Analysis and Synthesis of a Hybrid Nuclear-Solar Power Plant

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Abstract. The article presents a configuration of a Hybrid nuclear-solar power plant with small modular nuclear reactor. The live steam is superheated using molten salts. The molten salts are heated in a solar tower. To ensure continuous work the plant has a high temperature thermal energy storage system.

Keywords: small modular reactors, solar power plants, thermal energy storage, hybrid power plants

1 Introduction

The regulations for climate and environmental protection specify that electricity generation should be greenhouse gases free. The nuclear, solar and wind power plants measure up to these requirements in the greatest degree [1]. The current article presents a novel design which unites the favourable technical and ecological characteristics of the nuclear and solar power plants.

The large single units were until recently believed to be the nuclear technology's logical evolutionary path of development. Their high capital investments, long licensing procedure and erection time as well as the major influence on small electrical grid systems, created the perfect conditions new projects of small and medium nuclear reactors to be taken under serious consideration for further promotion [2]. The topical designs of small nuclear pressurized water reactors promise integral configuration of the primary coolant loop, lack of large diameter pipelines, a number of passive safety functions and overall simplification of the reactor [3].

At this point the main efforts in the nuclear research field are focused on safety issues. Even new projects for pressurized water reactors remain with unchanged conditions for the secondary loop and the turbine island. The live steam is saturated or slightly superheated with low parameters. Most of the steam turbine blades work in high moisture environment which results in energy losses and faster wear due to erosion. A widely used counter measure is the use of moisture separator and reheater but these are expensive and complex pieces of equipment.

This article presents a technological scheme of a Hybrid nuclear-solar power plant. The main goal during the configuration of the scheme is to realize out of the reactor steam superheating. This is fulfilled by coupling the Nuclear power plant with Solar tower power plant. The heat transfer fluid is a mixture of molten salts with an option for thermal energy storage up to 15 hours.

2 Main Features of a Nuclear Power Plant with mPower Reactor

The mPower nuclear reactor, developed by Babcock & Wilcox, is a typical small pressurized water reactor with design electrical output of 180 MW [4]. At this point the project is mainly focused on the reactor itself so the author had to synthesize and run full calculations for the secondary loop, complete material and heat flow balances for all of the elements of the scheme. This was made using the software product Thermoflex by Thermoflow Inc. [5].

Figure 1 shows a scheme of a Nuclear power plant with mPower reactor which served as a base model for the calculation. The mPower reactor has a steam generator integrated in the reactor vessel. The generated steam is slightly superheated and it drives a classical turbine. As in every pressurized water reactor the steam conditions suggest the use of moisture separator and reheater. The outlet steam is directed to a condenser and then to a feedwater heaters system.

The calculations, made with the design steam flow rate (267 kg/s), optimal feedwater heating and standard turbine efficiency values, confirmed the design electrical output of 180 MW at 33.89% overall plant electric efficiency.

The advantages of the project are precisely the integral structure of the primary loop, the passive safety functions and the proven technology on which it is based.

3 Main Features of a Solar Tower Power Plant

The molten salts technology is successfully applied in modern concentrated solar thermal power plants [6]. The heat transfer fluid is a mixture of $NaNO_3$ and KNO_3 [7]. Figure 2 shows a scheme of a thermal power plant with solar tower. The only difference with conventional fossil fuel power plants is the method for live steam generation.

The main advantage of the technology is the possibility for supercritical steam parameters. The molten salts are a very suitable fluid for thermal energy storage.

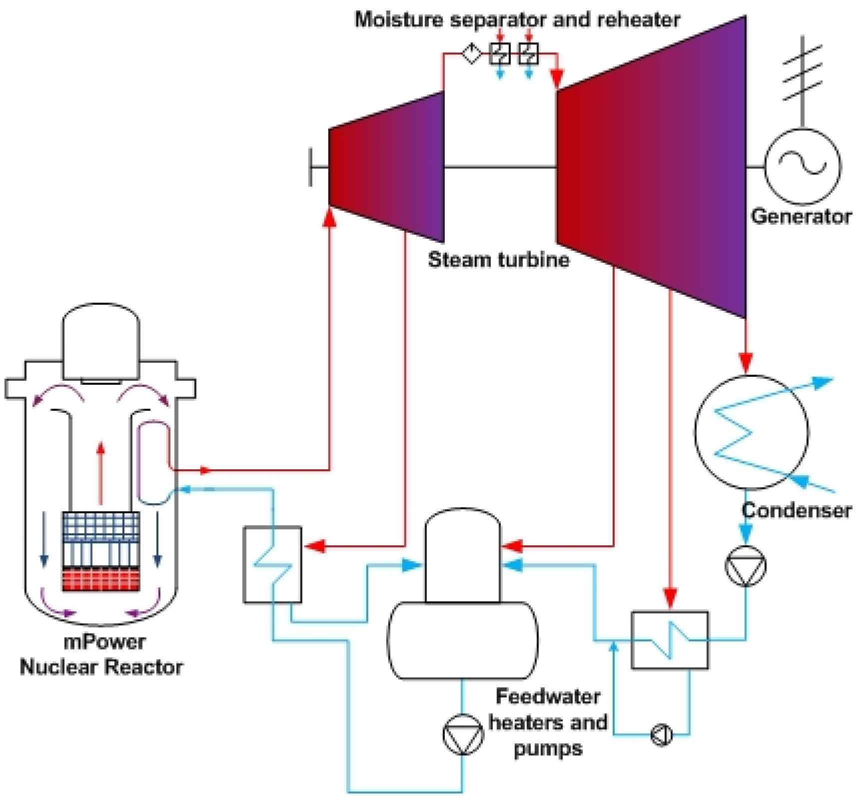

Figure 1. Nuclear power plant with mPower reactor.

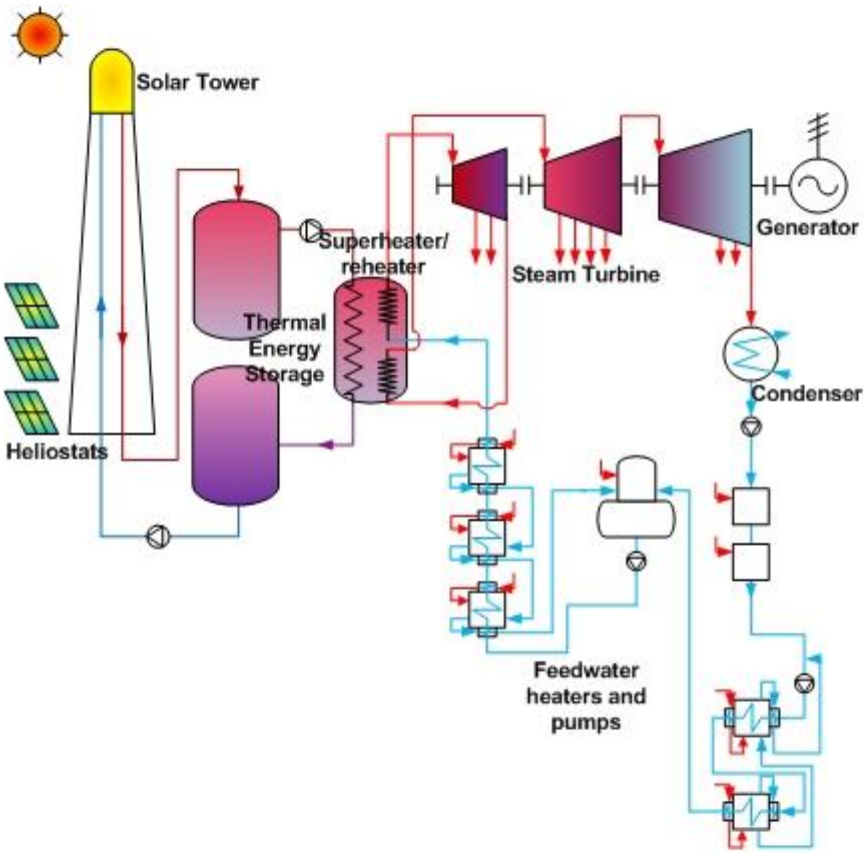

Figure 2. Solar tower power plant.

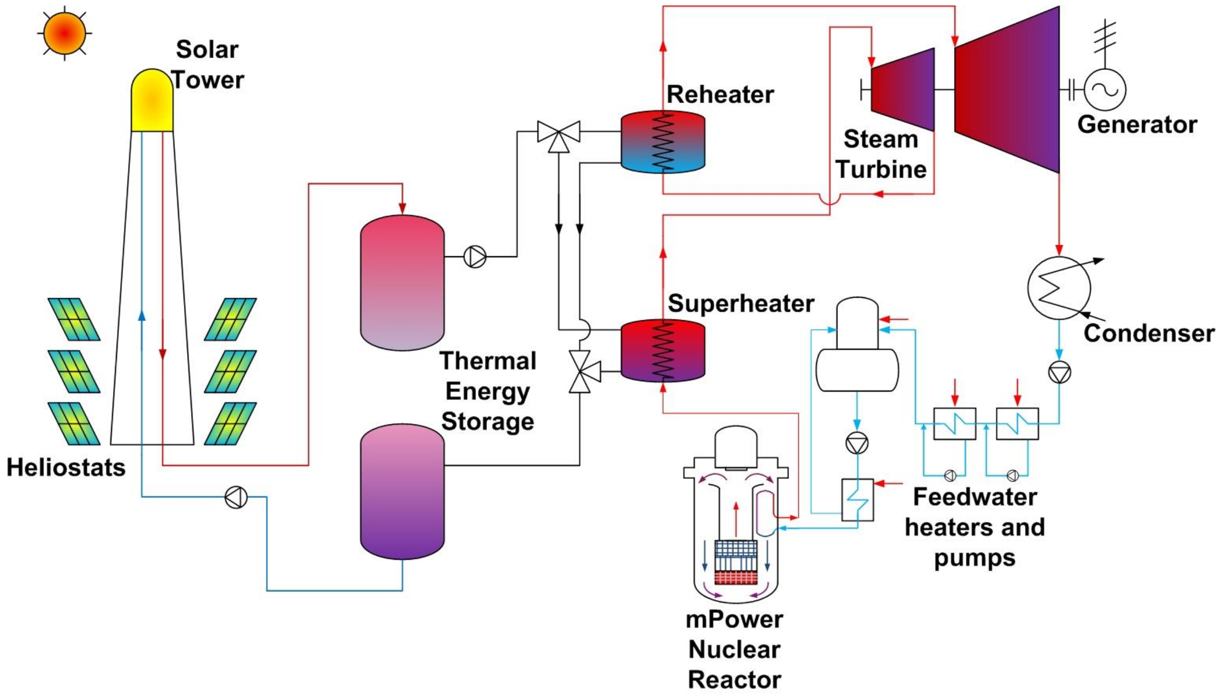

Figure 3. Hybrid nuclear-solar power plant.

4 Synthesis of a Hybrid Nuclear-Solar Power Plant

The steam generator of the nuclear power plant produces steam with temperature of 300°C and 57 bar of pressure. This steam is externally superheated with molten salts. The molten salts have an excellent heat accumulation capacity. Daytime sun radiation heats a large amount of salts which hoard up in special reservoir. This allows the solar power plant to generate electricity during the night by using the accumulated heat. The energy is utilized in a system of heat exchanges to produce superheated steam. Then the steam serves as a working fluid in a classical Rankine cycle.

The disadvantages of both nuclear and thermal power plants are evaded. The low parameters of the live steam are significantly increased and the solidification of the molten salts is avoided with optimal temperature range. The nuclear reactor working conditions remain unchanged. All of the components included in the hybrid power plant are standard and typical for the respective technology.

The main structure of the hybrid power plant is shown on Figure 3.

5 Performance Evaluation

The configuration of the hybrid plant was modeled using Thermoflex software. The results include complete material and heat flow balances of all of the elements of the scheme. The steam generator is the milestone in the model – the inlet and outlet fluid temperature and flow are equal to their project values and remain constant during the calculation. The turbine inlet pressure is lowered to address the hydraulic resistance of the superheater. The reactor thermal power has the designed value for the mPower reactor. The feedwater system consists of two heaters and a deaerator. The live steam temperature depends of the temperature of the heated molten salts and is fixed at 560°C. The thermodynamic balance of the molten salts heaters is formally calculated using a standard Thermoflex element. Table 1 summarizes and compares the technical and economic data of the reference Nuclear power plant and the Hybrid power plant.

Table 1. Comparison between Nuclear power plant with mPower reactor and a Hybrid nuclear-solar power plant

Parameters/ Plant configuration	**Nuclear power plant**	**Hybrid nuclear-solar power plant**
Turbine inlet temperature, (°C)	300	560
Turbine inlet pressure, (bar)	57	56
Condense rpressure, (bar)	0.07	0.07
Live steam flow, (kg/s)	267	267
Nuclear heat input, (MW)	530	530
Solar hear input, (MW)	0	258
Net electric Power, (MW)	180	314
Net electric efficiency, (%)	33.89	39.71

6 Analysis of the Results

The results show a 134 MW generated electricity increase:

$$P_{\mathrm{el}}^{\mathrm{SH}} = P_{\mathrm{el}}^{\mathrm{HPP}} - P_{\mathrm{el}}^{\mathrm{NPP}} = 314 - 180 = 134\,\mathrm{MW}$$

where $P_{\mathrm{el}}^{\mathrm{SH}}$ is the additional electric power generated by the Hybrid power plant, $P_{\mathrm{el}}^{\mathrm{HPP}}$ and $P_{\mathrm{el}}^{\mathrm{NPP}}$ are the net electric power generated by the Hybrid power plant and the reference Nuclear power plant.

The efficiency of the solar-to-electric power transformation is:

$$\eta_{\mathrm{el}}^{\mathrm{SH}} = P_{\mathrm{el}}^{\mathrm{SH}}/Q_{\mathrm{SH}} = (134/258) \times 100 = 51.94\%$$

where Q_{SH} is the solar heat input.

7 Conclusions

The study shows that the Hybrid nuclear-solar power plant has the following benefits:

- Increase of the efficiency of the Hybrid power plant compared to the reference Nuclear power plant;
- Increment of the nominal electric power;
- High efficiency of the solar-to-electricity transformation.

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