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Modelling of different cogeneration technologies in a power generating unit with pwr reactor in the context of a future polish nuclear power station

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This paper focuses on the analysis of technical possibilities of a nuclear combined heat and power (NCHP) unit. The possibility of implementing a cogeneration unit in the cooperation with a typical PWR (Pressurized Water Reactor) is assessed by means of the numerical modelling of a process. The base for the model are operational parameters of Ascó Nuclear Power Station in Spain. The power plant employs a PWR reactor with more than 1000 MWe capacity. It is similar in size to a power plant which is planned to be built in Poland. Economic analysis of Tricity region have shown that the optimal amount of heat to be extracted is approximately 270 MWt.

The investigated possibilities of heat extraction were the by-pass of a turbine, steam bleeding and partial removal of heat from the network of regenerating heat exchangers. Each of the methods has been assessed based on the criteria of electric power production drop, utilisation factor, weighted utilisation factor and interference with the base operational parameters. It was observed that the extraction of heat may lead to the increase of a power plant economy and fuel utilisation factor.

Keywords: nuclear energy, fuel utilisation factor, cogeneration

Background

Simultaneous production of heat and electric power in a thermal power plant is very beneficial and increases the utilisation factor of a fuel. The application of such technology in a nuclear power station reduces an overall demand for fossil fuels in energy system. Instead of burning coal to obtain hot water for a district heating and a communal usage, part of energy obtained from fission can be extracted and delivered to the consumer. In turn the emissions of CO_2 and harmful substances are reduced. Additionally, if proper technology is used some economical benefits can be gained. Profits can be obtained by selling an additional useful product.

Historically the research on the possibility of nuclear cogeneration was performed since the beginning of civil nuclear application in 1950s [1]. The research is still continued with different aspects in focus [2]. Environmental benefits are strongly considered [3]. Small and large scale applications are analysed [4,5]. Also different applications for extracted heat than production of hot water are researched [6]. Several studies were analysing the feasibility of application of nuclear in Poland [7,8]

The extraction of heat leads to the reduction of electric efficiency of a power station. Temperature difference driving the power producing cycle is lower. Therefore, analysis has to be performed in order to select parameters covering the loss of electric power capacity by large amount of useful heat.

Numerical model of a nuclear power station has been created in order to check the changes in process parameters occurring due to heat extraction. Additionally, a simple model of a district heating system was applied. The creation of the model and analysis of obtained results is the major focus of this paper.

Materials and methods

The model was developed using Aspen Hysys software. Modified Peng-Robinson method is applied during the calculations. In order for the operational parameters to realistically reflect an actual power plant they were based on Ascó Nuclear Power Station in Spain. The size and technical solutions of this power plant are similar to the one proposed to be built in Poland. AP1000 PWR reactor with 3415 MWt of thermal power capacity is applied. Heat from the reactor is extracted in two steam generators supplying turbines producing approximately 1100 MWe. General view of the model of a power plant in Aspen Hysys is shown in Figure 1.

Only a single steam generator is modelled. Primary loop presented in Figure 2 contains a reactor modelled as a heat

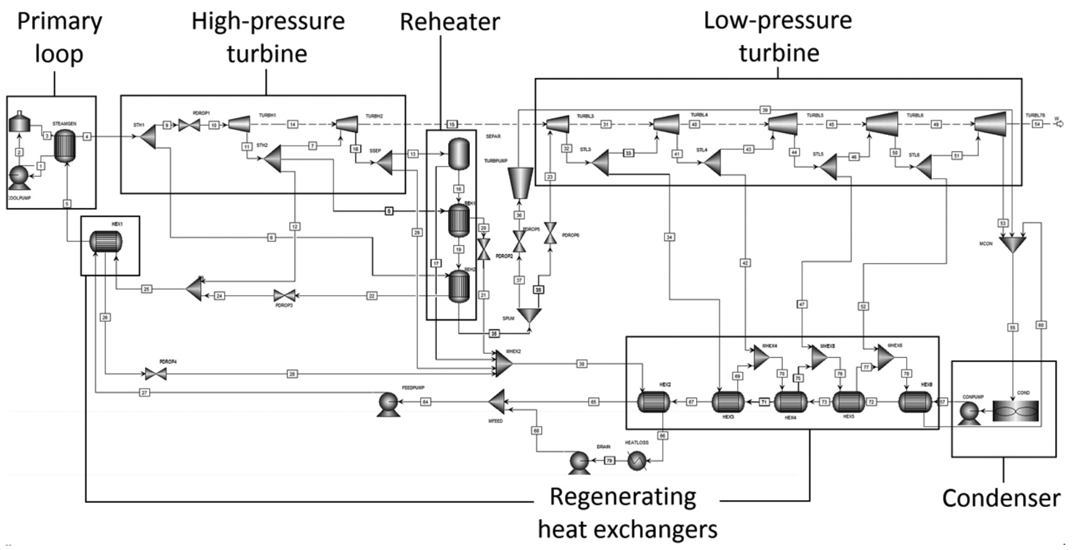

Fig. 1. General outlook of the model of an unmodified nuclear power plant

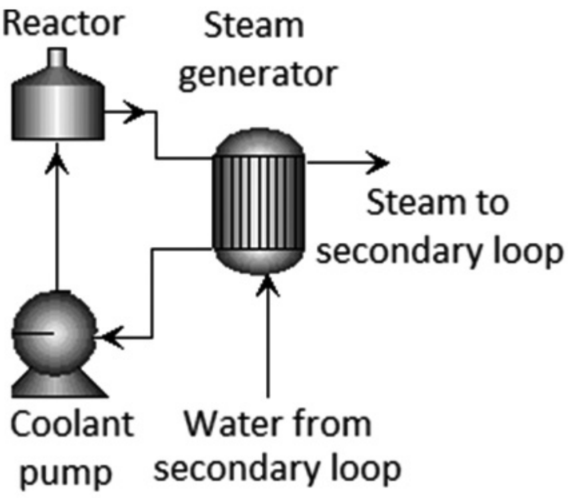

Fig. 2. Model of the primary loop

source with thermal power equal to the half of nominal AP1000 reactor power. Water in the primary loop is supposed to always remain in liquid state. This is ensured by high pressure of approximately 152 bar and a proper heat removal occurring in a steam generator. Cooling medium is driven by a coolant pump. On the secondary side preheated water in liquid state enters the steam generator modelled as a heat exchanger and leaves it as saturated steam with the pressure of 66.5 bar. Pressure loss of 16.6 bar is included in the heat exchanger model.

After evaporation the working medium is passed to the high pressure turbine where it is expanded to produce power. Parts of the flow are routed to other subsystems as shown in Figure 3. Before entering the turbine part of high quality steam is moved to a reheater.

The rest is expanded in the first stage o high pressure turbine. Next the flow is divided into three. One part is routed to the next stage of turbine, the other to reheater.

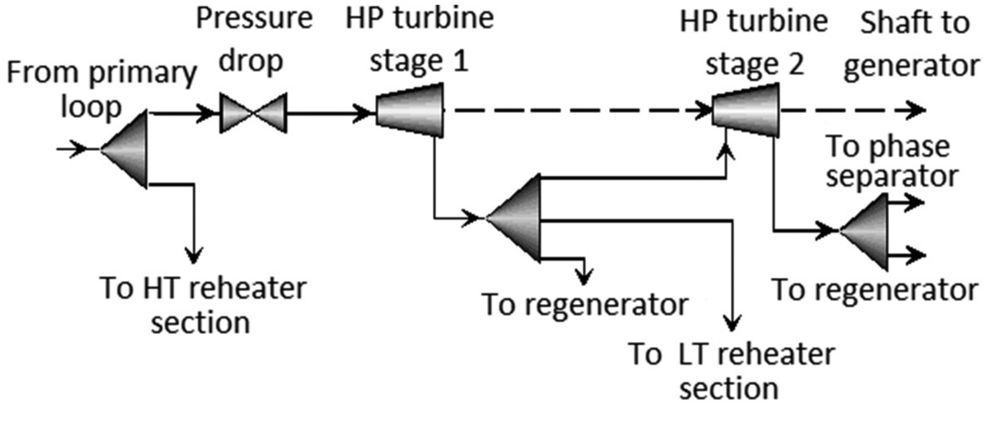

Fig. 3. Model of the high pressure turbine

The next part flows to the network of regenerating heat exchangers.

Flow after most of the stages of both high and low pressure turbines is divided to provide heat to this network. This includes second stage of high pressure turbine, in which during the expansion process steam enters two-phase region. After that the main part of the flow is moved to a phase separator. All splitters are modelled as blocks with specified ratio of flows leaving the element. Turbines are modelled as isentropic expanders with the efficiency of 0.72. Isenthalpic expansion valves are applied to model pressure drop.

Phase separator is modelled as a flash drum. It divides the flow of medium based on the phase. Liquid flows to the network of regenerating heat exchanger, steam is passed to the reheater which is divided in two sections. Initially it is preheated by part of the flow from stage 1 of the turbine. Then it uses heat directly from steam generator to improve the quality of steam.

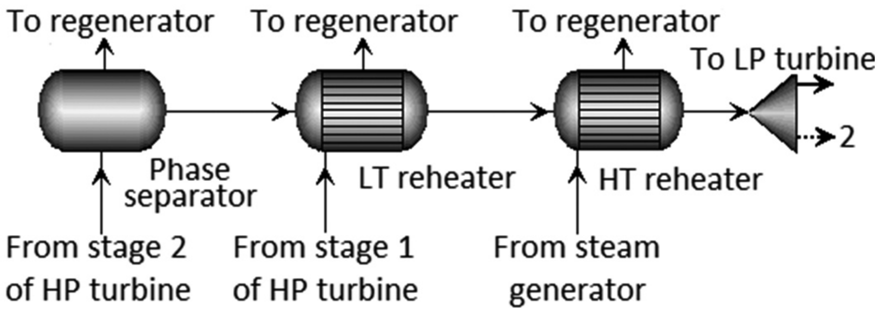

Fig. 4. Model of the reheater

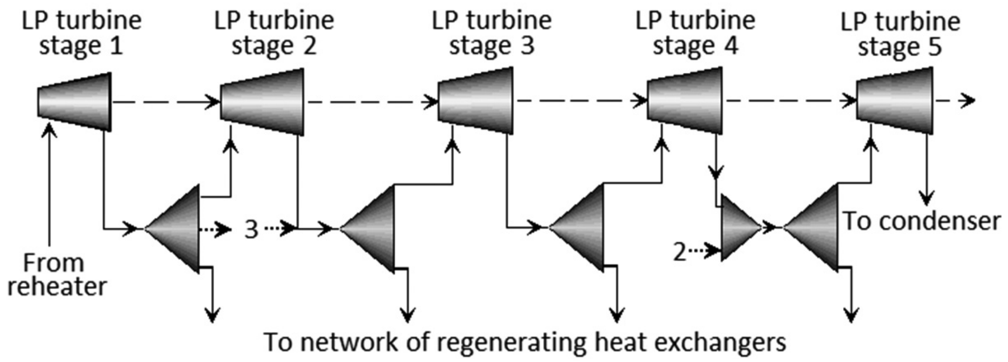

Fig. 5. Model of low pressure turbine

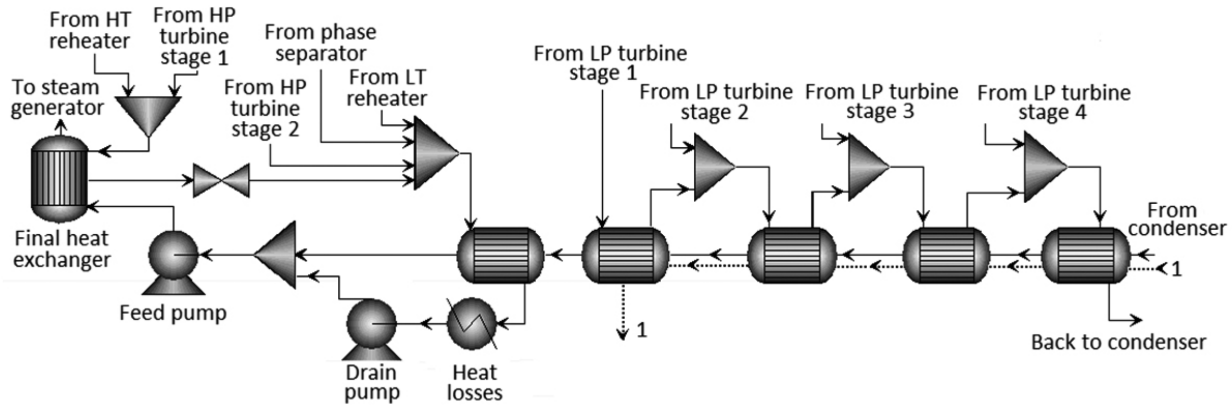

Fig. 6. Model of the network of regenerating heat exchangers

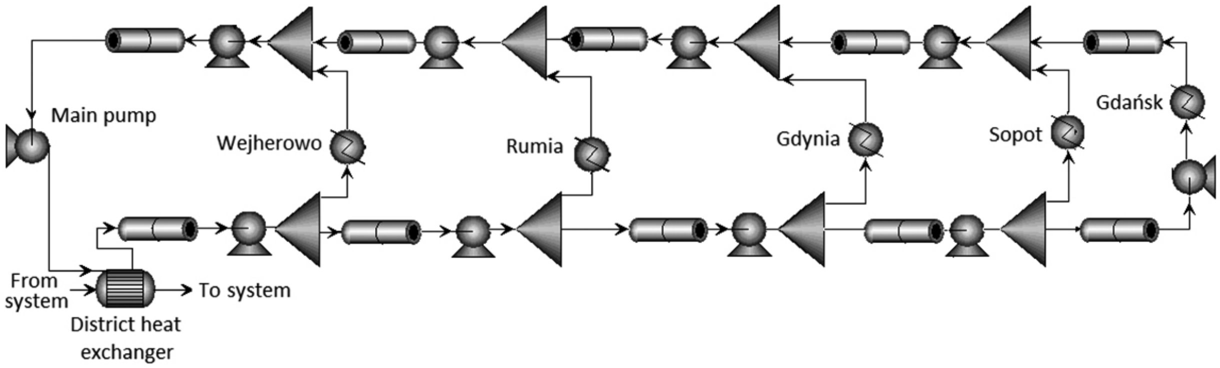

Fig. 7. Model of the district heating network

Before entering the low pressure turbine part of the flow is separated and is expanded in a small turbine driving the pumps of the power station. After expansion steam is used in the network of regenerating heat exchangers. In low pressure turbine parts of the flow are bled to the same network after each stage. Steam from the last stage flows to a condenser modelled as heat sink. Medium leaves the condenser as saturated liquid and is pumped further to the system by a main pump.

Water from the condenser enters the network of regenerating heat exchangers shown in Figure 6. There the temperature is raised initially by water from stages of low pressure turbine which, after giving away heat, are moved to a next changer and ultimately to the condenser. After that the medium is heated with water from the low temperature section of the reheater, condensate from the separator and second stage of high pressure turbine. In order to maintain numerical stability a heat exchanger modelling heat losses and a pump are added behind this exchanger. Water is then pumped to a final heat exchanger. The exchanger is supplied with water from high temperature section of reheater and the first section of the high pressure turbine.

Heating network is presented in figure 7. It is supplied with heat in district heat exchanger connected to the power cycle of the power plant. Pressure drops over long distances are modelled as pipeline elements. The effect of pressure drop is reduced using pumps. Local district heating networks are modelled as heat sinks. Each heat sink removes amount of heat equal to expected heat usage by a given community. Approximately 270 MWt of thermal power should be supplied with the temperature of 135°C.

Discussion

The district heating network can be connected to the system at several locations. Three are considered in this paper. They are shown in figures as dotted lines marked with proper numbers and referred to in the following text. These are:

1. the network of regenerating heat exchangers,
2. the removal of part of steam after the high pressure turbine (bleeding),
3. by-pass a stage of the low pressure turbine.

In the first case the part of heat is removed from the part of the network of regenerating heat exchangers supplied by low pressure turbine. It can be seen in Figure 6. Removal of heat with higher quality coming from high pressure turbine would lead to more significant losses of electric power. This method is the hardest to be analytically calculated as it involves changes in many streams.

The amount of heat which can be removed is limited by the parameters of water supplied to steam generator. The temperature should not be too low because this would require high heat load on the reactor. Larger heat production by the reactor is easily available in most cases but heat transfer from fuel rods to coolants is not. This would lead to dangerous increase of temperature of the reactor core. This problem is different than in the case of a conventional power plant, where heat production is the limiting factor.

Results of the calculations show that in order to maintain constant operating conditions in the steam generator the flow through secondary loop needs to be reduced. It leads to the decrease of electric power production by approximately 9.5%. In this case thermal power of the reactor is decreased by 3.5%. This reduction, however relatively small, requires more complex management of control rods in order to avoid inhomogeneous fuel burning. The decrease of electric efficiency is by 6.4%, from 0.328 at the base case to 0.307. Both utilisation factor and coal equivalent per MWh increase by approximately 15% in the case of utilisation factor and 8% in the case of coal equivalent. With analysed parameters the amount of produced heat is lower than desired and amounts to 211 MWt.

In the second part of steam is removed behind the reheater as can be seen in Figure 4. After giving away heat is returned to the final stage of turbine after mixing with steam from previous stage as shown in Figure 5. Steam bleeding decreases the flow through most of the stages of the low pressure turbine what immediately leads to the decrease of electric power. Thermodynamic parameters of the system do not change significantly, except for small differences in the network of regenerating heat exchangers. They are countered by slightly fraction of water transported to the first heat exchanger of the network.

The major thermodynamic disadvantage of this system is the fact that steam with relatively high quality has to be used. The application of this method is the trade-off between the fraction of bleeded flow and the quality of steam. Reactor thermal power remains the same. Output electric power is smaller by almost 19.3%. Utilisation factor increases by 7.3%, however coal equivalent is actually decreased by more than 2%.

By-pass of the single stage of turbine can be seen in Figure 5. An entire stage is removed and the same flow as would pass through it is giving away heat in the district heat exchanger. Technically it is the simplest of analysed solution if proper pressure reduction station will be applied behind the heat exchanger to ensure proper moisture content in steam entering the next stage of the turbine. The choice of turbine to be by-passed is determined by the similarity of its thermal parameters with the temperature and amount of heat required by the district heat exchanger. In the case of analysed system, the optimal choice is the second stage of low pressure turbine.

This solution leads to the reduction of electric power by the amount which would be produced by the by-passed turbine. In the case of the considered system it is roughly 17%. Fuel utilisation factor increases by 9.5% and coal equivalent by 0.7%.

Both second and third method are capable of obtaining high heat transfer coefficient by using condensation to improve it. They also can supply the required amount of heat to the district heat exchanger. Other advantage is the fact that they do not require changes at the primary loop. However, economical and environmental benefits are not as significant as in the case of the first method.

The application of the first method is the only one which could decrease the amount of fossil fuels used in energy mix when compared to the application of the unmodified power plant. Electric energy decrease which will have to be covered with conventional power station is relatively less chemical energy consuming than the amount of heat provided to the customers. However, this method cannot cover the entire need for heat and requires changes in the operation of the reactor.

Radiation risk increase is very small when compared to the standard nuclear power. Delivery of irradiated hot water to customers would require simultaneous leaks in the steam generator and the district heat exchanger, which is very unlikely. In the case of such problem any of those leaks is easily detectable by both radiation sensors and thermodynamic measuring devices and the flow of heating water can be stopped. Since the amount of heat produced by the reactor is the same in the case of modified and unmodified power plant condenser would not have to be redesigned to maintain safety margin for emergency cooling.

Conclusions

It is possible to obtain positive environmental and economical effects from the application of cogenerating nuclear power plants. Each of presented methods has its drawbacks. It appears that the best of them is the extraction of heat from the network of regenerating heat exchangers.

It should be noted that the numerical model was created basing on the plant designed to produce only electric. The creation of the nuclear power plant dedicated for cogeneration would significantly improve all of the factors. Especially, the improvements in the thermodynamics of the network of regenerating heat exchanger would reduce the need of changing the operational parameters of the reactor, which would improve both fuel economy and the safety of operation.

Public risk connected with the application of cogenerating nuclear power plants is very small. It can be expected, however, that many would oppose the idea of hot water coming from a nuclear power plants to their houses. The application of such improvement would require wide educational action.

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