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The influence of flow resistance in the main pipelines of secondary circuit on the power of EPR and AP1000 nuclear units

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Abstract

The article presents the influence of hydraulic resistance in the main pipelines of EPR (evolutionary power reactor) and AP1000 (advanced passive) pressurised water nuclear reactors secondary circuit on the electric power of these units. The change of hydraulic resistance in the passage pipelines of the high-pressure and low-pressure turbine parts and in the pipelines supplying the low-pressure and high-pressure regenerative heaters was taken into account. These two types of units were selected due to the different values of live steam parameters and different values of pressure drops in the turbine passage and regeneration system pipelines. The analysis shows that the flow resistance in the turbine passage pipelines has the greatest impact on the power and efficiency of the unit, followed by high-pressure regeneration pipelines, while low-pressure regeneration pipelines have the least impact.

Keywords: EPR; AP1000; Pipeline pressure drop; Power and nuclear unit efficiency

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1. Introduction

The understanding and mastery of the processes occurring in a nuclear reactor enabled the construction of the first nuclear units with relatively low thermal and electrical power. Some of the oldest nuclear units connected to the electrical network were built, among others, in Russia in Obninsk [1] with a thermal power of 36 MW_{th} and electrical power of 5 MW_{el}, and in Great Britain in Calder Hall [2] with a thermal power of 268 MW_{th} and electrical power of 49 MW_{el}. Over time, due to the minimisation of the unit cost of building 1 MW_{el} of power, nuclear units with higher thermal and electrical power were built. Here, we can distinguish nuclear units of the class 400 MW_{el} (VVER – Rus. *vodo-vodyanoi enyergeticheskiy reaktor* – water-water energetic reactor [3]), 600 MW_{el} (AP600 – advanced passive [4]), 1000−1200 MW_{el} (AP1000 [5−8], EPR – evolutionary power reactor [8−11], VVER [8,12,13]) and even those reaching the power of 1400 MW_{el} (APR1400 – advanced power reactor [14]) or 1600−1700 MW_{el} (EPR [8−11]). As can be seen, all of the aforementioned nuclear units, i.e. VVER, AP600, AP1000, APR 1400, EPR, belong to the PWR (pressurised water reactor) type nuclear units, which constitute the largest group among the nuclear reactors built in the world. According to the IAEA PRIS (International Atomic Energy Agency Power Reactor Information System) statistics [15], there are currently 417 operating nuclear reactors in the world with a total capacity of 373.735 MW_{el}. The largest number of PWR-type nuclear reactors is 306, with a total capacity of 293.147 MW_{el}, which is 73.7% of the number of PWR reactors of all types, and the share of PWR reactors is 78.4%.

Nomenclature

dp – pressure drop, $= p_{HE} - p_T$, bar
h – specific enthalpy, kJ/kg
$\dot{m}$ – mass flow rate, kg/s
p – pressure, bar
t – temperature, °C

Greek symbols

$\Delta\dot{m}$ – difference in mass flow rates, $= \dot{m}_{doc} - \dot{m}_{ebs}$, kg/s
$\delta\dot{m}$ – mass flow rate relative error,$= (\dot{m}_{doc} - \dot{m}_{ebs})/\dot{m}_{doc}$, %

Subscripts and Superscripts

doc – data from the documentation
ebs – data from the Ebsilon program
HE – steam at the inlet to the heat exchanger
T – steam in the turbine bleed

Abbreviations and Acronyms

AP600/1000 – advanced passive
APR1400 – advanced power reactor
CON – steam condenser
DE – deaerator
EPR – evolutionary power reactor
EPR OL3– evolutionary power reactor in Olkiluoto unit 3
EPR F3– evolutionary power reactor in Flamanville unit 3
G – electric generator
HPC – high-pressure cooler
HPRH – high-pressure regenerative heat exchangers
HPT – the high-pressure part of the steam turbine
IAEA PRIS – International Atomic Energy Agency Power Reactor Information System
LPC – low-pressure cooler
LPRH – low-pressure regenerative heat exchangers
LPT – low-pressure part of the steam turbine
M – electric motor
P – pipes
PWR – pressurised water reactor
R – nuclear reactor
SG – steam generator
SH – superheater, first and second stages
VVER – water-water energetic reactor

At the same time as the thermal and electrical power of nuclear units increased, efforts were made to increase their efficiency, which can be achieved by using classical methods that are also used in conventional steam power plants. The increase in the efficiency of nuclear power plants is achieved by increasing the pressure and temperature of steam at the inlet to the steam turbine and by reducing the pressure of condensing steam in the condenser [16−21]. In turn, the pressure of condensing steam in the condenser is influenced by the design of the condenser [22−24], the load of the unit [25], and the temperature [26−30] and mass flow of cooling water at the inlet to the condenser [31−33]. With the increase in the thermal power of the reactor, it is possible to produce more steam in the generators. The above parameters (pressure and temperature, the mass flow of steam at the inlet to the turbine, and the pressure of condensing steam at the inlet from the turbine) affect the power generated by the steam turbine, which affects the efficiency of the entire nuclear unit.

The second method of increasing the power and efficiency of nuclear units involves changes in the structure of the thermal system, e.g. by using low-pressure and high-pressure regeneration [16−19]. Thermal systems of the nuclear unit designed for cogeneration operation are also analysed, i.e. systems that simultaneously produce electricity and district heating [34−38]. Systems of nuclear units for hydrogen production [39,40] and seawater desalination [41,42] are increasingly being proposed and tested. In order to increase the efficiency and power, combined thermal systems of the nuclear unit with gas turbines [43−46] are also analysed, as well as in combination with conventional systems coupled by means of superheaters [47,48]. Combined systems with the nuclear unit significantly increase the power and efficiency of such systems, but significantly increase the construction costs due to significant interference in the structure of the thermal system.

The influence of the main parameters determining the efficiency of nuclear units, including the parameters of steam generated in generators and pressure in the condenser, has been the subject of a number of analyses, including the ones mentioned above. However, considering that nuclear units operate for 40−50 years with the possibility of extending to 60−80, even a slight increase in efficiency provides significant economic benefits. Therefore, due attention should be paid to the entire thermal system of the nuclear unit, and possible places in the system should be sought, the careful selection of which would allow for an increase in the power and efficiency of the system. One of such possibilities is the proper selection of pressure drops in the pipelines connecting the steam bleedings in the turbine with the regenerative exchangers and in the passage between the high-pressure and low-pressure parts of the turbine, which is the subject of this article.

During the design of a nuclear unit, the designers' main focus is on maintaining the required power and efficiency of the unit by ensuring the values of the main parameters, i.e. steam pressure and temperature at the turbine inlet, steam mass flow (obtained based on the required heat flow transferred in the steam generators), condenser pressure, feed water temperature at the steam generator inlet. It happens that during the design of a nuclear unit, pressure drops in the pipelines are assumed as a certain percentage of the steam pressure at the inlet. This practice is also found in conventional power plants. Therefore, it seems that they are not determined with due accuracy during their design. For a nuclear unit built with such adopted assumptions regarding flow resistance in the pipelines supplying the regenerative exchangers and in the passageway, there may be significant differences that affect the power and efficiency. The significant impact of these assumptions on the performance of the nuclear unit is presented in this paper. The EPR-type nuclear unit with the highest electrical power was selected for analysis, as well as the AP1000 nuclear unit, which was selected as the first nuclear unit to be built in Poland.

2. List of pressure drops in pipelines to regeneration exchangers

Based on the thermodynamic and economic analysis, the appropriate number of low-pressure and high-pressure regenerative exchangers was determined for the thermal systems of EPR and AP1000 units. Considering only thermodynamic considerations, the increase in the number of regenerative exchangers causes the increase in the temperature of the feed water at the inlet to the steam generators and the increase in the efficiency of the entire system [16,49,50]. However, with the increase in the number of regenerative exchangers, this increase is smaller and smaller, and taking into account economic considerations (costs of building additional exchangers), the optimal number of high-pressure and low-pressure regenerative exchangers can be determined. In conventional units, there are 2−3 high-pressure regenerative exchangers and 4−5 low-pressure regenerative exchangers [16,18]. For nuclear units, the number of high-pressure regenerative exchangers is usually 2 and the number of low-pressure regenerative exchangers is usually 4 [7,11,34,35,40]. Table 1 shows the steam pressure in the turbine bleeds (p_T) and at the inlet to the exchangers (p_{HE}), pressure drops in the steam pipelines (dp) supplying the low-pressure and high-pressure regenerative exchangers and the percentage share of the pressure drop in relation to the pressure in the turbine extraction for conventional units, and in Table 2 for EPR and AP1000 nuclear units, also taking into account the pressures in the passage.

Table 1. Steam pressure in turbine extractions and at the inlet to exchangers, pressure drops in steam pipelines supplying low-pressure and high-pressure regenerative exchangers, and percentage pressure drop for conventional units.

Unit (MW_{el})	Heat exchanger	p_T (bar)	p_{HE} (bar)	dp (bar)	dp/p_T (%)
360					
	LPRH1	0.382	0.378	0.004	1.0
	LPRH2	1.061	1.049	0.012	1.1
	LPRH3	3.14	3.08	0.06	1.9
	LPRH4	5.46	5.4	0.06	1.1
	HPRH1	21.41	21.05	0.36	1.7
	HPRH2	44.81	43.2	1.61	3.6
500					
	LPRH1	0.137	0.134	0.003	2.2
	LPRH2	0.924	0.897	0.027	2.9
	LPRH3	2.946	2.758	0.188	6.4
	HPRH1	13.63	13.27	0.36	2.6
	HPRH2	21.05	20.8	0.25	1.2
	HPRH3	43.57	42.91	0.66	1.5
1000					
	LPRH1	0.175	0.166	0.009	5.1
	LPRH2	0.553	0.525	0.028	5.1
	LPRH3	2.65	2.53	0.12	4.5
	LPRH4	5.98	5.8	0.18	3.0
	LPRH5	11.6	10.7	0.9	7.8
	HPRH1	24.5	23.3	1.2	4.9
	HPRH2	58	56.2	1.8	3.1
	HPRH3	104.3	99.1	5.2	5.0

3. Models of the analysed thermal systems

The secondary thermal cycles of the EPR and AP1000 units operate according to the Rankine cycle, are similar to each other and have the same main elements, e.g. the high-pressure and low-pressure parts of the steam turbine, a two-stage steam superheater after the high-pressure part of the turbine, a condenser, a deaerator, low- and high-pressure regenerative exchangers, cooling water, condensate and feed water pumps and an electric generator. There are also some differences between them, e.g. in the number of turbine stage groups for the high-pressure and low-pressure parts, an additional water heater for high-pressure regeneration for the EPR and a different method of condensate flow from low-pressure regenerative exchangers. The difference also concerns the heat flux generated in the reactor and the pressure of live steam at the outlet of the steam generator, which causes them to have different generated electrical power and efficiency.

The EPR and AP1000 nuclear power unit models were developed in the Ebsilon program [51]. The Ebsilon program has been used to model conventional power units [31,52−54] as well as nuclear power units [21,30,33,44,55−57]. Both models refer to the steady state of the thermal system operation. The Ebsilon program is dedicated to thermal-fluid calculations of complex thermal systems [51]. Models of EPR and AP1000 units were created in Ebsilon based on their balance thermal diagrams. In the construction of the models, ready-made components of thermal system elements contained in the program's database were used. The components are interconnected to form the primary and secondary layout of the nuclear unit, consistent with their thermal scheme. The models consist of components, such as turbine stage groups, regenerative exchangers, a deaerator, steam condenser, steam superheaters, a moisture separator, pipelines, pumps, valves, electric motors to drive pumps, an electric generator, and distribution and mixing nodes. For each component, the relevant design or balance data should be entered, e.g. for the turbine stage group – efficiency, for the regenerative exchanger – terminal temperature difference (TTD), and for the valves and pipelines – nominal pressure drops. In the heat exchanger model, the heat transfer equation according to Péclet's law is used and for turbine stage groups the Flugel-Stodola equation is used. In the online documentation of the Ebsilon program, it is possible to reach detailed descriptions of the models and the calculation formulas used, but this is laborious and beyond the scope of this article. According to the authors of the paper, the Ebsilon program is one of the most advanced programs for steady-state thermal-fluid balance calculations and is therefore used in scientific and research work at the Institute of Heat Engineering of Warsaw University of Technology.

In the model, it is also necessary to enter parameters at characteristic points, such as pressures in the turbine bleedings. In the developed models, the number of entered data for the design

Table 2. Steam pressure in turbine extractions and at the inlet to exchangers, pressure drops in steam pipelines supplying the low-pressure and high-pressure regenerative exchangers, and percentage pressure drop for EPR and AP1000 nuclear units, also taking into account the pressures in the passage.

Unit	Heat exchanger	p_T (bar)	p_{HE} (bar)	dp (bar)	dp/p_T (%)
EPR OL3					
	LPRH1	0.1311	0.1245	0.0066	5.0
	LPRH2	0.615	0.584	0.031	5.0
	LPRH3	2.13	2.02	0.11	5.2
	LPRH4	4.43	4.21	0.22	5.0
	HPRH1	19.96	18.96	1	5.0
	HPRH2	29.37	27.9	1.47	5.0
	Turbine passage	10	9.5	0.5	5.0
EPR F3					
	LPRH1	0.1703	0.1619	0.0084	4.9
	LPRH2	0.855	0.8123	0.0427	5.0
	LPRH3	3.451	3.215	0.236	6.8
	LPRH4	6.37	6.051	0.319	5.0
	HPRH1	20.81	19.78	1.03	4.9
	HPRH2	30.27	28.76	1.51	5.0
AP1000					
	LPRH1	0.405	0.393	0.0124	3.1
	LPRH2	0.866	0.839	0.0269	3.1
	LPRH3	2.565	2.482	0.0827	3.2
	LPRH4	4.268	4.137	0.1310	3.1
	LPRH5	17.858	17.306	0.5516	3.1
	HPRH1	28.270	27.373	0.8963	3.2
	HPRH2	0.405	0.393	0.0124	3.1
	Turbine passage	11.328	10.958	0.37	3.3

model for one unit is about 120. The Ebsilon program, on the basis of the created thermal system with the entered required parameters using mass and energy balances, determines mass flow rates at characteristic points of the thermal system for the nominal (design) condition. In the case of analysis of load changes, calculations are performed under the changed conditions of operation (off-design). In this case, the number of additional data is small (less than 10). It increases significantly in the case when the own characteristics of elements under changed operating conditions are introduced. For the analysed models of the EPR and AP1000 nuclear units, the values of pressure drops in the high-pressure to low-pressure (HP−LP) passage and in the pipelines (P1−P4) feeding the regenerative exchangers were given as input data to the model in the pipeline component. For the assumed input data, including pressure drops for these pipelines and in the HP−LP passage, the Ebsilon program determined the mass flow rate of the fluids and the performance of the unit, i.e. power and efficiency of the unit.

3.1. Model of the thermal system of the EPR nuclear unit

The diagram of the EPR nuclear unit system with parameters was taken from the data presented by Framatome in [11]. Based on the available thermal diagram, a thermal-flow model of the EPR nuclear unit was created in the Ebsilon program, as shown in Fig. 1. In the analysed EPR nuclear unit, the steam turbine consists of a high-pressure part (HPT) and three low-pressure parts. A condenser is located under each of the low-pressure turbine parts. In the model presented in Fig. 1, due to the identity of the three low-pressure turbine parts, they were aggregated into a single part (LPT), and the steam condensers (CON) were treated similarly. In the secondary circuit, there is a two-stage steam superheater (SH) located between the outlet from the HP part and the inlet to the LP part of the turbine. The high-pressure regeneration system consists of two regenerative exchangers (HPRH1−2) and a high-pre-

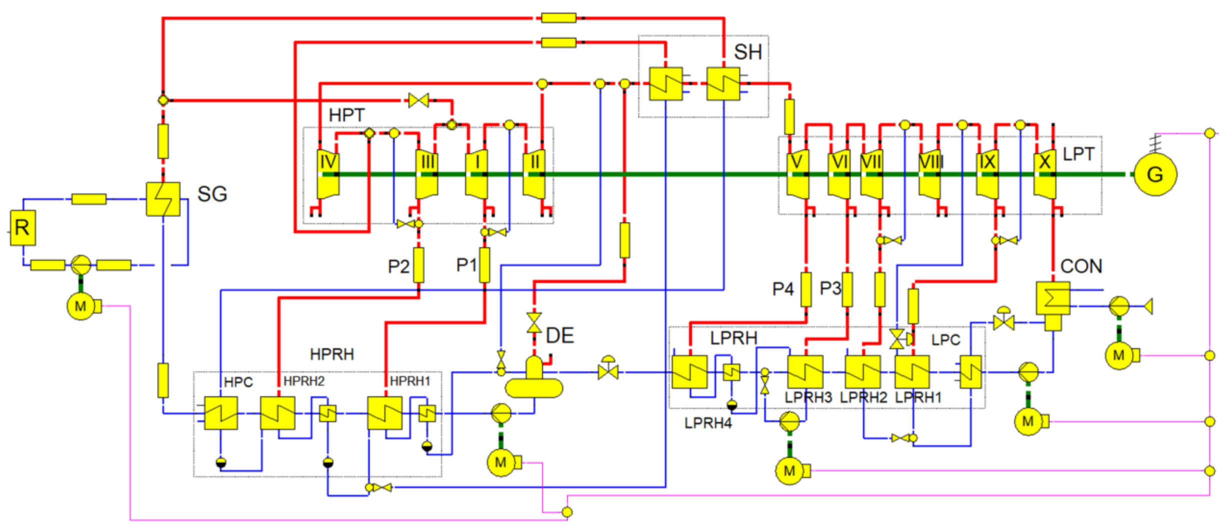

Fig. 1. Schematic diagram of the thermal system of the EPR nuclear power plant: CON – steam condenser, DE – deaerator, G – electric generator, HPC – high pressure cooler, HPRH – high-pressure regenerative heat exchangers, HPT – the high-pressure part of the steam turbine, LPC – low pressure cooler, LPRH – low-pressure regenerative heat exchangers, LPT – the low-pressure part of the steam turbine, M – electric motor, P – pipes, R – nuclear reactor, SG – steam generator, SH – superheater, first and second stages; blue line – water, red line – steam, green line – shaft, pink colour – electric lines.

ssure cooler (HPC). The low-pressure regeneration system consists of four regenerative exchangers (LPRH1−4) and a low-pressure cooler (LPC). The power of the analysed EPR nuclear unit is about 1700 MW_{el} and the gross efficiency is about 39% [9−11]. A detailed description of the model, as well as a list of parameters (temperatures, pressure, mass flow) at characteristic points of the thermal system, are presented in [21,30]. A detailed description of the system and individual components, as well as the thermal cycle, is presented in [21]. A description of the EPR and AP1000 reactors can also be found in the literature, e.g. in [58].

3.2. Thermal system model of the AP1000 nuclear unit

The AP1000 nuclear unit consists of a high-pressure turbine (HPT) part, a two-stage steam superheater (SH) and three low-pressure turbine (LPT) parts. The low-pressure regeneration system consists of four regenerative exchangers and a low-pressure cooler. The high-pressure regeneration system consists of two regenerative exchangers. The power of the analysed AP1000 nuclear unit is about 1200 MW_{el} and the gross efficiency is about 35% [1−7]. The input data for the model were taken from available documentation [7]. Based on the established structure and parameters, a unit model was created in the Ebsilon program (Fig. 2). Table 3 presents selected parameters (pressure, temperature, mass flow and specific enthalpy) for characteristic points of the system (1−14). The symbols in Fig. 2 are the same as in Fig. 1.

For the given pressures and temperatures at selected points in the thermal system, mass flows corresponding to the nominal power of the unit were determined in the Ebsilon program. Table 4 presents a comparison of mass flows and relative error at characteristic points of the system according to data from the documentation [7] and data obtained from the model in the Ebsilon program.

The maximum mass flow rate differences are 4−6 kg/s, but they occur for large mass flow rates, for which the relative error is equal to or below 0.52%. The maximum relative error does not exceed 1%, which can be considered a satisfactory model validation, considering also the fact that the Ebsilon model uses simplifications in the steam system from the glands and turbine seals.

Table 3. Pressure (p), temperature (t), mass flow ($\dot{m}$) and enthalpy (h) at characteristic points of the thermal system of the AP 1000 nuclear unit.

No.	p (bar)	t (°C)	$\dot{m}$ (kg/s)	h (kJ/kg)
1	57.61		1886.9	
2	55.71	270.72	1824.1	2785.62
3			61.3	2785.62
4	28.27		89.9	2685.60
5	11.33		1450.8	2539.99
6	34.13		82.9	2718.40
7	17.86		71.7	2610.47
8		226.67		975.76
9	4.27		43.1	2773.52
10	2.56		74.8	2686.30
11	0.84	94.78	47.8	
12	0.41		81.8	2472.54
13			1034.5	
14		42.61	1285.6	180.73

Table 4. Comparison of mass flows at characteristic points of the thermal system for the AP1000 nuclear unit according to data from [7] and the Ebsilon program.

No.	$\dot{m}_{doc}$ (kg/s)	$\dot{m}_{ebs}$ (kg/s)	$\Delta\dot{m}$ (kg/s)	$\delta\dot{m}$ (%)
1	1886.91	1882.78	4.13	0.22
2	1824.06	1820.79	3.28	0.18
3	61.32	61.79	-0.46	-0.76
4	89.91	89.83	0.08	0.09
5	1450.85	1446.07	4.77	0.33
6	82.94	83.58	-0.65	-0.78
7	71.72	71.86	-0.15	-0.21
8	125.08	126.30	-1.22	-0.98
9	43.07	43.41	-0.34	-0.80
10	74.76	75.11	-0.35	-0.46
11	47.84	48.20	-0.36	-0.76
12	81.79	81.09	0.71	0.86
13	1034.51	1034.30	0.22	0.02
14	1285.62	1278.88	6.74	0.52

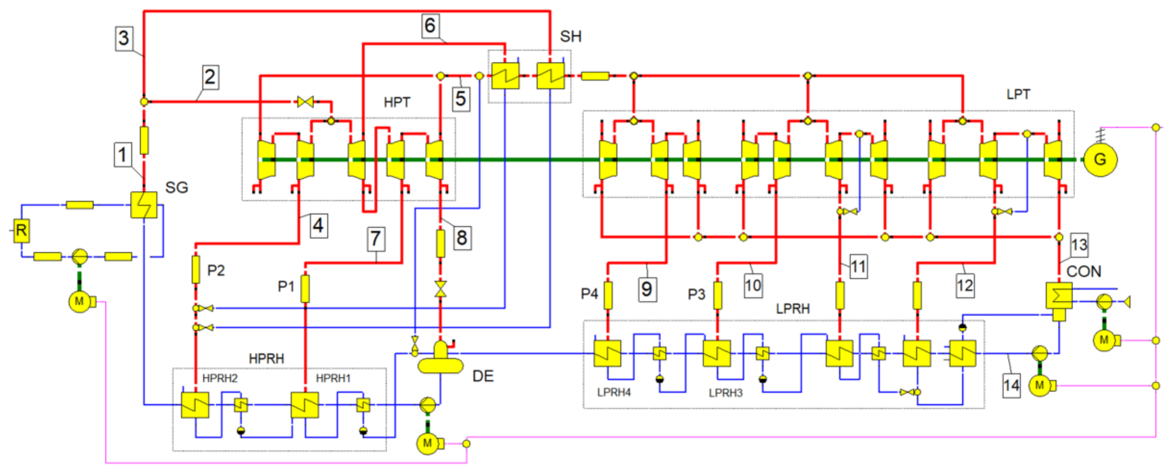

Fig. 2. Schematic diagram of the thermal system of the AP1000 nuclear power plant: 1–14 – characteristic points of the system (for legend see Fig. 1).

4. The influence of pressure drop change in the steam supply line on the performance of the regenerative heat exchanger

Regenerative exchangers can be divided into three zones (steam cooling zone, steam condensation zone and condensate cooling zone) [59−63]. High-pressure regenerative exchangers in the analysed nuclear units (HPRH1 and HPRH2) are supplied with wet steam, therefore, they do not have a zone of steam cooling to saturation. Low-pressure regenerative exchangers (LPRH3 and LPRH4) are supplied with superheated steam; therefore, they have three heat exchange zones. The temperature distribution in the high-pressure regenerative heat exchanger (HPRH1) together with its unit diagram from the Ebsilon program is shown in Fig. 3, and the temperature distribution for the low-pressure regenerative heat exchanger (LPRH4) is shown in Fig. 4. The temperature distribution applies to the EPR nuclear unit for the nominal system parameters (the pressure drop in the pipeline is equal to 5% of the pressure in the steam bleeding – according to Table 2) and pressure drops in the pipelines of 3% of the steam pressure in the steam bleeding.

Reducing the steam pressure drop in the pipeline supplying the high-pressure exchanger causes an increase in steam pressure and, at the same time, an increase in steam temperature at the inlet to the exchanger (the exchanger is supplied with wet steam). Higher steam temperature and greater steam mass flow cause more heat to be transferred in the exchanger, which results in an increase in water temperatures at the exchanger outlet.

Reducing the pressure drop in the steam pipeline supplying the regenerative high-pressure exchanger (HPRH1) from 5% to 3% causes an increase in the water temperature at the exchanger outlet by 1°C.

Reducing the pressure drop in the steam pipeline supplying the low-pressure exchanger (LPRH4) from 5% to 3% causes an increase in water temperature at the exchanger outlet by 0.7 C. This increase is mainly due to the increase in saturation temperature resulting from the higher steam pressure at the exchanger inlet.

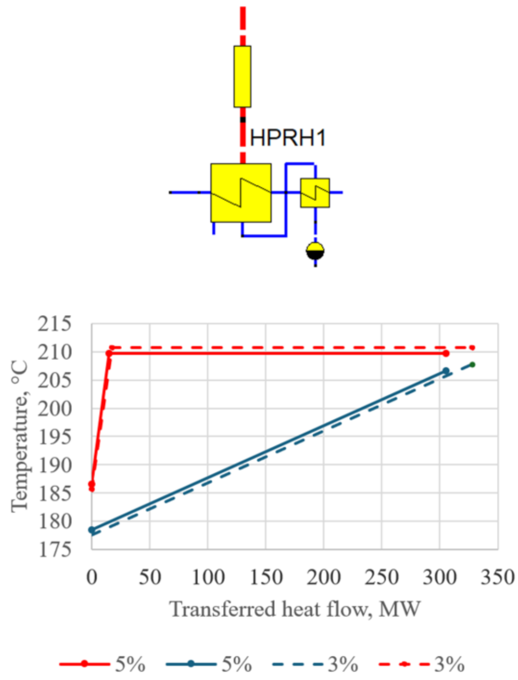

Fig. 3. Temperature distribution in the high-pressure regenerative heat exchanger (HPRH1) with its unit diagram from the Ebsilon program, for 5% and 3% pressure drop in the pipeline.

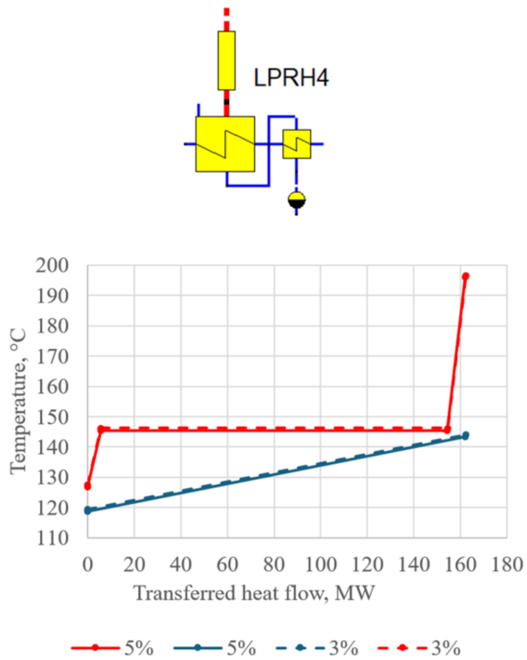

Fig. 4. Temperature distribution in the low-pressure regenerative heat exchanger (LPRH4) along with its unit diagram from the Ebsilon program, for 5% and 3% pressure drop in the pipeline.

5. Results

An analysis of the influence of changes in resistance in the pipelines connecting steam extractions with regenerative exchangers, for the EPR and AP1000 nuclear units, was carried out for two high-pressure regenerative heaters and two low-pressure regenerative heaters, as well as for the passage between the high-pressure and low-pressure turbine sections.

For the EPR nuclear unit, for the nominal gross power of the unit, the pressure drops in the pipelines for the analysed regenerative exchangers and in the passageway amount to 5% of the pressure value at the inlet (Table 2). The analysis was performed for reduced pressure drops to the levels of 4% and 3%, respectively. The results of calculations of the change in the unit power are presented in Table 5. Reducing pressure drops to 4% of the inlet pressure results in a power increase of 2.31 MW_{el} (0.65 MW_{el} results from the reduction of pressure drops in the pipelines to the exchangers and 1.66 MW_{el} results from the reduction of pressure drops in the passage). Reducing pressure drops to 3% of the inlet pressure results in a power increase of 4.58 MW_{el} (1.28 MW_{el} results from the reduction of pressure drops in the pipelines to the exchangers and 3.31 MW_{el} results from the reduction of pressure drops in the passage).

Table 5. Increase in the power of the EPR nuclear unit due to reduction of pressure drops in the pipelines to the regenerative exchangers and in the passage by 4% and 3%.

Heat exchanger	dp/p_T (%)	Power increase (MW_{el})	dp/p_T (%)	Power increase (MW_{el})
LPRH3	4	0.204	3	0.39
LPRH4	4		3	
HPRH1	4	0.446	3	0.89
HPRH2	4		3	
Exchangers in total		0.65		1.28
Passage	4	1.66	3	3.31
Unit in total		2.31		4.58

For the AP1000 nuclear unit, for the rated gross unit power, the pressure drops in the pipelines to the analysed regenerative exchangers and in the passage are 3% of the inlet pressure (Table 2). An analysis was made of how the change in pressure drops affects the unit power for pressure drops of 4% and 2%, respectively. The calculation results of the change in the unit power are presented in Table 6. For resistances of 4%, there is an increase in pressure drops compared to the basic variant, in which these drops were equal to 3%; therefore, in this case, we have a loss of electrical power of –1.63 MW_{el} (a power loss of –0.39 MW_{el} on the pipelines to the regenerative exchangers and a power loss of –1.24 MW_{el} in the passage). Reducing the pressure drops to 2% results in a power increase of 2.47 MW_{el} (a power increase of 0.51 MW_{el} resulting from the reduction of the pressure drops in the pipelines to the regenerative exchangers and a power increase of 1.97 MW_{el} resulting from the reduction of the pressure drop in the passage).

Table 6. Change in the power of the AP1000 nuclear unit due to changes in pressure drops in the pipelines to the regenerative exchangers and in the passage for 4% and 2%.

Heat exchanger	dp/p_T (%)	Power drop (MW_{el})	dp/p_T (%)	Power increase (MW_{el})
LPRH3	4	–0.13	2	0.16
LPRH4	4		2	
HPRH1	4	–0.26	2	0.34
HPRH2	4		2	
Exchangers in total		–0.39		0.51
Passage	4	–1.24	2	1.97
Unit in total		–1.63		2.47

6. Conclusions

In the EPR unit, reducing resistance from 5% to 3% in the pipelines supplying two low-pressure regenerative exchangers (LPRH3 and LPRH4) and two high-pressure regenerative exchangers (HPRH1 and HPRH2), and in the passage, gives a power increase of 4.58 MW_{el}, which is 0.266% of the nominal power. In the AP1000 unit, reducing resistance by 2% gives a power increase of 4.1 MW_{el}, which is 0.342% of the nominal power.

The greatest impact (for the pipelines analysed) on the power and efficiency of the whole unit is exerted by the flow resistance in the pipelines in the turbine passageway, less in the pipelines in the high-pressure regeneration and the least in the pipelines in the low-pressure regeneration. An increase in the power of the unit by 1 MW_{el} gives about 3.5 million PLN in revenue from the sale of additional electricity (assuming that the annual operating time of the unit is equal to 7 000 hours and the price of electricity is PLN 500/MWh). For a 4 MW_{el} unit, this profit amounts to about 14 million PLN. Therefore, a careful analysis of the influence of resistance in the live steam, interstage steam and regeneration system pipelines should be the subject of research and analysis. Among other things, it is necessary to take into account increasing the diameter of the pipelines and shortening their length, especially for high-pressure regeneration. These suggestions can be taken into account for newly designed PWR-type nuclear power plants, including those envisioned for implementation in Poland.

The flow resistance from the outlet of the steam generators to the inlet to the high-pressure section of the turbine can still be analysed, with special attention paid to pressure drops on valves upstream of the high-pressure part of the steam turbine. To be able to assess the possibility of reducing pressure drops along this section, one needs to know the geometry of the pipelines (pipeline diameters and lengths), the geometry of elbows, the characteristics of valves, and pressure drops at the stop and control valves. The authors of the paper do not currently have access to such detailed data. If such data can be obtained, the analysis will be continued in the near future.

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