Efficiency Analysis of a Combined Cycle with VHTR and VVER Nuclear Reactors

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Abstract. In this paper, the calculation of a combined cycle including a gas and steam circuits with two nuclear reactors is done. The first circuit of the thermal scheme is the gas cycle with a very high temperature reactor (VHTR) and the second circuit of the combined scheme is the steam cycle with the pressurized water reactor (VVER). VHTR which is one circuit reactor and uses Helium as a coolant and working fluid and VVER is a two circuit reactor which uses water as a coolant and steam as working fluid. The scheme was limited by the parameters of the two reactors and aimed at reaching the highest thermal efficiency of the power of the two reactors. The calculations showed the effect of changing the parameters of one reactor side to the other reactor side, on the total efficiency and power output. These parameters are the thermal power of VHTR core and the compression ratio of the gas turbine and their effect on the steam turbine power output, the steam cycle efficiency, the gas turbine power output and the gas cycle efficiency. Finally, the results showed high thermal efficiency of the scheme comparing to the two the thermal efficiencies of each single cycle.

INTRODUCTION

A combined cycle is well known for thermal power plants run by fossil fuels with fuel combustion in gas turbine combustion chambers [1]. The maximum temperature of the heat supply in the combustion chamber of the gas turbine with the existing structural materials and methods of cooling the turbine elements reached 1600 °C [2]. The development of such a combined cycle between two nuclear reactors with gas and steam circuits is unique and has its advantages.

First, the nuclear reactors are very expensive and unfortunately have limited lifetime because of that some parts of the reactor can't be replaced like the pressure vessel and the containment that are affected badly due to the neutron exposure while other parts can be replaced like the power side of the reactor and the steam generator in the two loop reactor like pressurized water reactors and the countries are in need to move to Generation IV reactors [3, 4] which are better in safety, sustainability, economics and nonproliferation and that make a push to build a Generation 4 reactor besides the old rector (shutdown) which lead to get the best use of the expensive parts of the old reactor besides gaining the advantages of the new one.

Second, it increases the total efficiency of the thermal power and the total electric power output in the case of using the gas cycle with a very high temperature reactor (VHTR) in superheating the steam of the VVER pressurized water reactor (reheating) which be other benefit if the VVER is still working.

The calculation is based on the characteristics of the two reactors to evaluate the idea from the power conversion point of view.

COMBINED CYCLE AND RESULTS

The design of the combined cycle is based on current reactor design which is VVER 1200 [5] and future project for reactor which is VHTR [6, 7] (Fig. 1).

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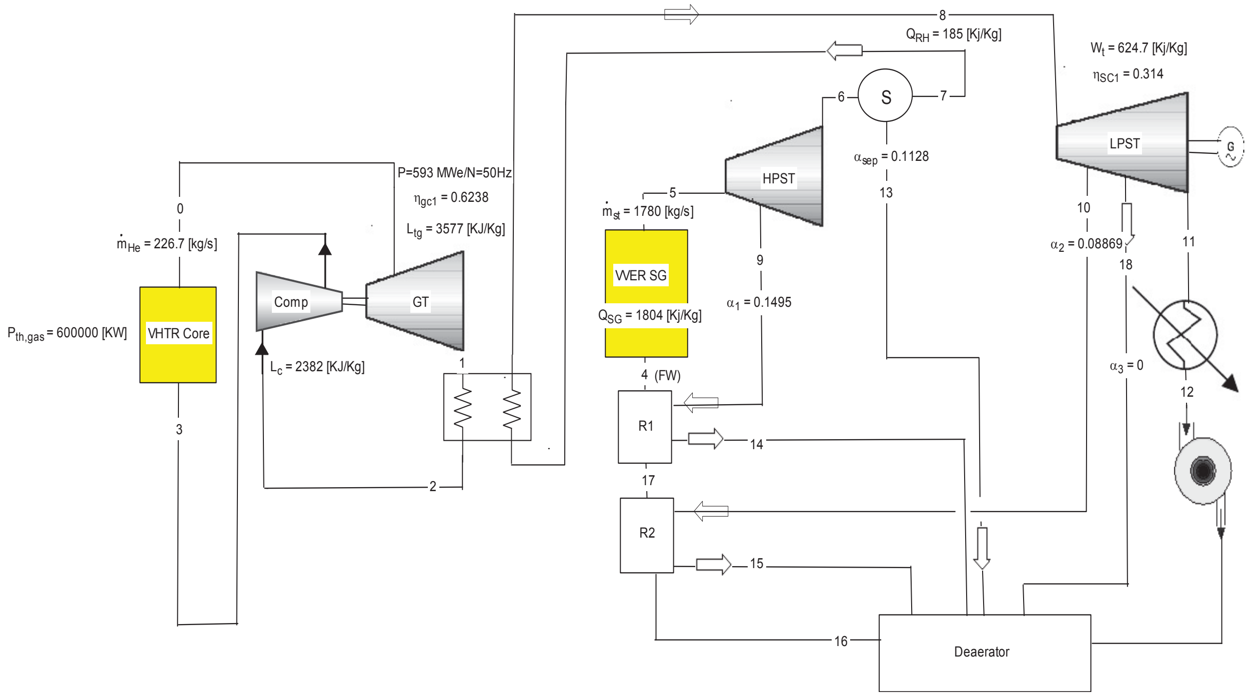

FIGURE 1. Combined cycle scheme with reactor

The parameters of the VHTR core are 7 MPa pressure, 490°C inlet temperature and 1000°C outlet temperature and thermal power 600 MW (Helium as working fluid).

The parameters of the VVER 1200 Steam generator are 7 MPa pressure, 1602 m^3/hr flow rate and inlet temperature of 225°C and thermal power 3200 MW (Steam as working fluid).

Following the theory and the assumptions, the properties of both working fluids, Helium for gas cycle (VHTR) (Fig. 2) and steam for the steam cycle (VVER) (Fig. 3) was found.

From initial data of calculation, the next results were obtained:

L_{tg}=3577 kJ/kg is gas turbine output power for 1 kg/s of Helium;

L_C=2382 kJ/kg is compressor consumption power for 1 kg/s of Helium;

η_{gc1}=0.6238 is efficiency of gas cycle of the combined scheme;

α_{sep} =0.1128 is steam bled from HPST;

α_1=0.1495 is saturated bled from separator;

α_2=0.08869 is first stage steam fraction bled from LPST;

α_3=0 is second steam fraction bled from LPST (initial parameter);

W_t=624.7 kJ/kg is steam turbines output power for 1 kg/s of steam;

η_{SC1}=0.314 is efficiency of steam cycle of the combined scheme;

η_{CC}=0.3628 is efficiency of gas cycle of the combined scheme.

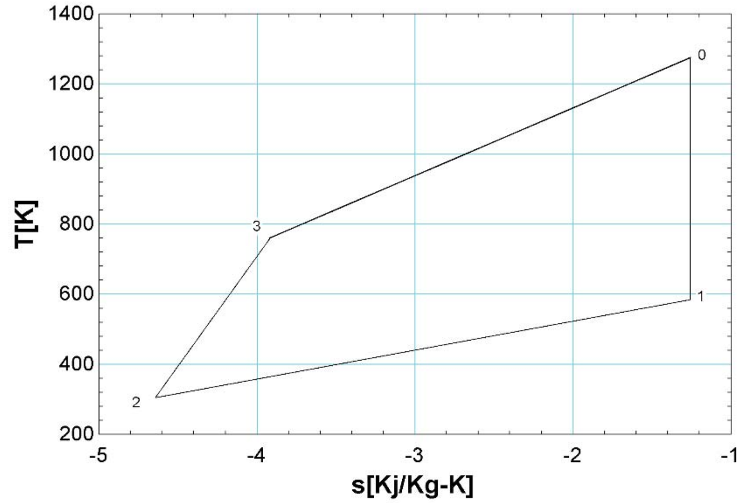

FIGURE 2. T-S diagram of gas cycle

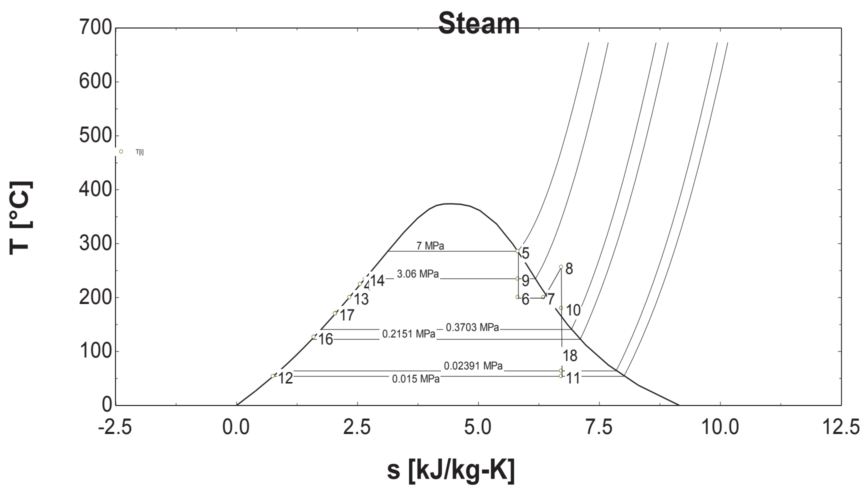

FIGURE 3. T-S diagram for steam cycle

By the help of engineering equation solver (EES) software, we have received the main relations and dependencies.

1. The effect of the compressor compression ratio (gas cycle side) on the power output, efficiency of both the gas and steam cycle and the combined cycle efficiency is shown in Fig. 4–8.

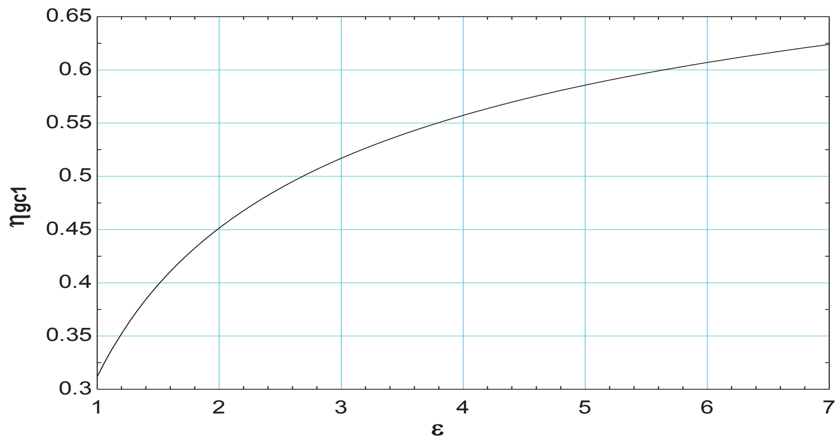

FIGURE 4. Gas cycle efficiency vs compression ratio of the compressor

The gas cycle efficiency significantly increases with the increase of the pressure ratio and that is logically due to lower temperature (Low T_L) and lower pressure at the outlet of the turbine which logically increase in the gas cycle efficiency and this is more dominant than the decrease of additional power due to decrease in Q_{RH}

$$\eta_{gc1} = \frac{\left(L_{tg} - L_c\right) m_{He} + Q_{RH} m_{St} \eta_{SC1}}{m_{He}\left(T_0 - T_3\right) CP_{He}}.$$

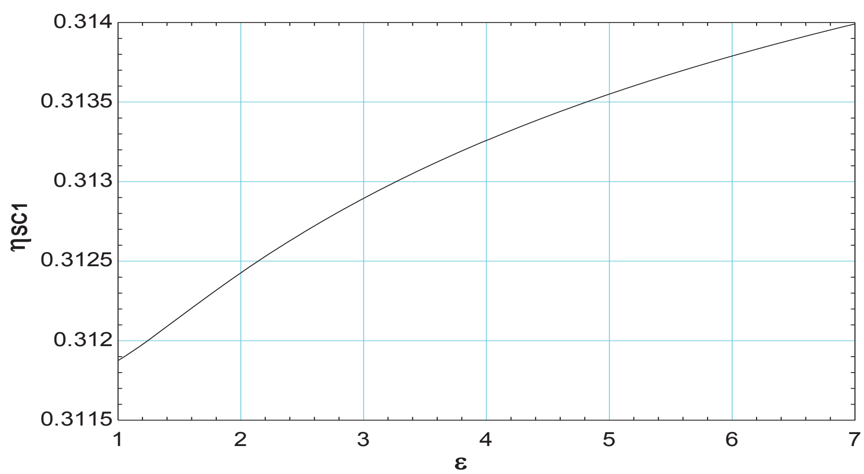

FIGURE 5. Steam cycle efficiency vs compression ratio of the compressor

The steam cycle efficiency was not so much affected by the increase of the compression ratio (2 % increase) and that is according to its definition $\eta_{SC1} = \frac{W_t - Q_{RH}\eta_{SC1}}{Q_{SG}}$ which eliminates the effect of the change of the heat exchange Q_{RH} from steam cycle efficiency side $\left(W_t - Q_{RH}\eta_{SC1}\right)$.

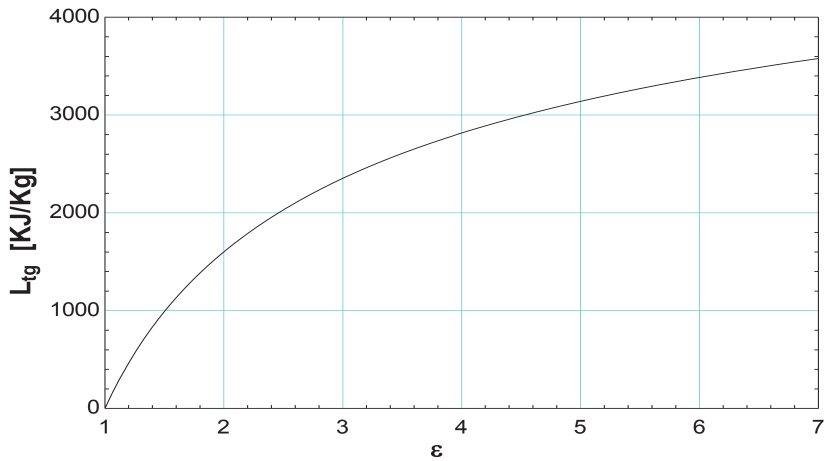

FIGURE 6. Gas turbine output power vs compression ratio of the compressor

The increase in the compression ratio leads to increase in the turbine power output and that is logic as it is the same as the expansion ratio in the turbine.

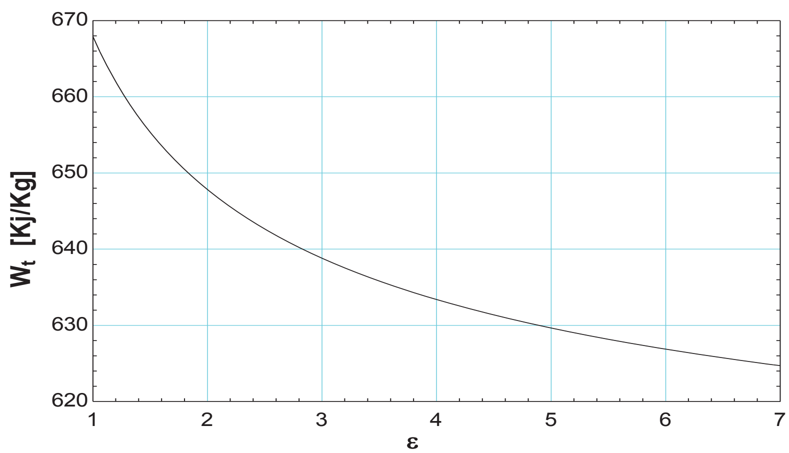

FIGURE 7. Steam turbines output power vs compression ratio of the compressor

The increase in the compression ratio leads to decrease in the power output in the steam turbine and that is because the increase of the compression ratio leads to decrease in the Q_{RH} transferred to the steam cycle and by the way decrease in the steam turbine power output.

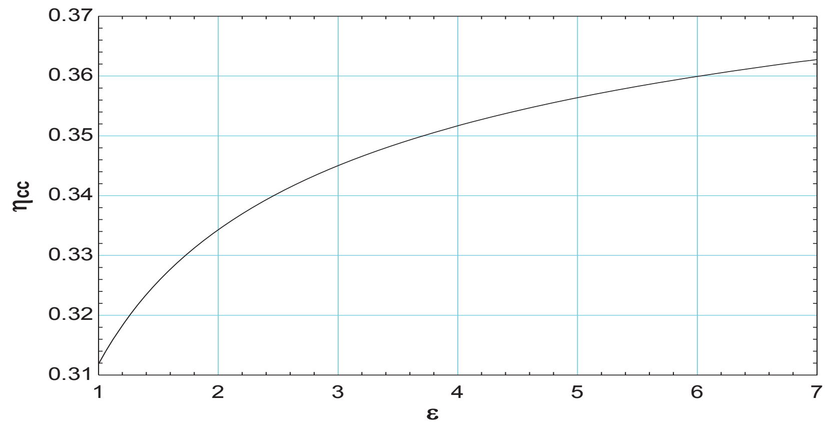

FIGURE 8. Combined cycle efficiency vs compression ratio of the compressor

The increase in the compression ratio leads to significant increase to the combined cycle efficiency as according to the definition $\eta_{CC} = \frac{m_{st}W_t + m_{He}L_{tg} - m_{He}L_C}{p_{th,st} + p_{th,gas}}$ and in our case the increase in the compression ratio leads to significant increase in the gas turbine output power and less effect of the decrease of the steam turbine power output which in total increase in the total power output.

2. The effect of the thermal power of the VHTR reactor on the power output, efficiency of both the gas and steam cycle and the combined cycle efficiency is shown in Fig. 9–11.

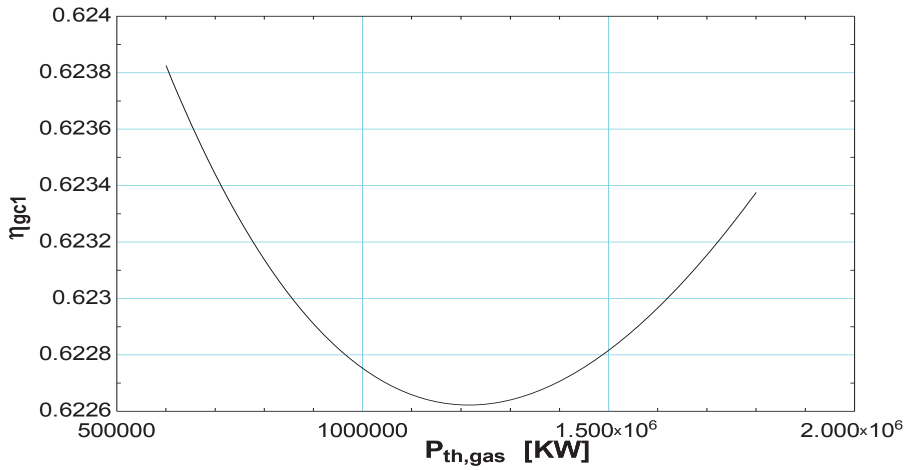

FIGURE 9. Gas cycle efficiency vs thermal power of VHTR reactor

The change in the thermal power of the VHTR is insignificant (less than 1 %) and that because there is no change in the temperatures of the input and output of the gas turbine as according to methodology followed, the increase of the VHTR thermal power is by increasing the helium mass flow rate.

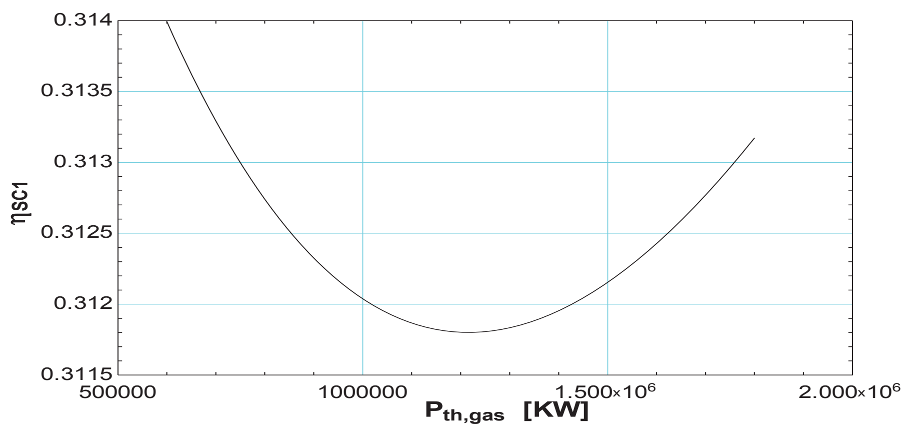

FIGURE 10. Steam cycle efficiency vs thermal power of VHTR reactor

The steam cycle efficiency was not so much affected by the increase of the thermal power of the VHTR (less than 3 % increase) and that is according to its definition $\eta_{SC1} = \frac{W_t - Q_{RH}\eta_{SC1}}{Q_{SG}}$ which eliminates the effect of the change of the heat exchange Q_{RH} from steam cycle efficiency side $\left(W_t - Q_{RH}\eta_{SC1}\right)$.

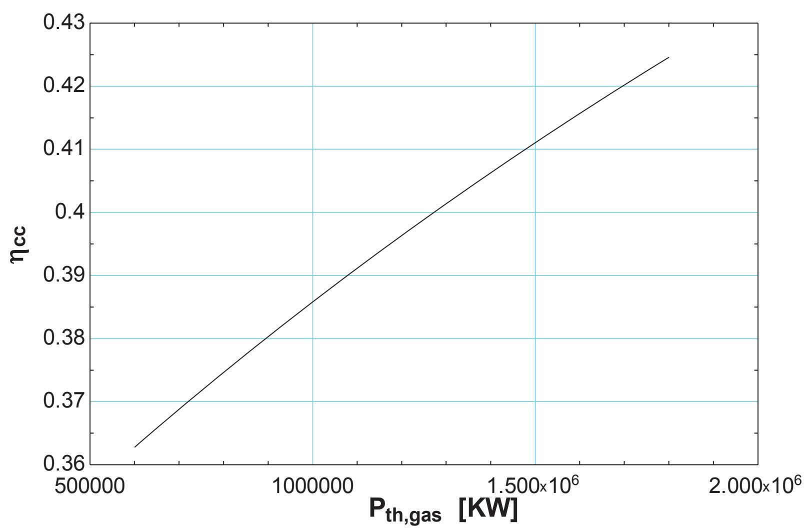

FIGURE 11. Combined cycle efficiency vs thermal power of VHTR reactor

The increase in the thermal power of the VHTR leads to significant increase to the combined cycle efficiency as according to the definition $\eta_{CC} = \frac{m_{st}W_t + m_{He}L_{tg} - m_{He}L_C}{p_{th,st} + p_{th,gas}}$ and in our case the increase in $P_{th.gas}$ leads to increase in the helium flow rate which leads to direct increase in the absolute value of the gas turbine output (in KW) and on the other hand increase in the absolute value of Q_{RH} (in KW) which leads to significant increase in the power output of the steam turbine also and the effect of the increase of the output of the two turbines more effective than the increase of the $P_{th.gas}$ which leads to this jump in the combined cycle efficiency.

CONCLUSION

The VHTR reactor with its high output temperature, allows for reaching high thermal efficiencies and with combining it with steam cycle in a combined cycle, this makes the efficiency higher and higher. In fact, it is not used with normal combined scheme as it was used for increasing the efficiency of existing nuclear reactor working on steam cycle like VVER 1200. On the other hand, we can also use the facilities of shut down reactor like its steam generator, steam turbines, pump and etc. The common reasons for rector shutdown is the deterioration of the pressure vessel or the containment, while other components like steam generators and steam turbines which are expensive and special for nuclear reactors can last for longer time and can also be replaced.

Through this research, the effect of the changes in the gas cycle parameters on the power and the efficiency on the both cycles were studied, like the effect of changing the compressor compression ratio of the compressor and the capacity of the reactor which is with significant effect. In our scheme, the gas bled from the gas turbine was used to superheat the steam. Figure 11 shows that increasing the capacity of the VHTR reactor leads to significant increase of the combined cycle efficiency. At first, with 600 MW thermal power of the VHTR core, the combined cycle efficiency was low, despite the high efficiency of the gas cycle. This can be explained by the fact that as the power of the VVER reactor with much higher capacity, which is 3212 MW thermal and with steam cycle (about 31 % efficiency) dominates. When the VHTR capacity increased, the difference between the power of the two cycles decreased and the higher effect of the efficiency of the gas cycle appeared.

In the studied scheme, we are limited by the use of the VHTR power for only superheating stem for the VVER steam cycle but it can be also used for shutdown reactor and getting the best use of its facilities.

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