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Coal-to-nuclear modernization of an existing power plant with a IV-th generation nuclear reactor

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Abstract

The paper presents an analysis of a transition from a coal-fired power plant to a nuclear unit. The main focus is set on the extensive usage of the existing parts of the already operating system. The key problem is the correct matching of a nuclear reactor and the steam island. It is assumed here that the reactor module operates under nominal conditions and the steam turbine is adapted to fit the reactor. The paper describes the numerical model of the steam turbine cycle for the off-design simulations. The developed model allows us to determine the changes in the steam cycle in order to match the required water and steam temperature values at the inlets and the outlets of the steam generator. The paper presents the suggested modifications and the evaluation of the operation after the transition.

Keywords: Decarbonization; Nuclear reactor; Steam turbine

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1. Introduction

One of the possibilities to decarbonize the energy sector is a transformation from coal-fired power generating units to nuclear energy sources. This pathway has become more recognized in the recent years – a number of publications deal with the modern problems of nuclear power plants. In [1], the Authors presented research on the parameters of the live steam in a cycle with a steam generator and a nuclear reactor. Cogeneration systems with nuclear reactors are under investigation in [2]. Transient thermal loading problems are the subject of the study in [3].

However, the publications mentioned above deal with nuclear reactors that are capable of delivering the steam at temperatures significantly lower than in fossil-fuelled power plants – in the range of 280–320 degrees of Celsius.

Also, the steam turbine cycles presented in these publications are closely integrated with the reactor module. It means that a nuclear power plant of this type must be built from the ground as a complete cycle including the steam turbine and the reactor core [4]. This feature is a handicap when considering a smooth transition from a coal-fired energy system to the one with low emissions. When it comes to repowering the existing power plants, only some of their infrastructure may be used: the water cooling systems, the power output systems and the connections to the energy grid [5].

Much more options are available with the so-called IV-th generation reactors [6]. In this case, a reactor core and a steam

Nomenclature

c_f – constant in the pressure-flow relation, kg/s/MPa
i – enthalpy, kJ/kg
N – electric power, MW
p – pressure, MPa
Q – heat delivered to the steam/water system, MW
T – temperature, ^{o}C

Greek symbols

η – efficiency, %

Subscripts and Superscripts

cond – condensate
el – electric, refers to generator power
fw – feed water
in – inlet
live – live steam, HP turbine inlet
N – nominal
out – outlet
reheat– reheat steam, IP turbine inlet
s – isentropic
sat – saturation conditions

Abbreviations and Acronyms

COND– condenser
DAE – deaerator
FW – feed water
FWT – feed water tank
HP – high pressure, HP turbine inlet
IP – intermediate pressure, IP turbine inlet
LP – low pressure
SE – steam expander
SR – steam pressure and temperature reducing station
XC – condensate heater
XR – additional feed water heater
XSP – steam cooler

generator may be delivered as separate enclosed modules to any site and connected to a steam cycle. A strategy that is proposed for energy systems with a significant number of fossil-fuelled power generating units is based on retrofits of the existing steam cycles [7]. Coal steam boilers may be replaced with nuclear reactors and steam generators [8].

A new generation of nuclear reactors allows for generation of steam at a high temperature [9]. The IV-th generation reactors are still in development with some of them being already at the testing stage [10] and others at the concept stage [11]. Yet the transition of the steam temperature from a typical level of around 300^{o}C to over 500^{o}C opens new alternatives for the implementation of the reactors in the existing power generating systems [12]. Nuclear reactors may deliver the steam at a temperature level similar to fossil-fuelled boilers [13]. It means that a steam island with a power generator may remain intact. This approach may greatly improve the economic side of decarbonisation [14] and fasten the process of the transition towards low-emission power generation [15]. The economic projections are promising according to [16]. Increasing the number of nuclear power plants will also enable us to stabilize the energy grid and allow for further development of renewable energy sources, which is emphasized by a number of researchers, for example in [17] and [18]. The carbon-fuelled plants must be carefully selected for the coal-to-nuclear transition [19]. An example of the analysis to choose the optimal plant is described in [20].

The research presented in this paper aims to evaluate the possibility of matching an existing steam cycle to a high temperature reactor. The evaluation is conducted through numerical modelling and simulations of the steam cycle before and after the boiler is replaced with a nuclear reactor. An existing power plant is chosen for the evaluation with a 900 MW power generating unit. In order to properly simulate the operation of the steam turbine and the auxiliary systems, a model is built based on the available results of measurements taken during the tests of the unit.

The key problem is the matching of the steam and feed water parameters between the implemented reactor module and the existing turbine. The main assumption is that all the necessary modifications are made in the steam system, while the reactor module – including the nuclear core and the steam generator – operates at its design conditions.

The following sections describe the methodology of the research and the results of the modelling obtained for a tested reactor. This paper discusses the technical aspects only and verifies whether and how it is possible to connect a nuclear reactor to a steam island. This work is a foundation for further economic study.

2. Methodology

The following assumptions are made for the modelling and the evaluation of the cooperation between an existing steam cycle and a nuclear reactor:

- The key parameters are values of the pressure and temperature of the live steam, reheat steam and feed water;
- After the modernization and under operation at the full load, the nuclear reactor module operates in its design conditions meaning that the aforementioned values of the pressure and temperature at the inlets and outlets of the steam generator are kept equal to their design values;
- All the adjustments are made to the steam cycle, while the reactor core and steam generator operate at their design conditions. Hence, the steam cycle operates at off-design conditions even at the full load regime;
- The adjustments may include additional heat exchangers added to the cycle and rerouting of the pipelines;
- The modifications must not increase the live and reheat steam temperature above the design levels for the turbine.

The research is conducted using numerical simulations. The model of the steam cycle includes its main machines and auxiliary systems: turbines, heat recovery exchangers, pumps and a condenser. The model is built using a source code developed in the Department of Power Engineering and Turbomachinery at the Silesian University of Technology. It was verified against measurement data obtained from the existing power plants in previous works and projects, for example [21] and [22]. The source code allows us to analyse the thermodynamic processes that occur in power generating units.

The model is adjusted to fit the measurement data from a particular power plant. The algorithm for the data processing is shown in Fig. 1. The first stage is the preparation of the input data, mostly the structure of the cycle. The model is built by adding machines and devices that constitute the steam cycle.

At this stage, measurements are also chosen for the input data. The preferred set of measurements comes from the performance tests of a cycle, which are conducted before a new power generating unit is commissioned or after every major repair. This type of measurements is performed at several levels of load with the unit not being controlled by the power demand from the grid. These measurements are preferred because they are preceded by periods of operation at a constant load, which guarantees stable conditions. In case such measurements are not available, one should use the measurements from a period of stable load during a standard operation.

Once the input data including the measurements and the cycle structure are set, the numerical model is applied to determine the values that describe the health state (the technical state) of the machines and devices in the thermodynamic cycle. The type of these values depends on the particular machine or device under the analysis. For example, a steam turbine is divided into groups of expander stages. Each group includes stages either between two consecutive steam extractions or between a turbine inlet or outlet and an extraction. Two parameters describe the health state of a group of expander stages. The first one is the isentropic efficiency of expansion defined as:

$$\eta_i = \frac{i_{in} - i_{out}}{i_{in} - i_{s,out}} \tag{1}$$

with the subscripts referring to the cross-sections of the steam path at the inlet and outlet of a group of expander stages. See also the nomenclature section of the paper.

The second parameter for the groups of turbine stages is the constant defined as:

$$c_f = \frac{m_N}{\sqrt{p_{N,in}^2 - p_{N,out}^2}} \tag{2}$$

from the pressure-mass flow relation:

$$m = c_f \sqrt{p_{in}^2 - p_{out}^2}. \tag{3}$$

The simplified Fluegel-Stodola equation is applied here. Since the flow is measured in chosen locations of a steam cycle only, a model of the whole cycle is required in order to obtain the flow through each group of the expander stages and to calculate the constants defined in Eq. (2).

The isentropic efficiency may be calculated directly for the groups of stages in the high-pressure and intermediate-pressure sections of a turbine for the pressure and temperature values measured at the inlets, outlets and at steam extractions. The calculations of the isentropic efficiency in the low-pressure sections are conducted using the following approach. One value of the efficiency is assumed for all the expansion stages, where the flowing fluid is wet steam. Then, the model of the whole steam island is applied to determine the efficiency using, among others, the measured electric power as the input data. This approach requires the equations that describe the following aspects of the operation:

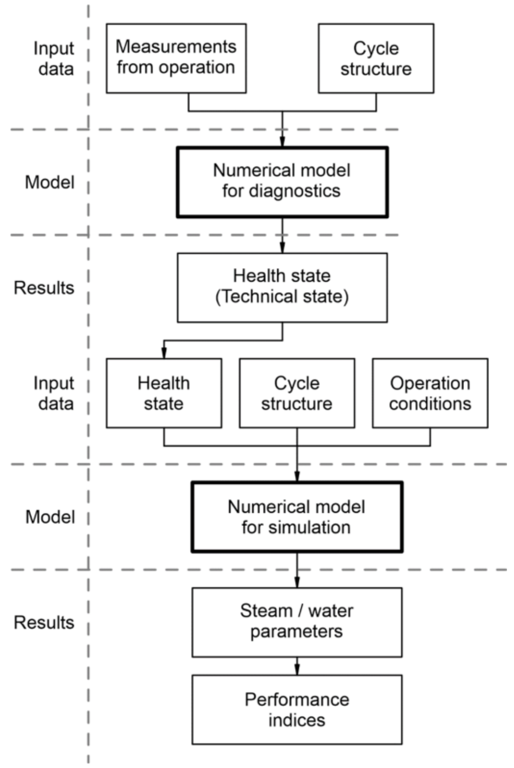

Fig. 1. Data processing to establish the numerical model of the steam cycle.

- mass and energy balances for turbine sections,
- mass and energy balances for heat recovery exchangers and deaerator,
- mass and energy balances for the condenser including the cooling water flow,
- pressure losses in pipelines,
- balance of the power output from turbine sections delivered to the power generator, including mechanical losses.

For the heat recovery exchangers, the values of the temperature differences are used as health state indicators. They are shown in Fig. 2. The differences are taken between the saturation temperature for the pressure in a heat exchanger and the outlet temperature values for cold and hot streams:

$$\Delta T_{fw} = T_{fw,out} - T_{sat}, \tag{4}$$

$$\Delta T_{cond} = T_{cond,out} - T_{sat}. \tag{5}$$

The resulting values may be positive or negative and reflect the ability of the exchanger to deliver the heat from the steam to the feed water. The health state indicators are established as functions of the load represented by the flow through the analysed machines and devices.

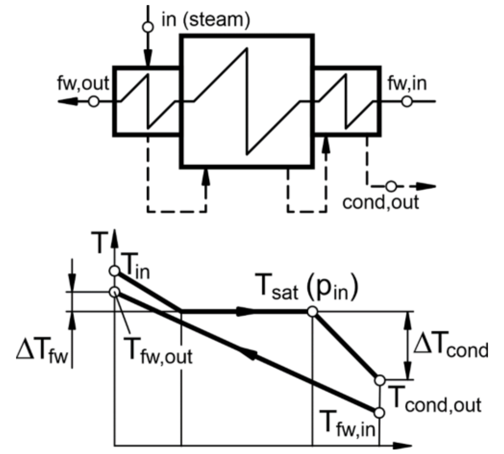

Fig. 2. Temperature differences in a heat exchanger.

Once the set of the health state indicators is obtained, the numerical model may be applied to the simulations of the off-design operation of a steam cycle. A new structure of the cycle is then established to reflect the proposed modifications required to match the reactor and the existing steam island. The operating conditions to be tested in the simulations are expressed in a set of values including:

- live steam pressure and temperature,
- reheat steam temperature
- cooling water temperature for the condenser,
- feed water temperature.

The simulation model determines the parameters of the working fluids in the main locations of the thermodynamic cycle. Then, it calculates performance indices, which include:

- power output N_{el},
- power required to drive the condensate pumps N_{cond} and the feed water pumps N_{fw},
- heat delivered to the steam/water in the steam generator Q,
- cycle efficiency η.

The cycle efficiency is used in the research presented here to compare different modernization options. It does not include the reactor efficiency since different reactor modules may be applied. This efficiency is defined as:

$$\eta = \frac{N_{el}-N_{fw}-N_{cond}}{Q}. \tag{1}$$

The proposed modifications to the steam cycle are verified against a range of values that affect the operation of the turbine and the auxiliary systems. The details of the modifications are described in the further sections of the paper.

3. Steam island

The arrangement of the steam cycle under investigation is shown in Fig. 3. It is a condensing steam turbine with high pressure, intermediate pressure and three low pressure turbine parts. Except for the high pressure turbine, all the parts are double opposed flow expanders.

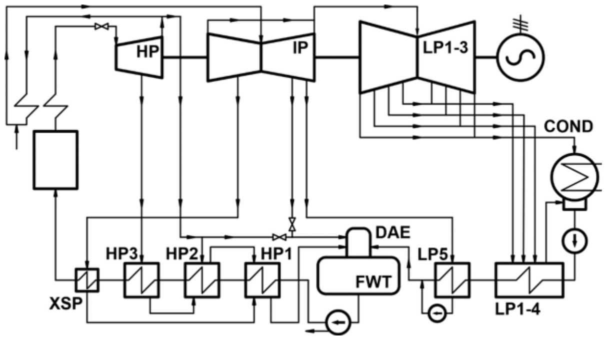

Fig. 3. Steam turbine cycle.

The heat recovery system consists of five main low pressure and three high pressure heat exchangers. There are additional exchangers located in both sections including a steam cooler / feed water heater fed from the intermediate part of the turbine. This is the last heat exchanger on the feed water path and its performance affects the final feed water temperature. The high and low pressure sections of the heat recovery system are separated by the deaerator and the feed water tank. The feed water pumping system consists of six pumps in a serial and parallel arrangement 3 by 2, but are shown for simplicity as a single pump in Fig. 3. The minimal permissible load is 40 per cent of the nominal load. Table 1 presents values of the main parameters that describe the operation of the turbine.

Table 1. Steam turbine design data.

Parameters	**Symbol**	**Unit**	**Value**
Electric power	N_{el}	MW	900
Live steam pressure	p_{HP}	MPa	25
Live steam temperature	T_{HP}	°C	600
Live steam flow	m_{HP}	t/h	2380
Reheat steam temperature	T_{IP}	°C	600
Steam to air heaters	-	t/h	40
Cycle efficiency	η	%	48.9

The health state analysis of the investigated steam island according to the methodology explained in Section 2 allowed us to obtain the values that may be applied in the off-design model of the turbine. The available measurement included five sets of data for five levels of the load.

The results of the simulations for the existing power plant are shown in Figs. 4–6. Figure 4 presents isentropic efficiencies for two chosen groups of turbine stages: an intermediate pressure one and a low pressure one. The efficiencies are shown as functions of the steam flow in these groups of stages and the range of curves in the horizontal direction reflects the range of flow in the turbine sections.

Figure 5 presents characteristic temperature differences for the second high pressure heat exchanger marked as HP2 in Fig. 3.

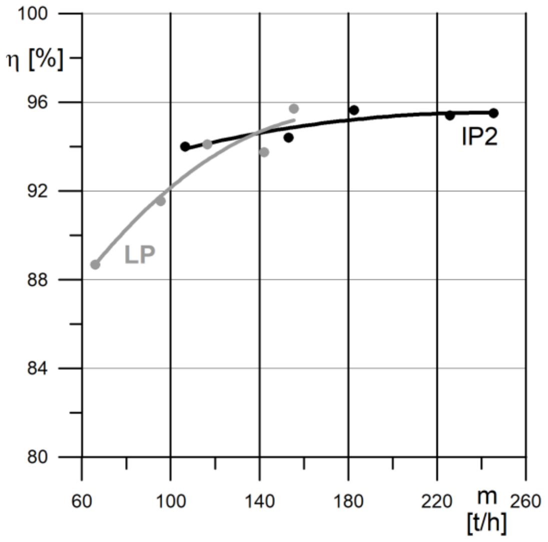

Fig. 4. Calculated isentropic efficiency of IP and LP groups of turbine stages.

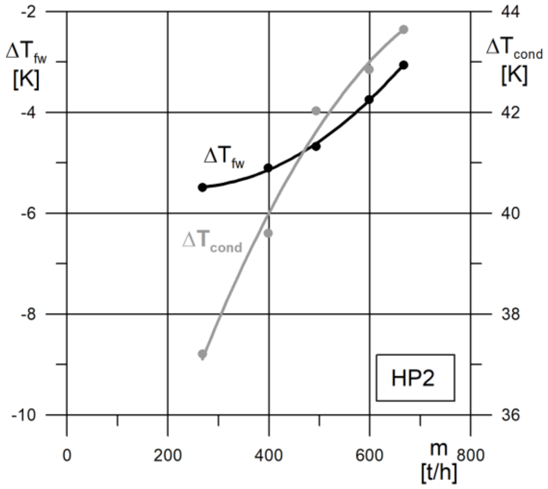

Fig. 5. Calculated temperature differences between saturation temperature in the HP2 heat exchanger and the feed water and condensate temperature.

The results of the simulation are shown in Fig. 6 in the form of the expansion lines of the steam. They are drawn in the enthalpy-entropy diagram. The expansion lines show the thermodynamic processes that occur in the turbines and in the reheater. Five lines refer to the five levels of load, for which the measurements were available.

The performance of the model with the steam island health state determined according to the described methodology may be verified against the measurement of the power output. The power output is calculated in the model and it depends on the performance of all the machines and auxiliary systems implemented in the model. Thus, the difference between the calculated and the measured values of the electric power indicates the quality of the numerical model. This comparison is shown in Fig. 7.

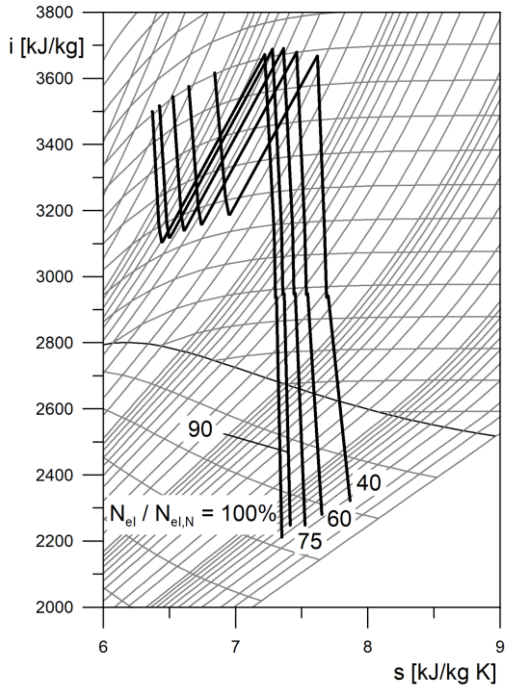

Fig. 6. Expansion lines for five different loads in the enthalpy-entropy diagram.

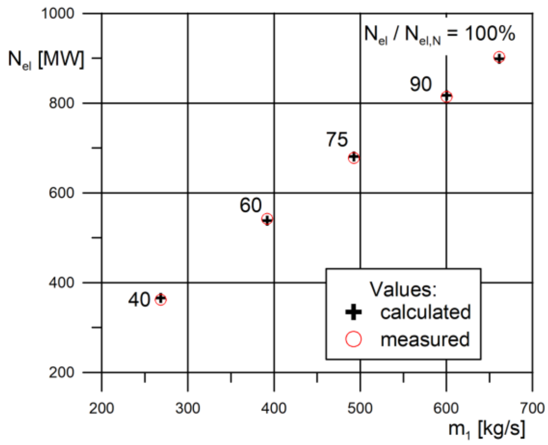

Fig. 7. Comparison between values of electric power – measured and calculated in the numerical model.

The obtained results indicate a very good quality of the numerical module. The differences between the calculated and the measured values are less than 0.5% for loads higher than 60% of the nominal load and less than 1.1 per cent for loads less than 60% of the nominal load. This is satisfactory since the modified steam cycle with a nuclear reactor is expected to operate under regimes close to the full load.

4. Steam island modifications

There are two problems to solve when connecting a nuclear reactor with a steam generator to an existing steam cycle: matching the parameters of the live/reheat steam and matching the parameters of the feed water.

Regarding the steam parameters, the following case is under investigation in this research: the steam temperature and pressure at the outlet of the steam generator are equal to or lower than the design values for the turbine. If the steam entering the turbine has parameters lower than the design values, then the turbine operates in off-design conditions. An important issue is the temperature of the reheat steam. Values lower than the design ones result in the possibility that the expansion in the low pressure turbine ends in the area of enthalpy-entropy diagram, where steam quality is lower than in design conditions. This would cause more intensive corrosion and faster component wear in the low pressure turbine.

The simulations performed within the research presented here proved that for the turbine described in Section 3 the quality of the steam was lower by no more than 2 percentage points when compared to the conditions corresponding to the same live steam pressure (the same live steam flow) for the design conditions. In some cases, the quality was even higher. The conclusion is that for the investigated turbine the decrease of the reheat steam temperature did not result in hazardous corrosion wear.

Regarding the feed water temperature, two cases are possible: the required temperature of the water entering the steam generator may be lower or higher than the feed water temperature at the outlet of the last recovery heat exchanger in the steam cycle. A simpler case is the first one when the feed water temperature must be lowered before entering the steam generator. The water may be cooled by a flow that bypasses the high pressure regeneration system. This is shown in Fig. 8.

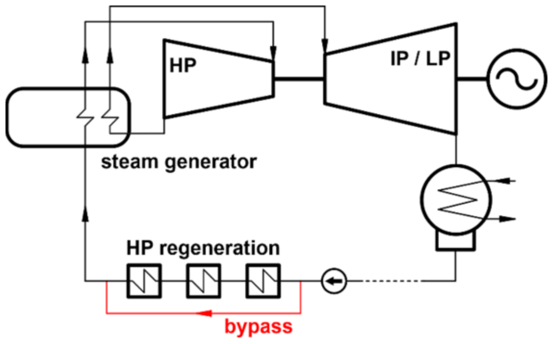

Fig. 8. Feed water cooled by a by-pass flow to match the required temperature for a steam generator.

The bypass water is extracted from the outlet of the feed water pump. The flow rate of the bypass stream must be chosen according to the temperature and the flow in the current conditions of the operation and should be added to the control system of the steam cycle. Since high pressure recovery heat exchangers typically have bypass pipes this modernization does not add to the investment costs, when implementing a nuclear reactor.

In the opposite case, when the temperature of the feed water is lower than required by a steam generator, an additional heat exchanger is necessary. Since the assumption in Section 2 is that the modifications are made on the steam cycle side, the additional exchanger must be fed with the additional steam. A suggested design is shown in Fig. 9.

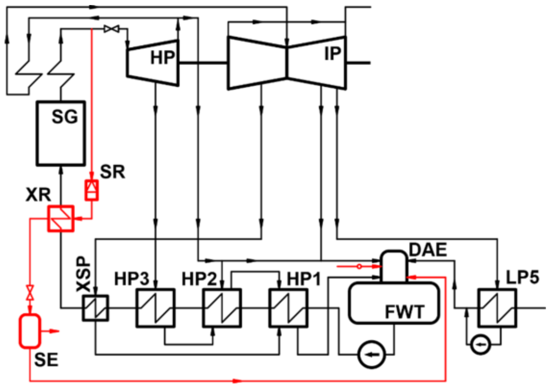

Fig. 9. Design with an additional feed water heater XR.

The additional heat exchanger XR is located upstream of the high pressure heat recovery system. The steam that feeds this exchanger is taken from the live steam pipeline. It is throttled in the station SR to the pressure value that corresponds to the saturation temperature that is higher by ΔT than the required water inlet temperature to the steam generator. The basic (reference) value of the temperature difference ΔT is 10 degrees Kelvin, although it may be optimized. For example, the steam generator inlet temperature of 300°C requires the saturation temperature in the additional heat exchanger equal to 310°C and it corresponds to the pressure of 9.867 MPa.

The steam is saturated in the expander delivering the heat to the feed water. The flow rate of the additional steam must be adjusted according to the flow of the feed water. This must be added to the control system of the power generating unit.

The condensate from the additional heat exchanger is still at a high pressure. For this reason, it flows into an expander SE. The pressure there is reduced to a level that is equal to the pressure in the deaerator. The steam and water fractions are delivered to the deaerator through separate pipelines.

It should be noted that in the presented modified arrangement of the steam cycle, the steam flow rate through the generator is higher when compared to the flow through the boiler in the original cycle for the same amount of steam entering the turbine. This is due to the additional flow of the steam that heats the feed water. This flow also goes through the high pressure heat recovery exchangers causing them to operate in off-design conditions.

5. Modified power plant

The results of the numerical simulations are presented for a fluoride salt-cooled high-temperature reactor module [23]. It is shown in Fig. 10 as already connected to a steam turbine. There is an inner loop of salt that flows through the reactor core. The heat delivered in the core is rejected in the intermediate heat exchangers and delivered to the outer loop of molten salt. The second loop feeds the steam generator.

The design data important to the research presented here are gathered in Table 2 and refer to the water/steam parameters only. Since the reactor is assumed to operate at its design conditions, the parameters in the core and the intermediate system are not

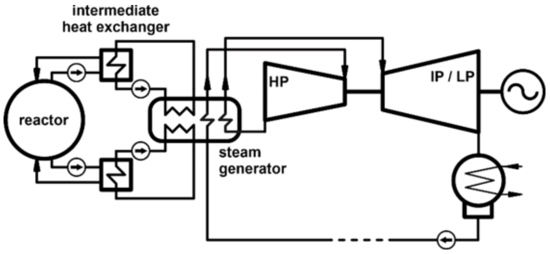

Fig. 10. Fluoride salt-cooled high-temperature reactor and steam turbine.

important to the analysis. The thermal power output of the nuclear module is much lower than the amount of heat required to generate steam for the turbine. For this reason, it is assumed that the module includes a number of reactors stacked in packages.

Table 2. Parameters of the fluoride salt-cooled high-temperature reactor.

Parameters	**Symbol**	**Unit**	**Value**
Live steam pressure	p_{HP}	MPa	19
Live / reheat steam temperature	T_{HP}, T_{IP}	°C	585
Feed water temperature	T_{FW}	°C	300
Power output	Q_{SG}	MW	140

The removal of the fossil-fuelled steam boiler and the addition of the nuclear reactor leads to the two main modifications listed below:

- There are no steam extractions to air heaters. In the original system, steam was taken from the extractions in the intermediate part of the turbine to heat the air flowing into the boiler. There is no need for that once the boiler is removed;
- There are no water injections to the live and reheat steam. This assumption is made to compare the operation of the cycle before and after the modifications. The water for the injections is taken from the feed water pumps outlets. It is used to maintain the temperature of the steam at desired levels. A perfect operation does not require any injections at all because the appropriate temperature levels are provided by the heat source, whether it is a fossil steam boiler or a nuclear module.

Table 3 compares the gross power output generated by the steam cycle under different conditions. The cases analyzed are as follows (with the symbols according to Table 3):

- 600/600/25 boiler – steam cycle before the modification, design steam temperature,
- 585/585/25 boiler – steam cycle before the modification, steam temperature lowered to the maximal permissible value for the steam generator,
- 585/585/19 boiler – steam cycle before the modification, steam temperature and pressure lowered to the maximal permissible values for the steam generator,
- 585/585/25 reactor – steam cycle with the reactor, steam temperature lowered to the maximal permissible value for the steam generator,
- 585/585/19 reactor – steam cycle with the reactor, steam temperature and pressure lowered to the maximal permissible values for the steam generator.

The temperature of the cooling water for the condenser is adjusted to be constant across the simulations. As mentioned above there are no water injections to the live and reheat steam. Yet the results for the steam cycle with fossil-fuelled boiler are shown with the steam extractions for the heating of the air flowing into the boiler. This is because the reference point is the original cycle with the extractions.

Table 3. Gross power output for the modified steam cycle.

p_{HP} [MPa]	T_{HP} [°C] / T_{IP} [°C] / p_{HP} [MPa] / boiler or reactor				
	600/600 25 boiler	585/585 25 boiler	585/585 19 boiler	585/585 25 reactor	585/585 19 reactor
25	900.56	880.79	-	883.23	-
19	665.61	651.65	651.65	658.92	658.92

The 19 MPa pressure level is the maximal specified for the steam generator delivered with the nuclear reactor mentioned at the beginning of this section. However, this level is too low for supercritical steam turbines, for which the live steam pressure should be above the critical value of 22 MPa for the full load operation. It is expected that the final permissible pressure for the steam generator will be higher because the steam temperature level is suitable for supercritical steam turbines. Also, a higher steam pressure requires modifications in the steam generator only and not in the nuclear reactor. For this reason, the matching between the reactor module and the steam turbine is analyzed here for the total range of pressure for the steam turbine that is up to 25 MPa.

The values of the cycle efficiency obtained from the numerical simulations are shown in Fig. 11. The presented cases are the same as in Table 3. The dashed parts of the curves for the modified turbine cycle refer to the range of pressure that may be applied to the currently available steam generator that is up to the limit of 19 MPa. The rest of the curves drawn with solid lines refer to the steam generators able to withstand higher pressure – here up to 25 MPa.

The efficiency is lower for lower steam temperatures, which results from the thermodynamic principles of power plant cycles. It is further lowered for the cycle cooperating with the nuclear reactor because an additional steam flow is used to heat the feed water and that flow also goes through the steam generator. In each point for each curve in the presented graph, the steam cycle operates in off-design conditions.

Figure 12 presents the heat transfer conditions in the additional heat exchanger XR. Firstly, the steam flow is shown that is required to increase the feed water temperature to the level appropriate for the steam generator – here it is 300°C, see Ta-

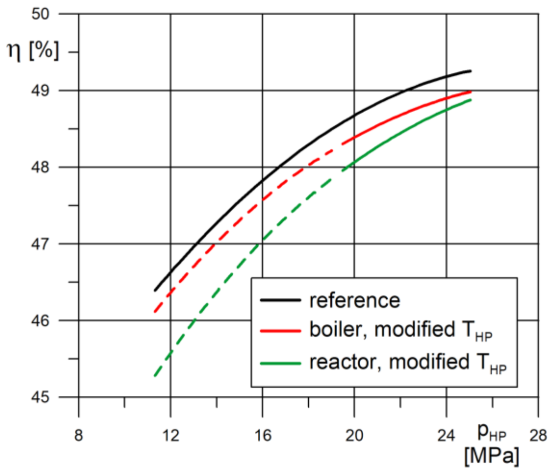

Fig. 11. Cycle efficiency for the modified steam cycle.

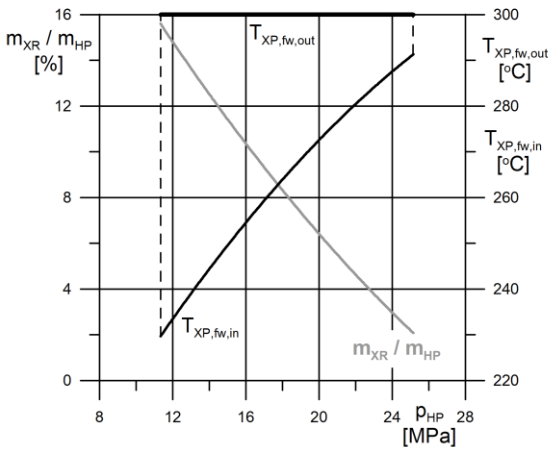

Fig. 12. Relative steam flow to the XR heat exchanger and temperature at the exchanger inlet and outlet.

ble 2. Secondly, Fig. 12 shows the temperature of the feed water at the inlet and outlet of the exchanger.

The steam flow is presented as a value relative to the live steam flow to the HP turbine section. This relative steam flow becomes higher for a lower load represented by the live steam pressure. This is because the temperature of the feed water entering the XR exchanger becomes lower for a lower load and more portions of steam are needed to increase its temperature. These heat exchange conditions are reflected in the values of the cycle efficiency in Fig. 11.

6. Conclusions

The results of numerical simulations show that the coupling of a nuclear reactor with a steam generator to an existing steam island is technically possible. The required modifications are done on the steam/water side only. The investments include new heat exchangers, steam expander, valves and piping.

The efficiency for the steam cycle analysed here is lower than for the unmodified cycle. This is because the steam generator described here required a lower steam temperature. A dedicated steam generator with a higher allowable pressure level should be designed and applied to a specific existing cycle converted from carbon to nuclear. Nevertheless, the cooperation is possible between any high pressure reactor module and an already operating steam cycle.

The pressure restriction for the steam generator described in Section 5 is expected to be neglected in the future. It is irrational to manufacture high temperature reactors with a low steam pressure because the potential of supercritical steam turbines would not be used.

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