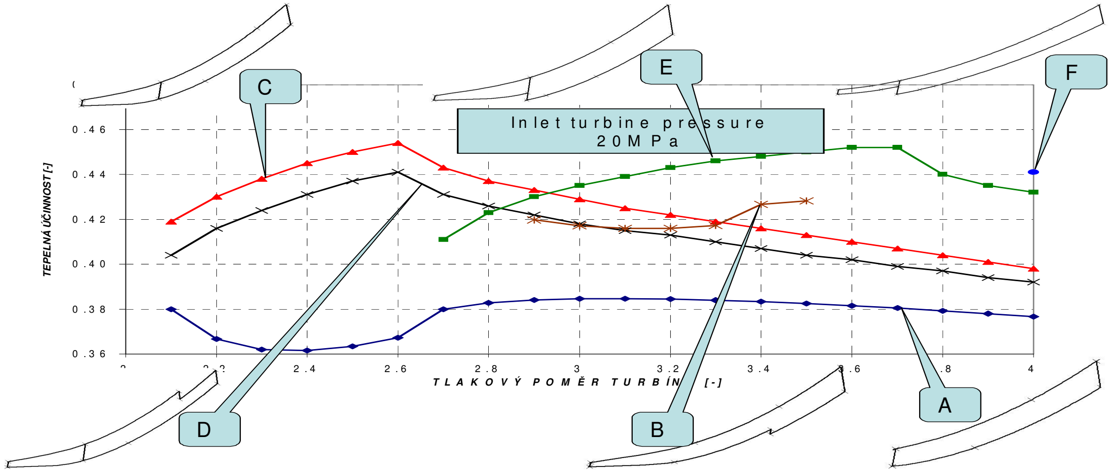
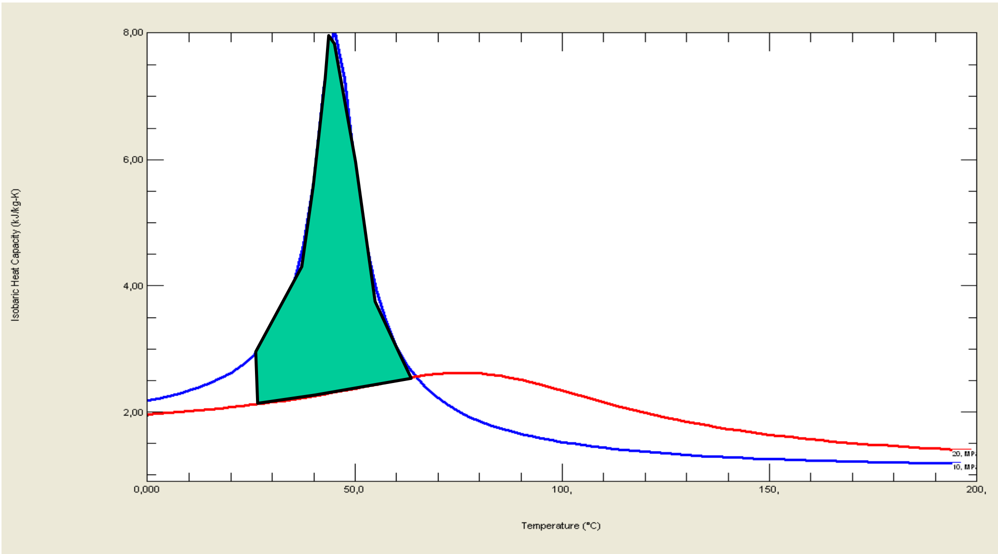
CO2 cycles architecture



The principle:

Loss of low temperature heat, at low pressure isobar



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QAI **Special aspect of energy conversion**

Modern general approach towards cycles with high efficiency is:

• go to maximum temperatures, approach arising from basic calculations with ideal gases, but the temperatures above 600 ℃ are connected with great problems with materials, mechanical properties and mainly corrosion.

- **the goal of this study is to check possibilities for finding a new approach**

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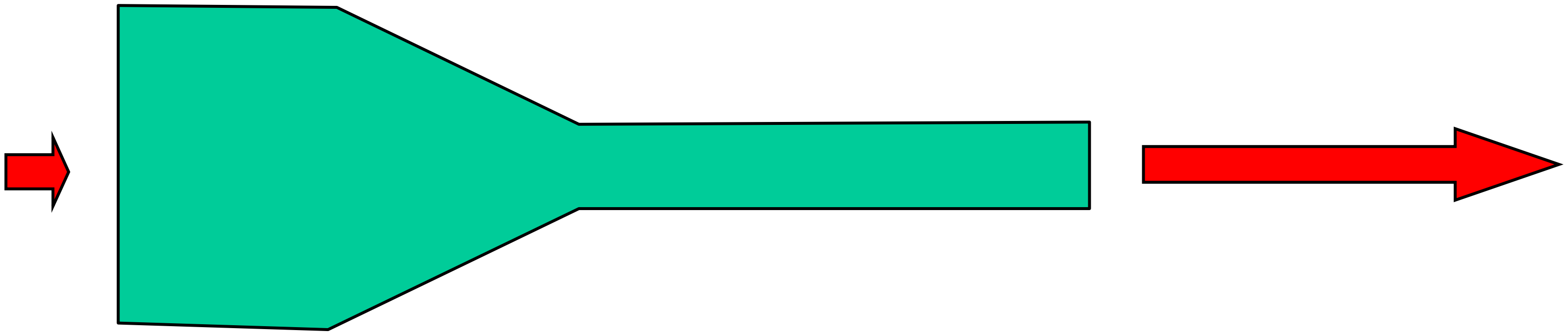
General effect of flow acceleration



Flow acceleration effect

$$\Delta h = \Delta w^2/2$$

Straightforward interpretation of this equation is that a part of thermal energy is changed into kinetic energy.

Kinetic energy is reversible!

This process is connected with **pressure and temperature drop.**

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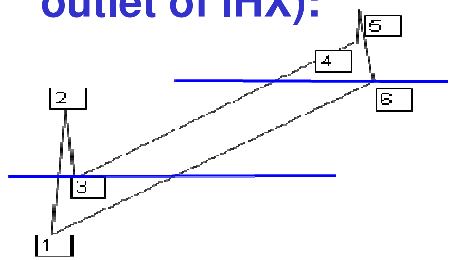
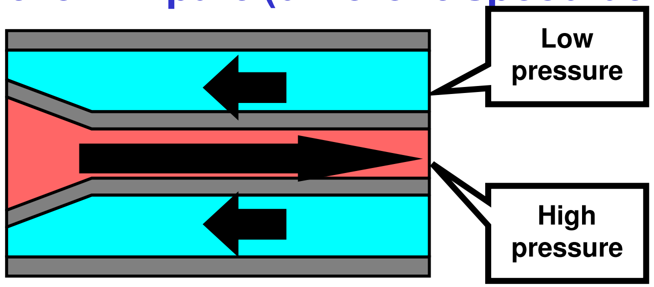
Ideal cycles

Standard Brayton cycle with regeneration, high speed in high pressure isobar, the same diameter in entire HP part (different speed at inlet and outlet of IHX):

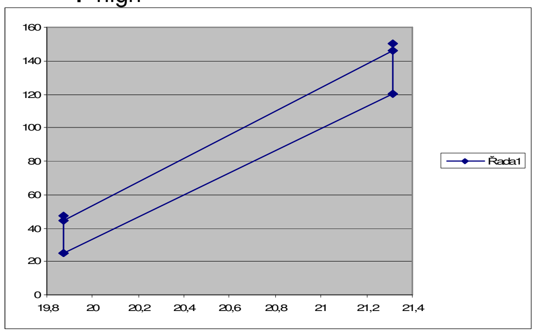


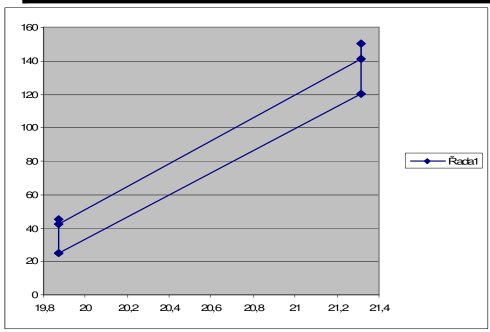


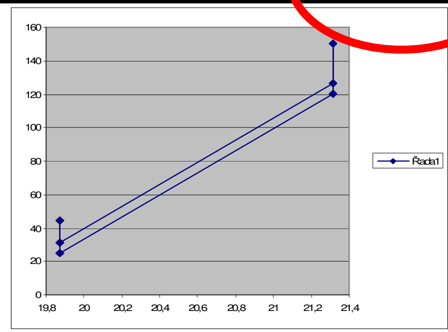
Input data:

t_{low} = 25°C
t_{high} = 150°C
Carnot efficiency : 0,295
For Brayton cycle:
p_{low} = 5MPa
p_{high} = 6MPa

Q_{in} (kJ)	Q_{out} (kJ)	A_{out} total (kJ)	w (m/s)	efficiency
142,9	103	39,8	**200**	**0,242**
128,9	85,9	43	**300**	**0,334**
84,7	31,1	53,6	**500**	**0,632**







Conclusions: **The efficiency grows above Carnot cycle!!!**

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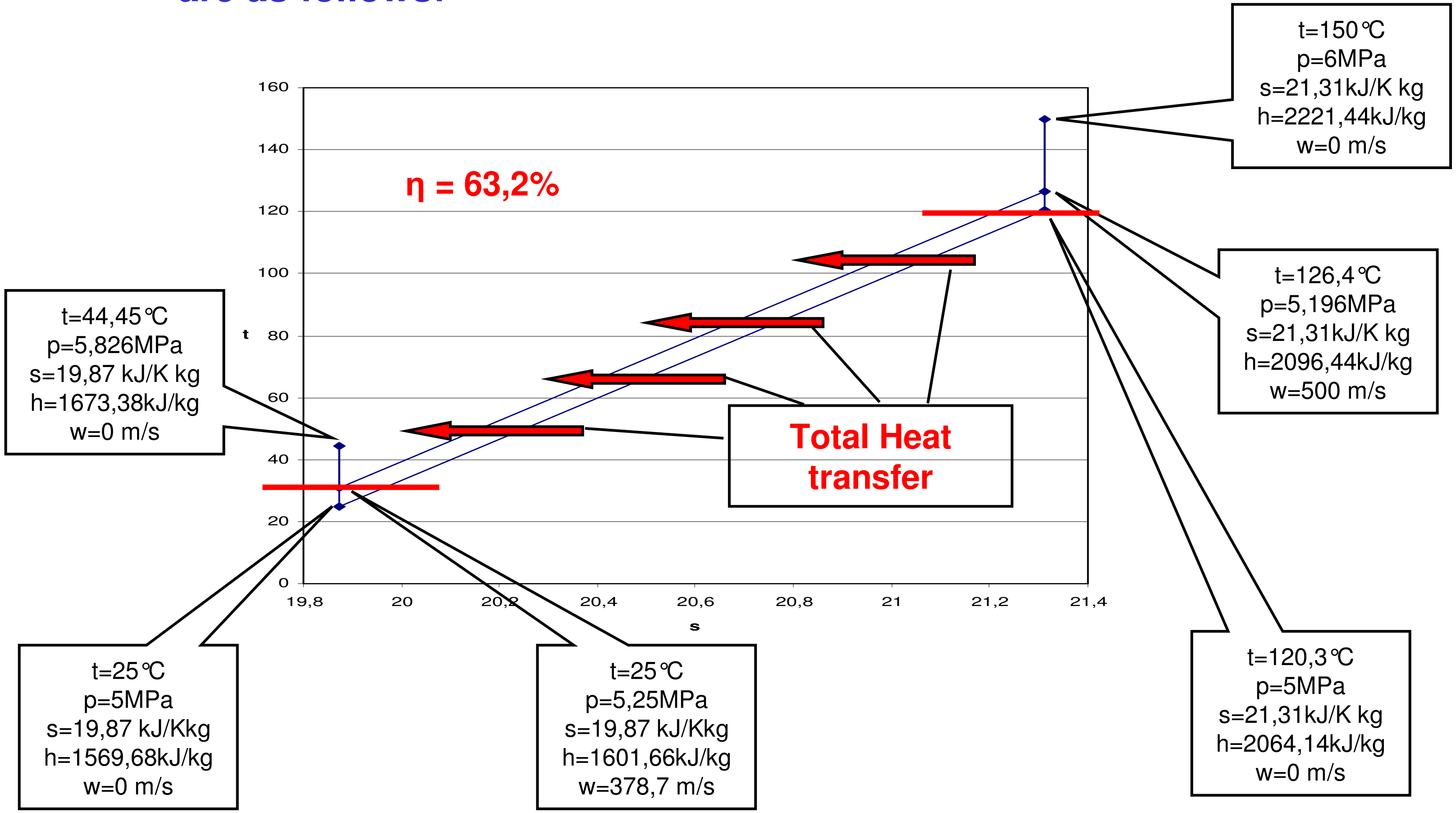
Ideal cycles (2)

To clarify the results of the last calculation, important thermodynamic data are as follows:



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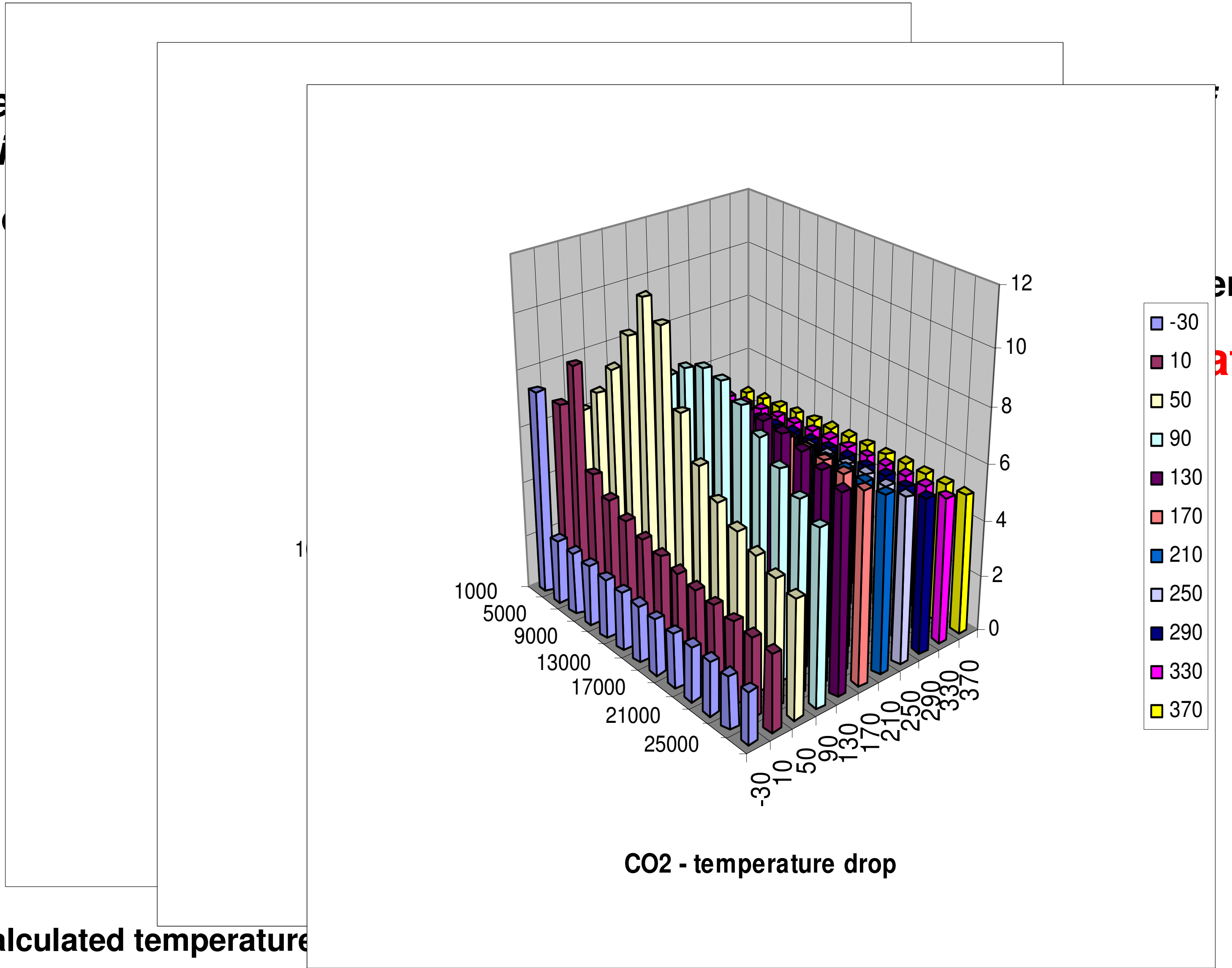
Media

It is nece… flow accelerati…

•In nearly i…

•In water – … er;

•In CO_2, … ature cycles.



Calculated temperature…

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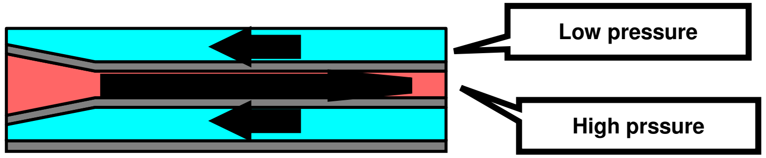
Main principle - losses

As was mentioned, the losses are the key factor determining the technical possibility of flow acceleration usage in the intermediate heat exchanger of Brayton cycle (and other applications).

The next table shows results of heat exchanger basic calculations (Dittus-Boelter, Weisbach) of pressure losses for different tube diameters. Only high speed part was analyzed. The regenerative heat is taken from the example at the beginning of this presentation (slide 4), different length of duct was analyzed with similar results.



Heat exchanger calculation - high speed part

helium			
t (°C)	50	p (kPa)	8000

del t d [m]

w (m/s)	0,0001	0,001	0,002	0,005	0,01	0,02
50	0,60	9,52	21,86	65,64	150,81	346,47
100	0,69	10,93	25,11	75,41	173,24	397,99
200	0,79	12,56	28,85	86,62	199,00	457,18
300	0,86	13,62	31,28	93,94	215,81	495,79
500	0,95	15,08	34,65	104,04	239,02	549,13

del p MPa d [m]

w (m/s)	0,0001	0,001	0,002	0,005	0,01	0,02
50	39,035	2,246	0,951	0,305	0,129	0,055
100	132,212	7,608	3,221	1,034	0,438	0,185
200	447,800	25,768	10,910	3,502	1,483	0,628
300	914,123	52,602	22,270	7,150	3,027	1,282
500	2246,252	129,258	54,724	17,569	7,438	3,149

Results comments:

- **The analyzed example of an ideal cycle shows that through flow acceleration, a pressure difference of a few hundred kPa can be achieved, so pressure losses must be lower, a few tens kPa**
- **the temperature difference from flow acceleration should be also low, a few tens of °C**
- **from tables on the left we can see that these requirements cannot be achieved together**

Conclusions:* *Flow acceleration, connected with pressure and temperature effect, cannot be exploited in standard heat exchanger!

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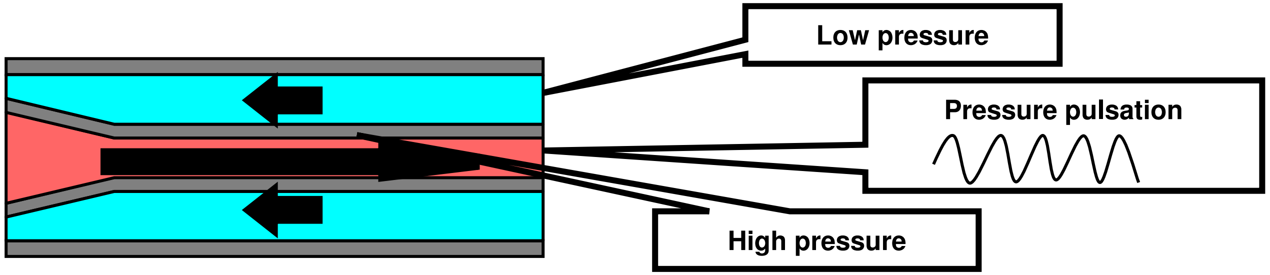
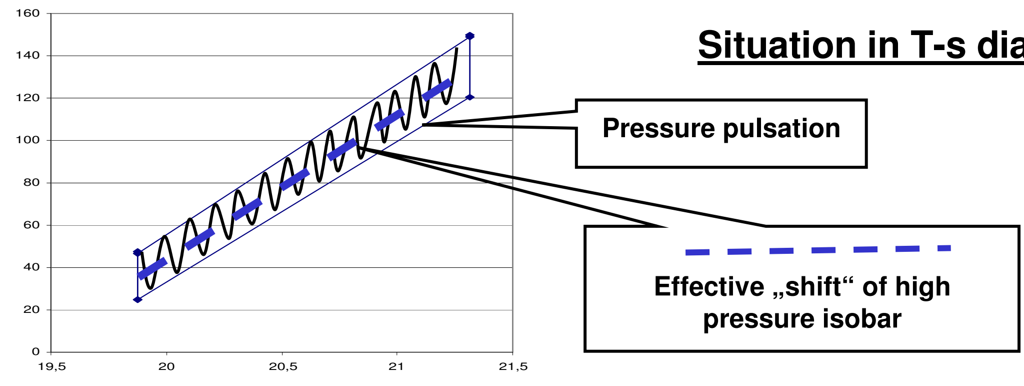
Pressure losses reduction method A

Flow Oscillations

There is real potential to reduce high pressure losses of the high flow speed using pressure pulsations. This solution is roughly confirmed by experiments done in supercritical CO_2 loop



<u>Situation in T-s diagram</u>



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Pressure losses reduction method A

Stability of flow was analysed by many scientists, Podowski, Zhao, Ambrosini and others. The goals are different, for example:

The goals defined by Zhao:

(1) To develop a methodology for SCWR stability assessment both for thermal-hydraulic and nuclear-coupled stabilities,

(2) To compare the stability of the design proposed to that of the BWR

(3) To develop guidance for SCWR designers to avoid instabilities with large margins

The goal of our effort is:

- **achieve flow oscillations with maximum speed of significant amount of media together with minimizing pressure losses**

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Pressure losses reduction method A

Methodolgy for the optimization is:

1. **produce an analytical model**
2. **conduct 1D calculation**
3. **conduct CFD calculation**
4. **experimental verification**

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Pressure losses reduction method A

1. Analytical model

Very diffcult task, we compared the methodology of DWO with the requirements, main problems are:

- **the thermodynamic properties change abruptly, analytical expressions are very complicated and have no physical basis**
- **in the DWO, the effect of flow to the wall is defined by standard Weisbach expression**
- **no strong triggers are defined in DWO**

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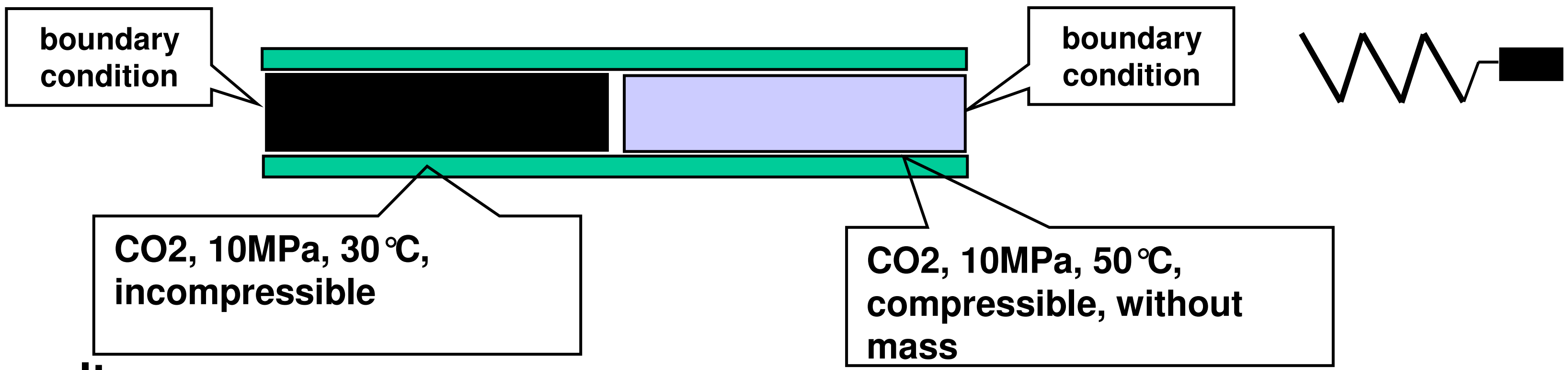
Pressure losses reduction method A

2. 1D models, all models are „mass connected“, change of position is calculated

Different 1D models were defined for oscillations optimization, all models are connected with NIST database:

2.1. Two elements model in specified tube



Results:

- **The model can roughly optimise the triggers, at this stage there is optimum pressure drop at outlet**
- **The model shows significant growth of temperature on the high temperature side, which is a very counterproductive factor for IHX**
- **The losses cannot be effectively evaluated from this model**

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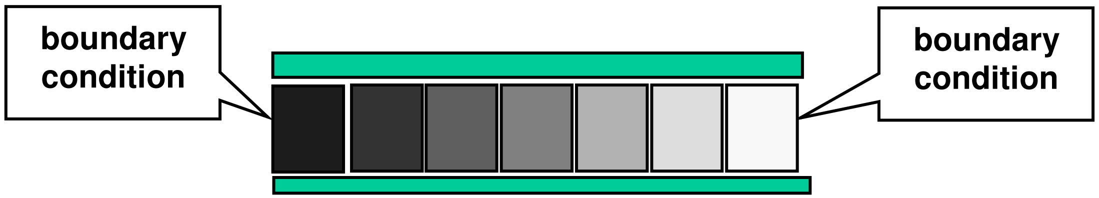
Pressure losses reduction method A

2. 1D models

2.2. Multiple elements model in specified tube

The input temperature is growing and fixed in each element, the temperature changes (from energy equation) are calculated in the second step



Results:

- **The model leads in principle to the same results as the previous one**
- **The model shows better the wave propagation**
- **The losses cannot be effectively evaluated from this model**

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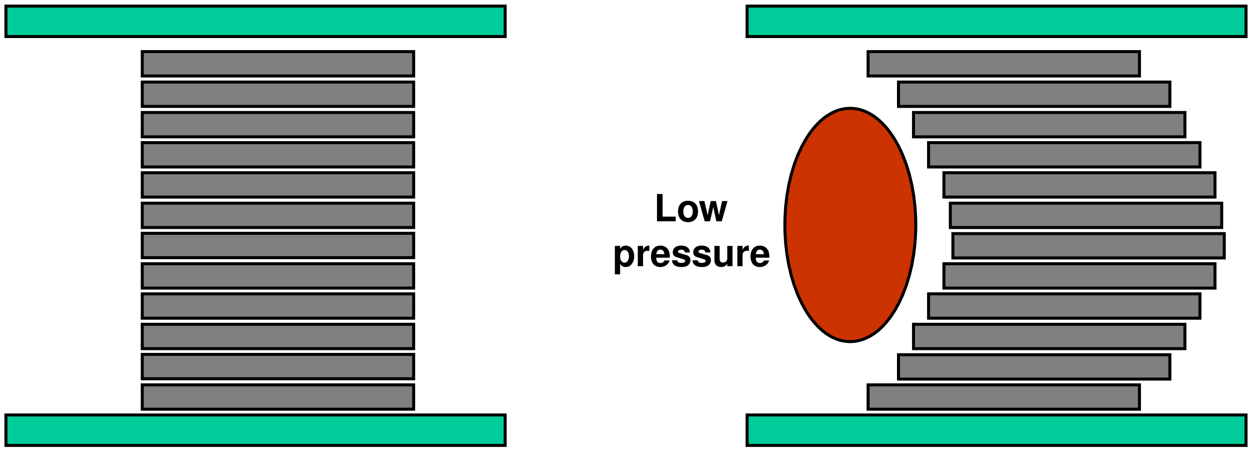
Pressure losses reduction method A

2. 1D models

2.3. Radial model



Results:

- The model shows the velocity profile
- The model can very roughly calculate the losses
- The losses are strongly affected by pressure after wave propagation

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Pressure losses reduction method A

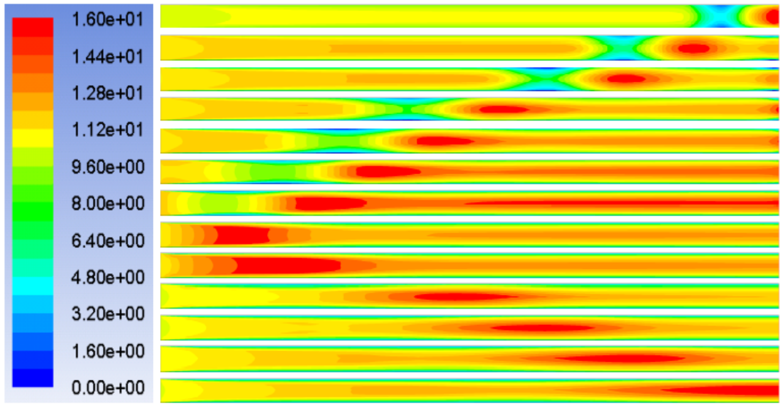
3. CFD calculations

Calculations were made with Fluent 12

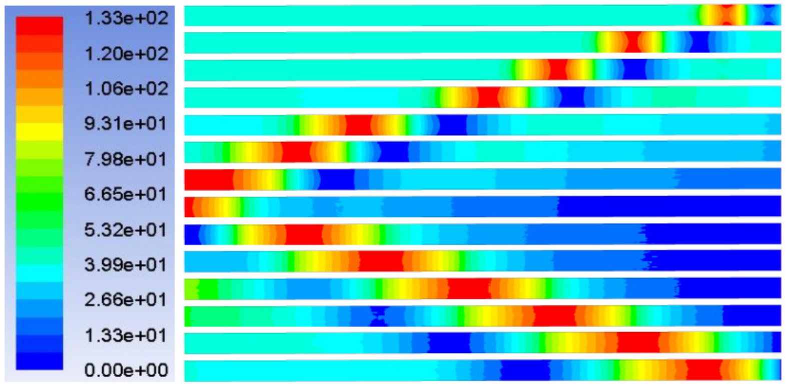
- Problem with NIST connection, some simplifications had to be accepted
- Very short time step for dynamic calculations necessary (0,000001 s)
- Long calculation time

The pictures show the situation:

- Duct D 20mm, L 500mm, initial velocity 10m/s, pressure 9MPa, output closed for 10 μs, figures show the situation after opening:



Velocity profiles



Pressure wave propagation

Results:

- The CFD is not a suitable method for optimization
- The velocity profiles show minimum effect on losses

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Experimental results (1)

- **OPERATION OF EXPERIMENTAL SCO2 LOOP IN CZECH REP.**

Brayton cycle with regeneration was tested in supercritical loop:

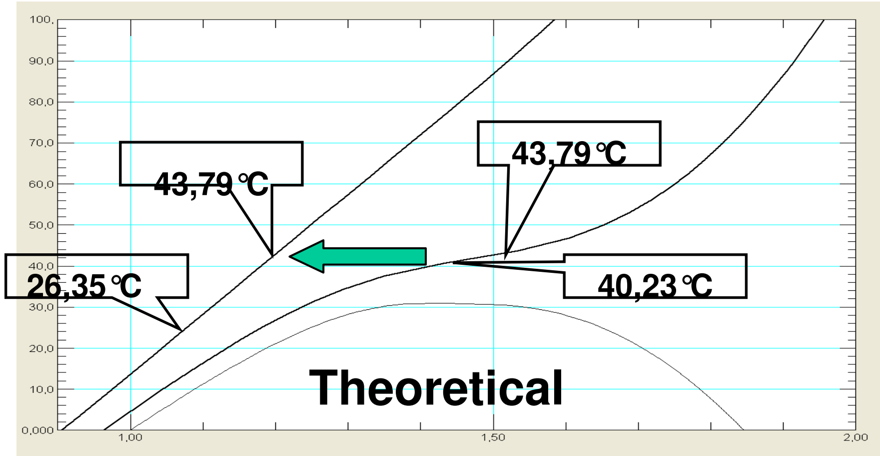
- Pressure up to 50MPa
- Temperature up to 300°C (higher must be checked)
- Flow rate up to 12m3/hour
- Power of primary pump 125kW
- Electrical heating input power 500kW
- Power of engine up to 500kW

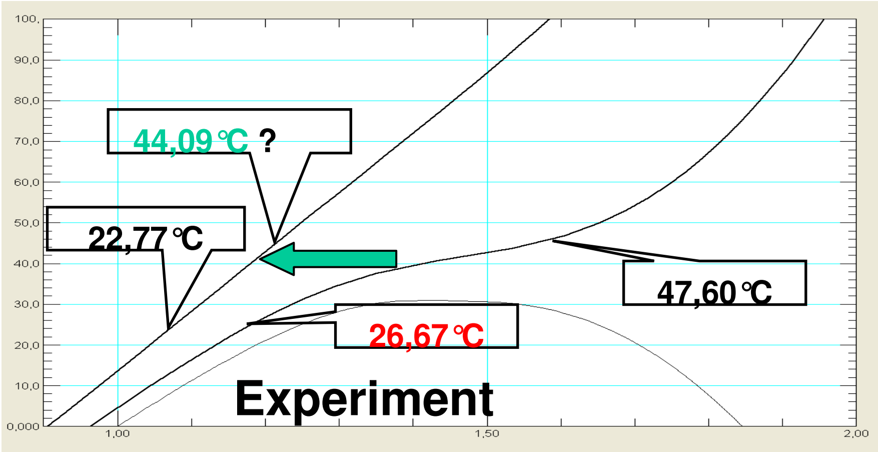
Cycle parameters

- **Low temperature 14,88°C**
- **High temperature 92,36°C**
- **Low pressure 9,30 MPa**
- **High pressure 22,80 MPa**

Results:

	Ideally calculated values	Measured values	Ratio
Cooling heat (kJ/kg)	100,75	32,56	0,32
Recuperative heat (kJ/kg)	36,57	130,9	3,58





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Experimental results (2)

OPERATION OF EXPERIMENTAL SCO2 LOOP IN CZECH REP.

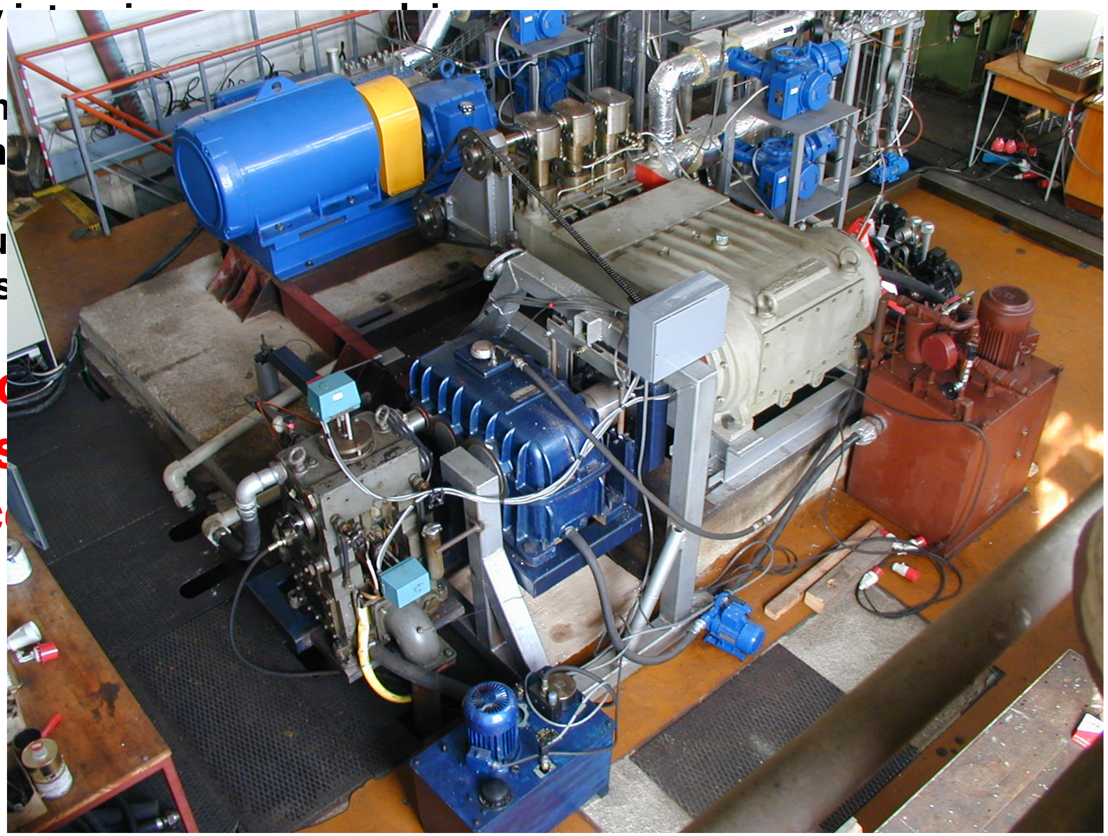
Comments to the experiment:

1. On the high pressure isobar, a „simple“ high speed flow was not observed, but very

2. The efficiency of th for evaluation of th

3. „Green“ temperatu depended on press

4. Evaluation fr similar trends with flow acc



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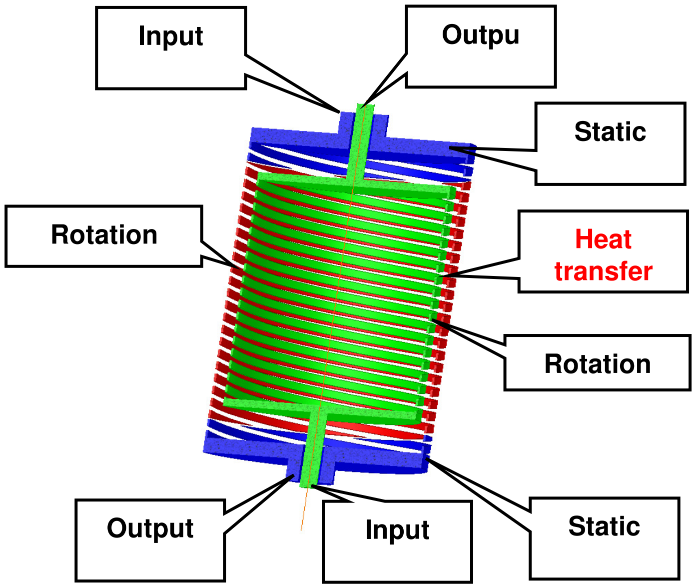
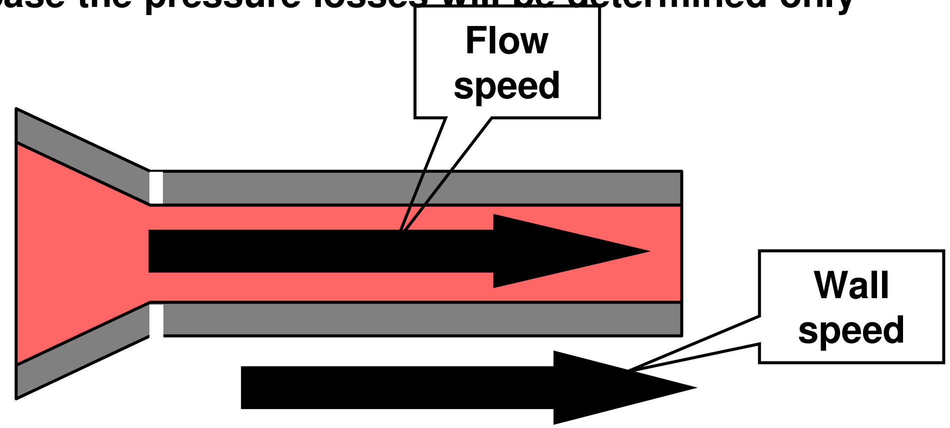
Pressure losses reduction method B

It is possible to reduce high pressure losses when the channel wall will be shifted with similar speed as the flow. In such case the pressure losses will be determined only by the speed difference.

Centrifugal heat exchanger





Comment to the design:

•this is, in comparison with a standard heat exchanger, very complicated device. An engineering design of the sealing might be very difficult

•it must be exploited and optimized together with optimization of energy conversion cycles, not every part of the heat exchanger must be realized in such a difficult way

•with respect to difficult design – and therefore high price – it is very important to use some microchannel solution

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Pressure losses reduction method B

Centrifuge

The following tables allow to obtain a first opinion about pressure changes at input (output) disk and the groove:

MEDIUM			
helium			
t (°C)	20	p (kPa)	8000

v (m/s)
n(1/min)

r(m)	100	300	500	700	900	1100
1	10,47198	31,41593	52,35988	73,30383	94,24778	115,1917
2	20,94395	62,83185	104,7198	146,6077	188,4956	230,3835
3	31,41593	94,24778	157,0796	219,9115	282,7433	345,5752
4	41,8879	125,6637	209,4395	293,2153	376,9911	460,7669
5	52,35988	157,0796	261,7994	366,5191	471,2389	575,9587

Presure growth in rotating input volume
p (MPa)

	100	300	500	700	900	1100
1	0,001388	0,012495	0,034708	0,068028	0,112455	0,167988
2	0,005553	0,04998	0,138833	0,272113	0,44982	0,671953
3	0,012495	0,112455	0,312375	0,612255	1,012095	1,511895
4	0,022213	0,19992	0,555333	1,088453	1,79928	2,687813
5	0,034708	0,312375	0,867708	1,700708	2,811375	4,199708

Presure growth in peripheral grove
p (MPa) Grove mm 1

	100	300	500	700	900	1100
1	0,000139	0,001249	0,003471	0,006803	0,011245	0,016799
2	0,000278	0,002499	0,006942	0,013606	0,022491	0,033598
3	0,000416	0,003748	0,010412	0,020408	0,033736	0,050396
4	0,000555	0,004998	0,013883	0,027211	0,044982	0,067195
5	0,000694	0,006247	0,017354	0,034014	0,056227	0,083994

Comments to the results:

- **to reach the goal of minimizing pressurization by radial acceleration, large diameter of centrifuge and low rotational speed can be used**
- **for necessary speed, (He near to 500 m/s) pressurization is many times higher than the pressure drop received through flow acceleration**
- **in low thickness groove the pressurization is of acceptable scale**

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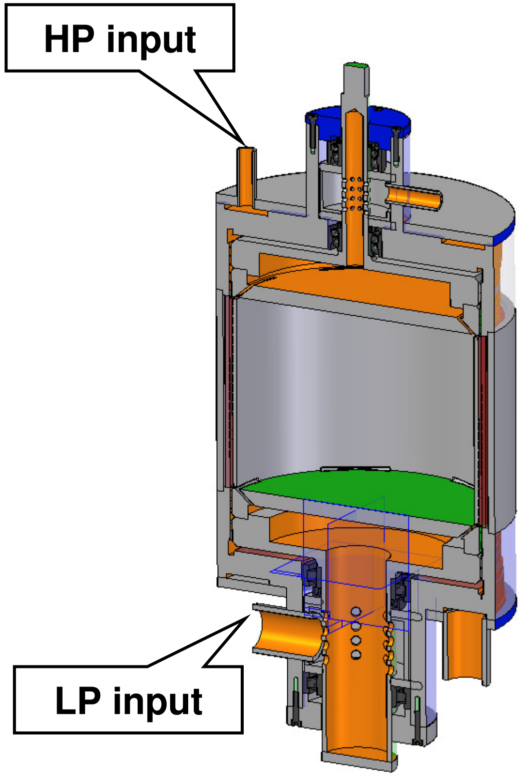
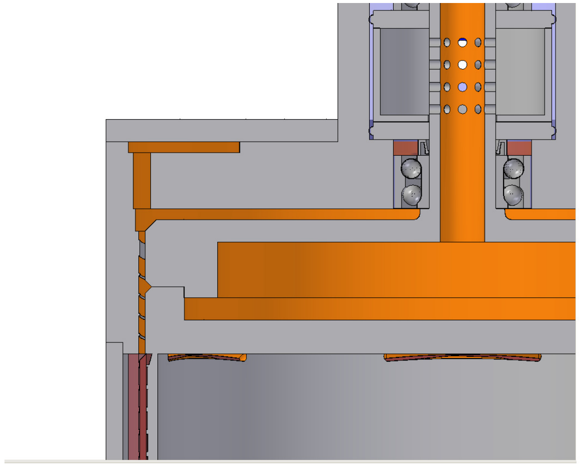
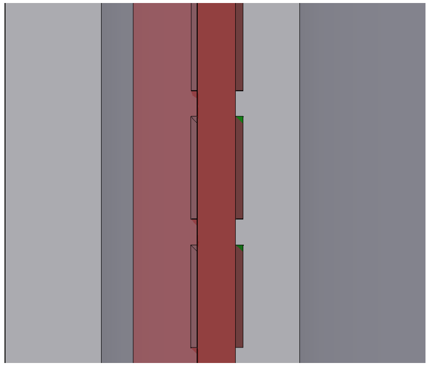
Pressure losses reduction method B

Centrifuge real design







Comments to the design

- it is in fact possible to optimize the design
- the overall heat transferring area is many times lower in comparison with classic IHX
- critical component – sealing, the problem can be avoided using gliding of magnetic bearing

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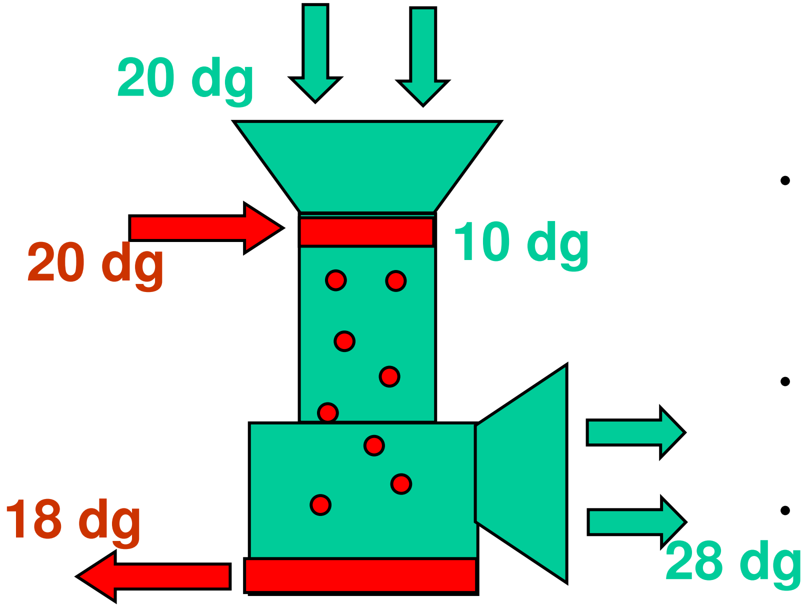
Pressure losses reduction method C

Inserted heat-transferring medium

In order to avoid the case of standard heat exchanger, the possibility of using an inserted heat transferring medium is very roughly described. The goal is to shift the heat transfer process from the wall, where the pressure losses arise, to the interior where the speed is high. This solution is more general, not very suitable for IHX of the analyzed Brayton cycle.



Preliminary results

- The heat transfer is similar as in co-current heat exchanger, so the amount of inserted medium must be large
- In this case, loss of energy to acceleration is too high
- At this stage, it is **not an acceptable solution** to avoid the losses on the wall

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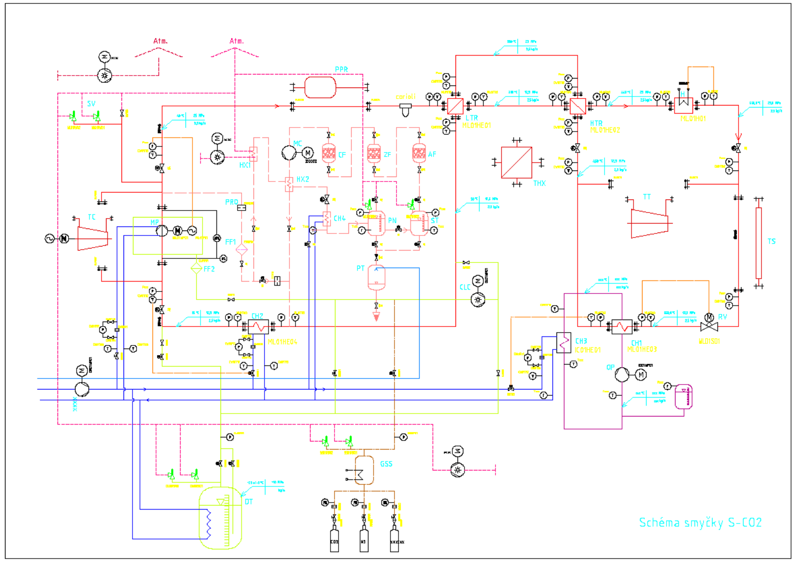
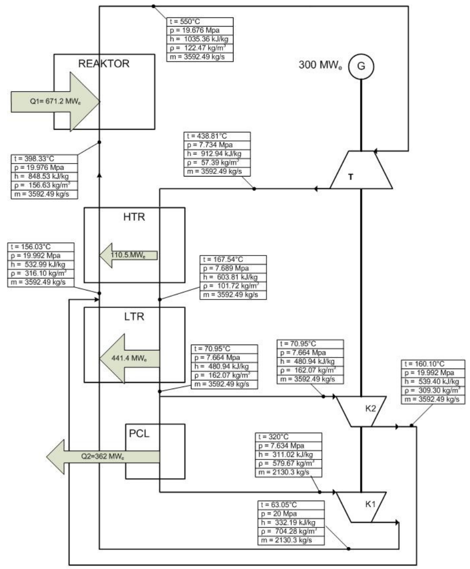
Experimental loops in Rez



Small loop
- •Pressure up to 25MPa
- •Temperature up to 550°C
- •Flow up to 12m3/hour
- •Power of primary pump 125kW
- •Electrical heating input power 500kW



Legenda:
HTR …vysokoteplotní rekuperátor
LTR … nízkoteplotní rekuperátor
PCL … chladič
T … turbína
G … generátor
K1 … hlavní kompresor
K2 … rekompresor

Obr. 1 - Referenční oběh 300 MW_e dle (1)

Large loop
- •Pressure up to 25MPa
- •Temperature up to 550°C
- •Electrical heating input power aprox. 8000kW

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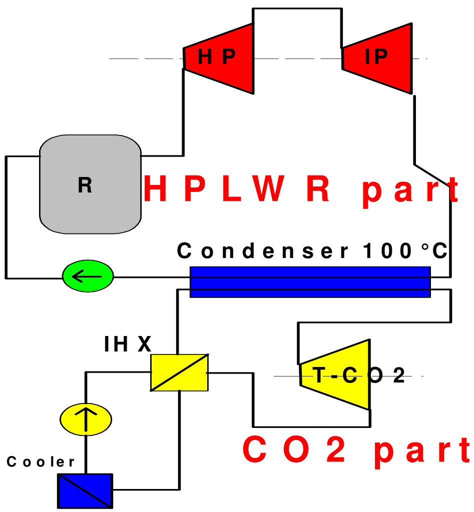
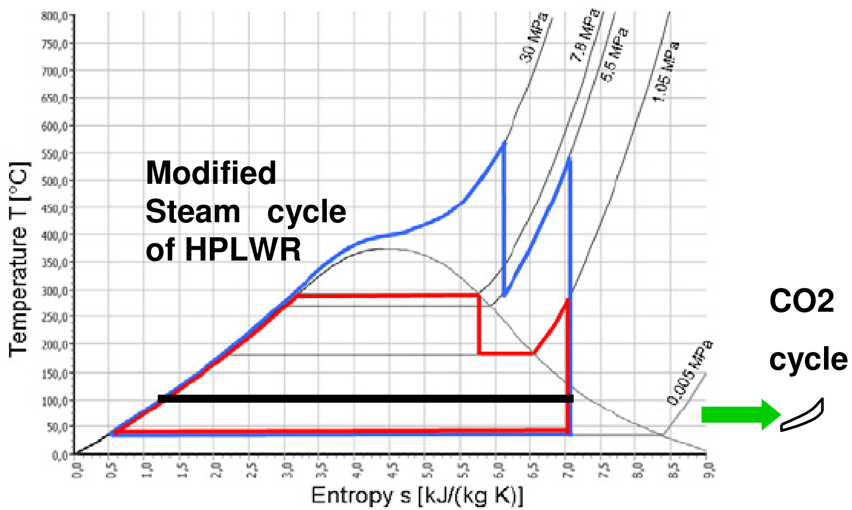
Application

The standard application follows from PWR and SCWR conversion steam cycles, also application in fossil fired plants can be useful, as steam and CO_2 combined cycles

Using only CO_2 cycles in fossil fired plants is disputable, as only high temperature heat is necessary.

As example is shown below:





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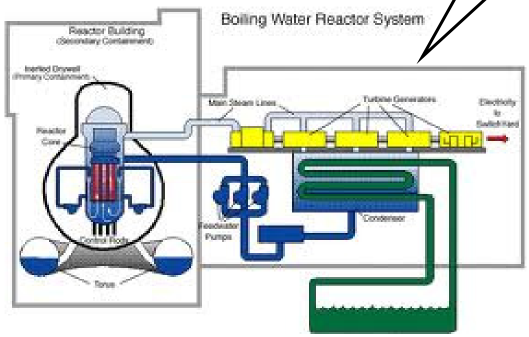
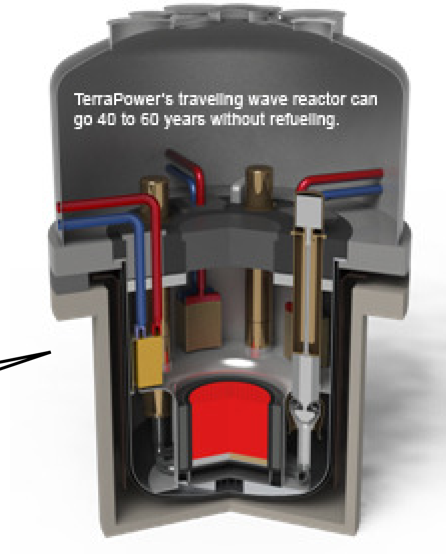
Special effects of application



FUKUSHIMA

Reducing operational temperature to e.g. 150°C, leads to the pressure 0,5MPa, reduces the weight of the vessel and the system 20 times – more safety during earthquake events



Terra Power Traveling wave reactor

Critical problem – material – 600°C, 50 years of operation, 500dpa?
reducing temperature to 200°C– better situation

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Conclusions

- It is very tricky to lead a discussion about higher efficiency of the cycle then the Carnot efficiency
- The main difference is: Carnot is static, cycle with FA is dynamic
- It seems almost sure that FA cannot be exploited in standard heat exchanger with nozzle, as pressure losses are too high
- FA acceleration can be used mainly in low temperature cycles
- Optimal way for development appears to apply flow oscillations
- By experiment and basic calculation, the efficiency of the cycle with upper temperature of 100°C can be estimated to approx. 30%.

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