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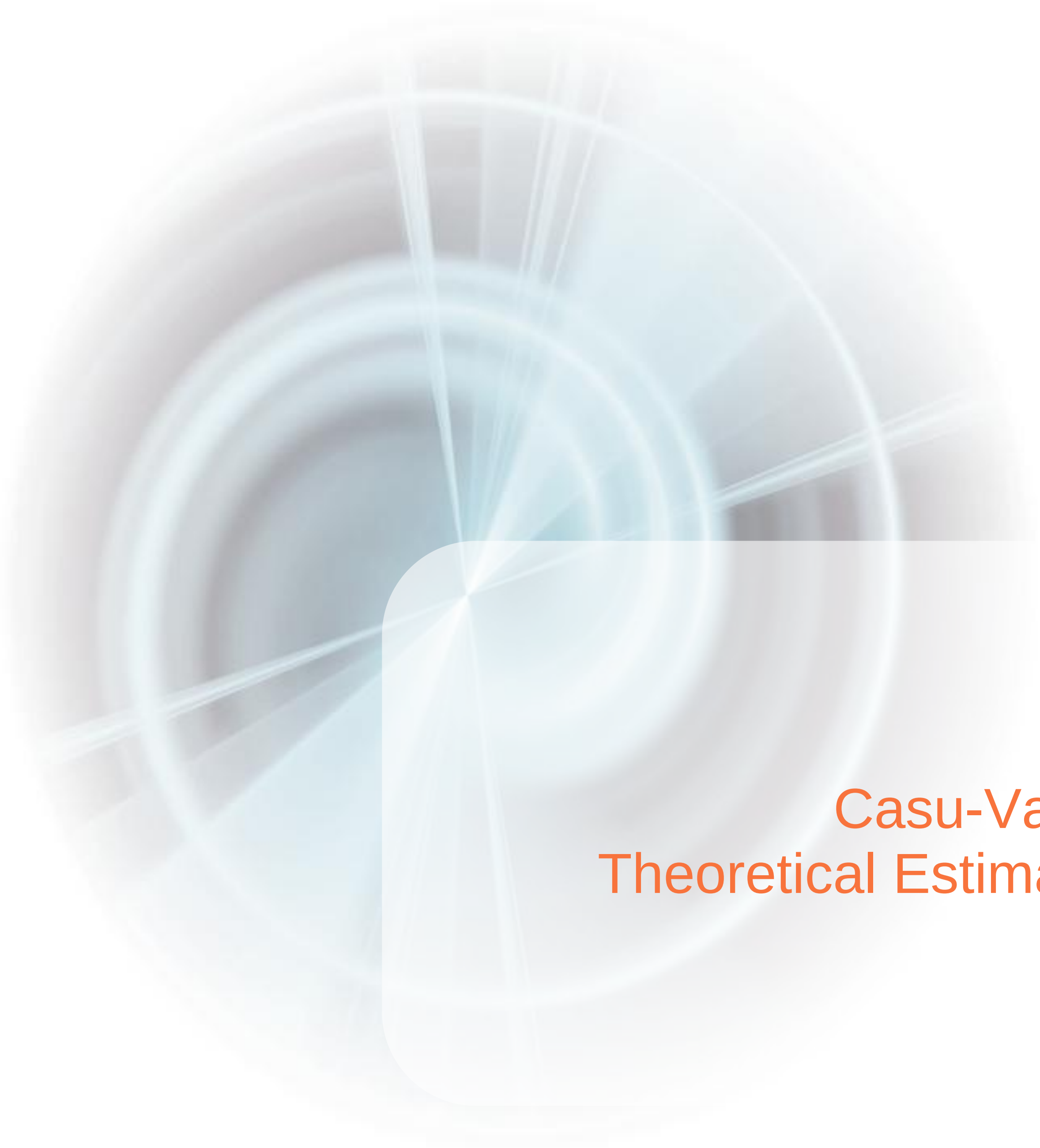

Casu-Vasu Theoretical Estimate

Institute for Energy Technology

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Report title

Casu-Vasu
Theoretical Estimate

Summary

The CASU-VASU concept has been theoretically evaluated.

The following general statements can be made:

A perfectly isentropic (no heat exchange) or a perfectly isothermal (constant temperature) process will both give a 100% efficient energy storage, disregarding mechanical friction. The losses in a real process are associated with the thermal gradient needed to give the heat flow that keeps the process somewhat isothermal, or the loss of heat from a non-perfect isolation of the isentropic process. In addition there are losses related to the mechanical operation of the pump.

The intented target of the Casu-Vasu concept is to remain close to the isothermal process. First, the cooling assosciated with the extraction of gas from the outer chamber should translate into a reduced heating of the inner chamber. Second, the excess heat of the high temperature chamber can be transferred to the outer chamber, allowing a higher pressure to be maintained there during the pumping.

Unfortunately, he energy needed to bring the outer tank back to room temperature is not the same as the energy surplus that must be extracted in order to bring the inner tank down to room temperature. The increasing temperature of the outer chamber will mean less entropy is generated in moving gas from one chamber to the other.

The arguments for having two tanks, both initially at elevated pressure, are valid. The argument for putting one tank inside the other also seems to be valid, and does indeed give a separate energy gain. However, the energy gain is not as large as indicated in previous estimates.

The temperature of the outer chamber will have to be maintained in order to preserve the efficiency. It can be discussed whether this is significantly simpler than to insulate only the VASU. Similarly, a more isothermal pumping could reduce entropy generation in the pump, but this is true independent of the current patent idea.

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1 Problem statement

The questions as asked were:

“2 QUESTIONS ENTROPY

You have two tubes, the CASU is located in the VASU, one :

CASU 200 litres and the second :

VASU 800 litres

You close the hermetic system with the two tubes at 400 MPa. 1,000 litres. The temperature will be C20° (293 K). The gas is N2, neutral and no freezing risks.

Now you compress during 12 hours the CASU to 2,000 MPa, the VASU will be then at appr. 10,000 Pa.

The “Comp Factor” : The temperature exchange between the two chambers will be x% per hour per chamber from the average of the both. For example, Comp Factor 20% - if we have 393 K in CASU and 193 K in the VASU without further compressing/expansion, after one hour the temperature will be 373 and 213 respectively ((393-193)/2)*20%=20)

QUESTION 1

After 12 hours what will the temperature in the CASU be (1a) and in the VASU (1b).

To be considered : as the gas in VASU will be expanded and therefore a decrease in its temperature, the imported (compressed) gas that goes in to the CASU will therefore be lower.

The compressor will require 10% mechanical loss from the ingoing energy.

How much energy is required to do this work (1c).

QUESTION 2

You will now go back from 2,000 MPa in the CASU to 400 MPa in the booth tubes during 12 hours.

What will the temperature be after 12 hours of expanding in the (2a) CASU and in the (2b) VASU.

Do not forget that the temperature will therefore go down in the CASU (by expansion) and the VASU will increase its pressure, and therefore be warmer.

The generator will lose 10% mechanical loss.

How much could the generator produce (2c)

For the formula to be described for the calculation, please also integrate the “Comp Factor” as part of the result, ie. after ∞ the temperature will be the same in the two chambers.

3 QUESTIONS GENERAL

1. What will be the theoretical efficiency of CasuVasu system based on the information given? What is unique from IFEs expert point of view?

2. What will be the efficiency in real life of CasuVasu system based on the experience of IFE?

3. Which questions does IFE suggest are important?”

2 Model

Regarding to the questions asked, the following assumptions had to be made:

Heat loss is assumed to be limited by the thermal conductivity of the wall between the chambers, to avoid complications in the thermal conductivity over the chamber walls, with radiation and convection effects competing. The constant thermal conductivity is simpler to model, for a one day workshop, this was a priority.

Thermal losses to the surroundings are assumed to be negligible. This is made to model the advantage of the CASU/VASU over competing models with the surroundings as the dominant thermal reservoir. In the following, the outer(larger) chamber is termed chamber A, the inner(smaller) chamber, is called chamber B.

Compression is performed by a piston-pump with constant volume. Alternatively, constant pump power or constant flow rate were considered, the piston pump was considered more realistic, and more intuitively understandable. It gives a more transparent modeling, and the physics would be roughly the same in any other compression mechanism. The thermal inefficiency of the pump is used instead of the 10% mechanical losses asked for in the problem statement, as a constant pump efficiency is highly unrealistic. Pumps become less efficient as the pressure gradient increases – this is captured in the use of an isentropic pump rather than a friction-limited pump.

The pump is modelled as a piston chamber going isentropically from volume zero to a fixed volume while in contact with chamber A. Then the contact valve is closed, and the piston chamber isentropically compressed until the pressure reaches the pressure of the chamber B. At equal pressure, the valve between the piston and chamber B is opened. Then the volume in the piston is reduced to 0 at pressure equal to chamber B pressure. This process is then repeated for each time step.

When thermal conductivity is set to zero, the set of compressions constitute a complete isentropic compression, and the resulting temperature at 200 bar roughly matches that of the calculations done by Serck. The correction comes from two elements – the heat transfer in the pumping step, as the newly compressed gas is released into the chamber B, and the fact that the gas volume that will be transferred is limited by this temperature – the estimates presented from Serck did not include the fact that the temperature increase gives a pressure increase limiting the compression before the intended amount of gas is transferred. This will similarly mean that the outer tank is not completely emptied.

The process is stopped at 200 bar, then the numbers from this simulation are used as starting parameters for a reverse simulation.

When thermal conductivity is non-zero, the temperature will equilibrate somewhat after each timestep, allowing a process close to an isothermal process.

The thermal conductivity is modelled as an energy transfer(heat), then the new energy in each chamber is used to recalculate pressures and temperatures in both chambers.

For the energy transfer from chamber to chamber, the model is assumed to give a fair representation of the CASU/VASU system. For the pump, a more isothermal process could have been modelled, but this would introduce complications in the assumptions about where the energy transfer from the piston should be equilibrated. This was judged to be outside the limited scope of the project.

3 Theory

Standard equations for isentropic processes are used for the single timesteps.

The gas constants were chosen as Cv 5/2 J/Kmol, Cp 7/2 J/Kmol and gamma 7/5, corresponding to the values used by Serck, and valid for the pure N_2 gas.

See spreadsheet in appendix for details.

The pressure(p), gas amount (R), temperature (T), volume(V) and energy (E) are calculated for each of the following states in each time step:

- Chamber A before extracting first gas volume
- Chamber A after expanding gas to ecompass chamber and piston
- Chamber A after excluding piston volume
- Piston before compression
- Piston after compression
- Chamber B before connecting to piston
- Chamber B after connecting to piston (irreversible step)
- Chamber B after compression of piston volume into Chamber B
- Chamber A after optional thermal energy transfer (irreversible step)
- Chamber B after optional thermal energy transfer

Starting values are denoted pA1 (pressure in chamber A at start), TB1 (temperature in chamber B at start) etc,

The decompression is modeled exactly equivalent, only that all compression steps become decompression steps and vice versa.

The decompression is continued for two different time spans, one until the amount of gas transferred is equal to the original gas amount (time 2), and one until the pressure of the tanks is equal (time 3).

Due to the irreversible nature of the step were the compressed gas from the piston is brought into contact with the gas in the VASU chamber (where heat is transferred from piston to chamber, while some gas is transferred to the piston to maintain constant pressure) the reverse process will leave the chambers at equilibrium in a different condition from the starting situation. The heat transfer will leave the outer chamber at a slightly lower temperature, but with more gas, while the inner chamber has a higher temperature, but less gas than in the starting configuration. Thus some equilibration will have to take place in order to bring the system to its starting value.

The efficiency of the process is assumed to be the energy recovered until the point where the gas amount has been brought back to the starting value.

The thermal connection with the surroundings needed to extract the entropy generated by the irreversible processes (inefficiency) is not modeled.

This choice was made because the point of the exercise was to compare the CASU/VASU to a system where the chambers are in contact with an external reservoir rather than with each others, thus the external connection would confuse the understanding of the core technology.

4 Results

For the completely isentropic process, the following values were obtained:

Cv	2,5		Heat conductance		0
Gamma	1,4				
A (CASU)			B (VASU)		
p1	V1	T1	p1	V1	T1
40	800	293	40	200	293
p2	V2	T2	p2	V2	T2
21	800	244	200	200	593
p3	V3	T3	p3	V3	T3
36	800	267	57	200	414
40	800	278	40	200	375
Efficiency until gas flow completed				0,97	
Efficiency until pressure is equal				1,00	

There is a numerical imperfection due to the finite time steps, so the numbers should be considered to be approximations. As we see, the efficiency is close to the expected 100% from a fully isentropic process, but the small irreversibility in the gas mixing step mentioned before means the system does not return to the original state.

The increased heat of the VASU means only half the gas could be transferred before 200 bar pressure is reached.

The temperature in the CASU is reduced, while that of the VASU is increased. However, the energy transfer needed to bring the two systems to room temperature is vastly different. The VASU contains a little more gas than the CASU, and at a 3 times bigger temperature difference.

The isentropic calculation leaves a temperature of almost 600K in the VASU.

The maximal heat transfer than can be obtained will leave the CASU and VASU at approximately the same temperature. This turns out to be about 500K for the chosen system. The temperatures converge with heat conductance, and efficiency changes monotonously, so a value corresponding to values close to convergence is chosen.

Cv	2,5		Heat conductance		10
Gamma	1,4				
A (CASU)			B (VASU)		
p1	V1	T1	p1	V1	T1
40	800	293	40	200	293
p2	V2	T2	p2	V2	T2
32	800	473	200	200	485
p3	V3	T3	p3	V3	T3
52	800	382	51	200	378
52	800	382	52	200	378
Efficiency until gas flow completed				0,53	
Efficiency until pressure is equal				0,53	

This efficiency number does not include mechanical friction, only thermodynamics.

How the heat transfer rate translates into a final temperature depends on the intensity profile of the pump operation. The 20% per hour thermal loss means that more than half of the heat will be transferred, as most of the compression will have more than 5 hours of equilibration to loose the built up heat. Thus this situation will be ending with a temperature in the range of 550K (middle between 600K for isentropic and 500 for isothermal) as in the following example:

Cv	2,5		Heat conductance		0,3
Gamma	1,4				
A (CASU)			B (VASU)		
p1	V1	T1	p1	V1	T1
40	800	293	40	200	293
p2	V2	T2	p2	V2	T2
25	800	317	200	200	552
p3	V3	T3	p3	V3	T3
48	800	352	46	200	334
48	800	351	48	200	338
Efficiency until gas flow completed				0,63	
Efficiency until pressure is equal				0,63	

Assuming that the pump requires 10% energy for mechanical friction, all these efficiency numbers should be increased correspondingly.

Note that in all scenarios, the inefficiency results in a heating of BOTH chambers by the end of the process. This heat will need to be vented before the storage process can be completed. Letting off the heat during the process will defeat the purpose of the device.

5 Conclusions

Having thermal contact between the CASU and the VASU reduces efficiency from the theoretical 100% of a fully isentropic system, to about 50%, reduced to about 40% when including mechanical friction. This represents a large gain over a system with isentropic compressor work and thermal connection, but a loss compared to a system with fully isothermal compression.

The outer chamber will in this case reach a temperature almost as high as that of the inner chamber in the fully isentropic case. Thus thermal insulation is as important for this system as for the normal system.

The system will increase temperature over completion of a cycle, this excess energy needs to be vented after the complete cycle in order to maintain efficiency.

Answers to general questions:

What will be the theoretical efficiency of CasuVasu system based on the information given?

Approximately 40-50%, with very strong (unrealistic) system requirements.

What is unique from IFEs expert point of view?

This is difficult to answer without a full patent/literature search. The advantage may be that the compressor will be enclosed within the thermally isolated region, which may be an advantage compared to trying to insulate a high pressure tank in thermal contact with the compressor. Otherwise, the core issue of the patent, namely the location inside the VASU, does not seem to give a huge efficiency gain. Thus the patent may not be a significant advantage against competitors with a similar two-tank idea with different handling of the thermal problems.

The availability of dry N2 rather than moist air may also be a significant benefit, but this is connected to having two chambers, not to having one inside the other.

2. What will be the efficiency in real life of CasuVasu system based on the experience of IFE?

IFE has limited experience in this field. The main limitation will probably be thermal losses to the surroundings from the 450-500K tank. This will reduce the system efficiency by about 1 %-points for each 10K temperature reduction. Assuming 10% mechanical losses and a 50K thermal loss, this would give a 30-35% efficient system. Electric losses in the pump/decompression are assumed to be covered by the 10% number.

3. Which questions does IFE suggest are important?

What are you competing against?

Isothermal compression with an actually isothermal compressor can reach close to 100% efficiency. Typical compressors are not isothermal, but advanced isothermal compressors are being developed, allowing high efficiencies. Typically, a compression in multiple steps, with cooling water circuits to increase heat exchange is a possibility, or using a phase-change material.

Isentropic compression is equally possible, if insulation of a 500K tank is obtained. What is easier to insulate - a 50% efficient insulation of an isentropic system or a 100% efficient insulation of the CASU/VASU?

Changing parameters of the tanks give minor modifications of the statements, but nothing has changed the main conclusions.

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