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Super powerful steam superheaters and turbines for hybrid nuclear power plants[☆]

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Abstract

The paper deals with the problem of the passage to hybrid nuclear power plants at the expense of outer steam superheating after nuclear steam-generating plant up to temperature equals to 600°C. For the practical realization of such power unit it's required to construct new super powerful steam superheater and new high temperature steam turbine with power capacity equals to 1,700–2,000 MW. The fundamental solutions of these difficult technical problems are considered in the paper.

Keywords: hybrid nuclear power plant, outer steam superheater, superpowerful steam turbine, two tier stage, two tier low pressure cylinder

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1. Introduction

The series of events at the nuclear power plant (NPP) in Fukushima, Japan have cast a pall of doubt and anxiety over the future of nuclear power. Remarkably, Germany swiftly took the decision to go non-nuclear as fast as is practicably possible.

The German approach to nuclear power is part of a wider trend internationally to consider decommissioning all NPPs. Set against this backdrop, the construction of new NPPs will meet social resistance in the decade ahead, almost inevitably restricting the number of plants built. This will add pressure to an already challenging technical environment, as more electricity will have to be squeezed from a limited number of assets to cope with the looming energy gap which, in turn, is the ineluctable result of the general political stasis in the developed world as regards the renewal and replacement of power stations.

A smart response to the political and economic pressures would be to re-engineer currently operational reactors to produce extra output. One way of doing this is to develop hybrid nuclear power plants.

The essence of a hybrid NPP is to use a fossil fuel to superheat wet steam, after the steam-generating plant, in an outer steam superheater. Steam superheating leads to both increased turbine enthalpy drop and increased mass flow due to removal of the separator.

The outer steam superheating application allows to increase the power capacity of NPP in two times.

It is precisely this concept we would like to expand

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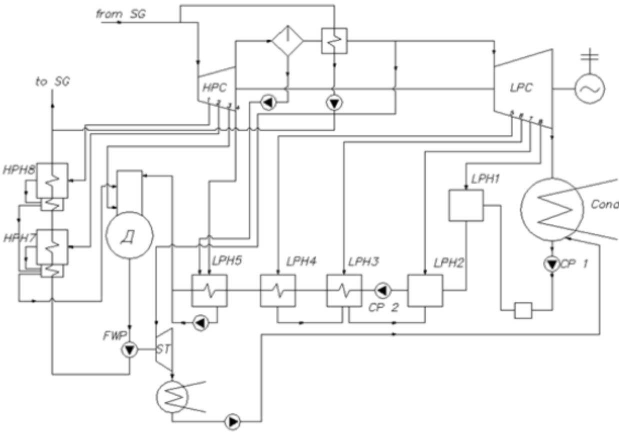

Figure 1: Conventional nuclear power plant turbo-installation thermal diagram

on in detail.

2. Characteristics of the standard turbo-installation with power capacity 1,000 MW

As a framework for further investigation, the thermal diagram of a turbo-installation with a K-1000-5.9/50 steam turbine was chosen – see Fig. 1.

Saturated steam at pressure $p = 5.9$ MPa enters a double-flow high pressure cylinder (HPC) where it expands. The steam pressure and humidity after the HPC are 0.58 MPa and 14.4% respectively. Steam with these parameters goes through 4 separator-superheaters (SS), where moisture is separated and the steam is superheated by live steam flow up to a temperature of 250°C. Steam pressure after the separator-superheater is 0.51 MPa. SS steam then enters 4 double flow low pressure cylinders (LPC). The cylinders are integrated by pairs, in two groups: 1–2 and 3–4. The steam leaves the cylinder groups for two condensers where cooling water serially goes though their tubes. Due to the connecting configuration, the pressure in the first condenser is 4.3 kPa but 5.5 kPa in the second one.

After the condensers, the condensate is pumped by first stage condensate pumps through the condensate purification plant, low pressure heater 1 (LPH 1) and enters the direct-contact LPH 2. Second stage condensate pumps pump the condensate though surface heaters LPH 3,4,5 and the de-aerator.

Table 1: General properties of turboinstallation K-1000-5.9/50

Electric power N_e, MW	1,000
Live steam mass flow G_0 ,kg/s	1,631
Average pressure in the condenser, p_c , kPa	4.9
Feed water temperature, t_{fw}, °C	220
HPC internal relative efficiency, η_{oi}^{HPC}, %	83
LPC internal relative efficiency, η_{oi}^{LPC}, %	82
Heat rate, q, kJ/kW/h	10,390
Turbo-installation electrical efficiency, η_e	0.3466

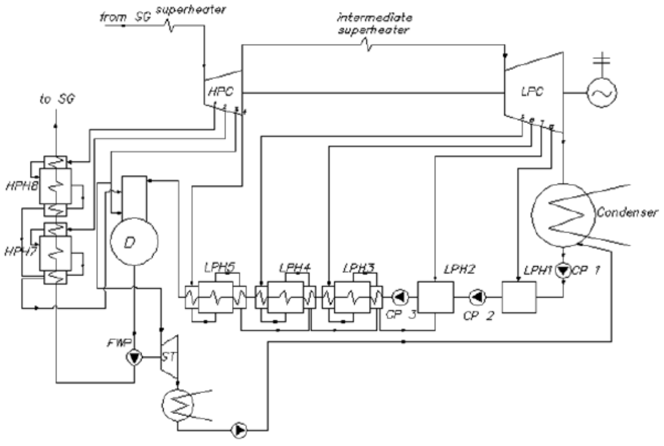

Figure 2: Nuclear power plant turbo-installation thermal diagram with initial temperature 600°C and intermediate superheating temperature 620°C

After the de-aerator the feed water is pumped by two feed pumps with a steam turbine drive through high pressure heaters (HPH) 6 and 7 and enters the steam generator of the nuclear steam-generating plant.

In the process of the thermal diagram calculation it should be taken into account that the condensate from the separator enters LPH 5 and the condensate of the heating steam after the steam to steam superheater is pumped to the feed water line before the steam generator.

Primary characteristics of the standard turbo-installation are presented in Table 1 [1].

3. Thermal diagram of an NPP with outer steam superheating up to 600°C

This diagram (see Fig. 2) differs from the standard turbo-installation thermal diagram in that the wet steam, after the nuclear steam-generating plant, goes through an outer superheater where its temperature increases from 274°C to 600°C and it is at this temperature that the steam enters the high pressure

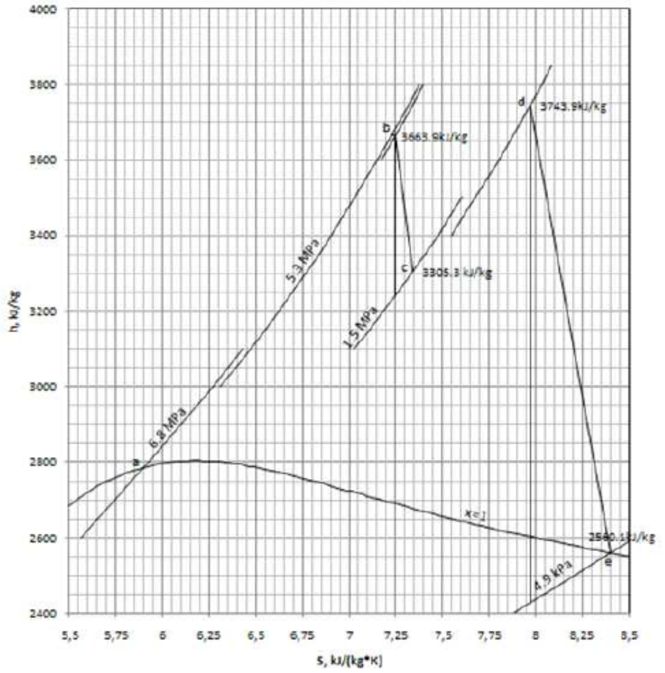

Figure 3: Process of steam expansion in a turbine with initial temperature 600°C and intermediate superheating temperature 620°C

cylinder of the steam turbine. In this case of superheating, the separator-superheater becomes unnecessary and is removed from the thermal scheme. Cutting out the separator leads to a mass flow increase though the turbine low pressure cylinder of 42% [1].

The steam turbine drive of the feed pump steam supply is realized from the steam extraction line for the de-aerator. Steam, after the high pressure cylinder, goes to the boiler-superheater for reheating and its temperature rises to 620°C. At this temperature it enters the low pressure cylinder.

As a result of initial steam temperature rising to 620°C before the LPC, the expansion process takes place in an environment of superheated steam. This fact removes the losses due to steam wetness and eliminates LPC blade erosion wear too. Fig. 3 illustrates the process of steam expansion in the turbine with initial steam temperature of 600C and intermediate steam superheating up to 620°C.

Point a on the chart corresponds to the steam thermodynamic state after the nuclear steam-generating plant. Line a-b defines the superheating process in the outer steam superheater and b-c is a representation of steam expansion in the HPC. The steam thermodynamic state after intermediate superheating is depicted by point d. Line d-e is the graphical description of the steam expansion process in the LPC.

Table 2: General properties of turboinstallation K-2050-5.3/50

Electric power N_e, MW	2,050
Live steam mass flow G_0, kg/s	1,631
Average pressure in the condenser p_c , kPa	4.9
Feed water temperature t_{fw}, °C	220
HPC internal relative efficiency, η_{oi}^{HPC},%	88
LPC internal relative efficiency, η_{oi}^{LPC},%	88
Heat rate, q, kJ/kW/h	8,706
Turbo-installation electrical efficiency, η_e,%	41.4

Adoption of the new steam conditions and thermal diagram allows one to considerably increase the equivalent enthalpy drop and to increase steam mass flow through the LPC by 42%. Therefore, steam turbine power capacity increased to 2,050 MW and turbo-installation electrical efficiency rose to 41.35%.

It should be noted that the utilization factor of the fossil fuel combustion heat used for the generation of the additional 1,050 MW is 51%. The main characteristics of the new turbo-installation are presented in Table 2.

The outer steam superheater with an extremely large steam mass flow of 1,630 kg/s and a new super powerful steam turbine with power capacity of 2,050 MW are brand new elements of the installation under consideration.

These newer elements deserve closer inspection.

4. Superheater for the NPP with outer steam superheating

At present, an outer steam superheater application fired by fossil fuel is the most feasible way to superheat large mass flows of wet steam.

The practicalities of this method are grounded in extensive Russian experience in super powerful power-boiler design and the construction of boiler plants.

Worthy of particular mention is serial boiler TGMP-204 of the Taganrog Boiler-Making Works Krasny Kotelschik with steam capacity 2,650 t/h.

The steam at the boiler outlet has a temperature of 545°C and pressure of 25 MPa.

The following associated issues were resolved during the design process:

1. Ensuring high reliability;
2. Ensuring low hydraulic resistance;
3. Achieving high efficiency;
4. Complying with environmental requirements.

It is necessary to use heat-resistant steel for some heat transfer surfaces due to the high steam temperature (600°C). Accordingly, for the exit section of the superheater EI695R steel is used and the platen superheater is made of 1H12W2MF steel. H18N12T steel is used for the lower part of the radiant section tubes. Notably, unconventional boiler steels are used in the new superheater. It is planned that the prototype of the outer superheater will be equipped with a large number of temperature probes to: check the thermal behavior of the heat exchanger tubes and enable corrective action to ensure that the superheater operates reliably.

The second aim is to achieve a hydraulic resistance limitation of 1 MPa in the primary steam superheater. It is a complicated question due to the very large steam mass flow, and one solution that cuts hydraulic resistance is associated with a reliability problem. For this problem wider diameter tubes (60/54 mm) with low absolute roughness k of 0.01 mm were used. In addition, in order to reduce hydraulic resistance for the purposes of ensuring boiler reliability, the working medium passed over the heat exchanging surfaces in one go, as opposed to conventional power boilers where the working medium goes through the high-beat areas of the heat transfer surface in several passes so as to increase mass velocity. Compensation for the negative impact of this decision on reliability is achieved at the expense of heat-resistant steel.

The superheater attains thermal efficiency of 95.4% through the use of natural gas as a fuel and the use of a regenerative air-heater with waste gases at a temperature of 120°C. The temperature of the waste gases level prevent corrosion of the air-heater. The use of an effective set of technologies and construction decisions aimed at fulfillment of environmental requirements also promote superheater efficiency.

As regards natural gas combustion, the main toxic components are nitrogen oxide and dioxide (NO and NO_2). Superheater ecological efficiency is defined by the total concentration of NO (C_{NO_x}) which must not exceed the regulatory value: $C_{NO_x} \leq C_{NO_x}^{reg.\,value}$.

Under Russian Federation eco-standards [2] NO_x concentration in dry waste gases at normal conditions and standard excess air coefficient of α_{waste} = 1.4 must not exceed 125 mg/m for boilers of the steam capacity more than 1,000 t/h. In the boiler-superheater design staged combustion, in a system with waste gas recycling and a TKZ-VTI low-emission burner, was used for environmental purposes. In the TKZ-VTI burner shielding entering of recycling gases through the special ducts uses with requirement recycling rate equal to 6–7% at nominal load. The placing of burners in the boiler-superheater should be considered with respect to resolving environmental and reliability issues. Burners are placed in 3 tiers of 6 burners each on the front and rear walls in the low radiation area. The gas flow through each burner is 5.91 m/h. The layout of the 36 burners disperses the zone of intensive combustion, which increases the reliability of the furnace waterwall operation and reduces the formation of toxic substances. The operational experience of powerful power boilers shows that use of the aforementioned technologies and construction decisions delivers NO_x concentrations in waste gases in the region of 110 mg/m [3, 4]. Importantly, the technologies cost considerably less than flue gas denitrification equipment.

The new boiler-superheater has the following characteristics:

- Mass flow of primary steam: 1630 kg/s
- Steam pressure at the inlet: 6.8 MPa
- Steam pressure at the outlet: 5.8 MPa
- Steam temperature at the inlet: 274°C
- Steam pressure at the outlet: 600°C
- Mass flow of secondary steam: 1,450 kg/s
- Secondary steam temperature at the inlet: 420°C

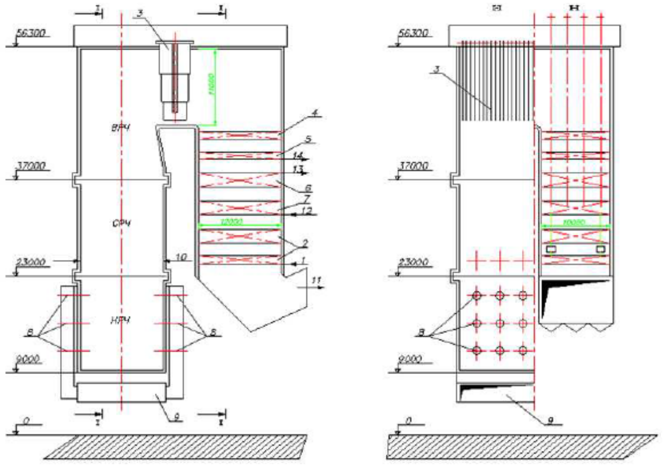

Figure 4: Boiler-superheater for the hybrid nuclear power plant. 1-wet steam inlet, 2-first stage of high pressure(HP) superheater, 3-platen superheater, 4-second stage of HP superheater, 5-third stage of the HP superheater, 6-first stage of the low pressure(LP) superheater, 7-second stage of the LP superheater, 8-burners, 9-hot air duct, 10-secondary air nozzles, 11-waste gases, 12-secondary steam inlet, 13-secondary steam outlet, 14-primary steam outlet

- Secondary steam temperature at the outlet: 620°C
- Fuel heat capacity: 36,300 kJ/m
- Fuel consumption: 59.1 m/s
- Efficiency: 95.4%

The boiler-superheater design was made on the basis of thermal, aerodynamic and construction calculations, see Fig. 4.

The superheater is a U-shaped direct flow boiler where superheated steam flows over all heat exchange surfaces, including waterwall surfaces.

The overall size of the superheater is close to the overall size of the TGMP-204 series power boiler.

5. K-2050-5.3/50 steam turbine for a hybrid NPP

The super powerful steam turbine for NPP with out-of-reactor superheating of steam is a tandem unit with one high pressure cylinder and four low pressure cylinders (Fig. 5).

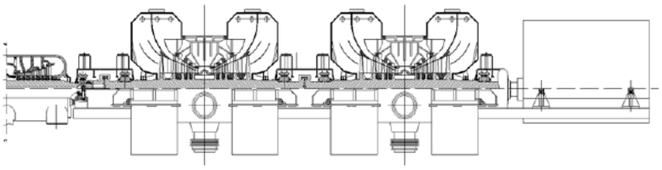

Figure 5: Longitudinal cross-section of a super powerful steam turbine for a hybrid NPP

The live steam parameters before the turbine (pressure p and temperature t), taking into account the loss of pressure in the external superheater were assumed as $p = 5.3$ MPa, $t = 600°\mathrm{C}$. Steam flow G corresponds to the productivity of reactor WWER-1000 and is $G = 1631$ kg/s. The pressure in the condenser is the same as in the existing K-1000-5.9/50 turbine and is taken to equal $p = 4.9$ kPa.

The turbine has throttling steam distribution. Live steam comes by four steam pipelines to four stop-control valves. The outlet steam pipelines, after the valves unit, are connected by pairs to two steam pipelines, ensuring steam supply to the flow part of the turbine.

The high pressure cylinder is designed as two-flow, with nine stages in each flow. Since its volume rates increase during superheating the steam from 274°C to 600°C, the lengths of blades of the first stages l happen to be rather big – 82 mm. When steam expands in the flow part of HPC from 5.3 MPa to 1.5 MPa the lengths of blades rise practically linearly. The lengths of moving blades of the last stage of HPC is 630 mm at average diameter $D = 1.3$ m. The length of rotor between bearings is 10,088 mm.

After HPC, as in the case of the standard K-1000-5.9/50 turbine produced by LMZ, steam comes by two pipelines to four LPCs, located in pairs, on both sides of HPC.

The main character of the new LPC is that its flow part is made as two-level, based on the above described two-tier stage.

Thus, the flow part of the new HPC matches two separate turbines with independent blades units designed for the same live and final steam parameters. In the lower level 6 stages are located and the blade length of the last stage is $l = 1,200$ mm. The upper level turbine is comprised of 4 stages. The blade lengths of the last stage of this turbine are 430 mm in the upper tier and 770 mm in the lower tier.

The total length of each LPC between the end

Table 3: Technical parameters of K-1000-5.9/50 (LMZ) and K-2050-5.3/50 turbines

Parameter		K-1000-5.9/50	K-2050-5.3/50
Nominal power, MW		1074	2050
Rotational speed, 1/s		50	50
Live steam parameters	pressure, MPa	5.9	5.3
	temperature, °C	274	600
Steam parameters after reheater	pressure, MPa	0.51	1.3
	temperature, °C	260	620
Number of steam intake for regeneration		8	8
Feed water temperature, °C		218	220
Nominal temperature of cooling water, °C		20	20
Pressure in the condenser, kPa		4.9	4.9
Number of stages	HPC	2×5	2×9
	LPC	2×5	2×6
Number of steam exhaust		8	8
Live steam flow, kg/s		1,631	1,631
Steam flow into condenser, kg/s		972.4	1,156
Length of moving blade of the last stage, mm		1,200	1,200
Middle diameter of the last stage, m		2.8	2.9
Length of turbine, m		51.6	56.2
Internal relative efficiency of LPC, %		84.4	84.1
Relative mass of turbine, kg/kW		2.4	1.6
Number of generators		1	1

walls of the flanges is 10,400 mm.

The technical parameters of the new K-2050-5.3/50 turbine and standard K-1000-5.9/50 turbine of LMZ is shown in Table 3.

The comparative results of the 2 turbines, given in Table 3, show that the new turbine for a hybrid NPP with external steam superheating, while it doubles the increase in power compared with the standard K-1000-5.9/50 turbine of LMZ has notably lower metal consumption at practically the same internal relative efficiency.

When estimating the internal relative efficiency of the two-tier LPC of the new turbine for NPP with an external superheater, it is necessary to bear in mind that all stages of this LPC work in an environment of superheated steam and, hence, in contrast to the LPC of the standard K-1000-5.9/50 turbine LMZ losses due to humidity are absent.

As a result, the relative internal efficiency of the two-tier cylinder is 89%, and oi for LPC of the standard K-1000-5.9/50 LMZ turbine appears to be 2% lower. However, the specified values of efficiency are received regardless of any steam overflow to regenerative heaters. These selections reduce the efficiency of the standard cylinder by approximately 2.6%, and by almost 5% in respect of the two-tier LPC, since the relative influence of regenerative overflow on the efficiency of the top tier appears to be higher due to the smaller absolute flow of steam through this part of the LPC. Accordingly, η_{oi}= 84.4% for the LPC of the K-1000-5.9/50 turbine, and η_{oi}= 84.1% for the two-tier LPC of the new turbine.

The increase of turbine length by approximately 4.8 m is due to the essential rise of stages number in the high pressure cylinder.

6. Conclusions

1. The calculation of the NPP thermal diagram showed that super heating the outer steam up to 600°C relative to the nuclear steam-generation plant enables an increase in the power capac-

ity of the plant working with a WWER-1000 nuclear reactor from 1,000 MW to 2,050 MW alongside an efficiency increase of 8%.

2. The additional power capacity (1,050 MW) is generated at the hybrid NPP with an efficiency rate of 51%, comparable with the efficiency level of combined cycle plants.
3. The designed outer steam superheater enables an increase in steam temperature from 274°C to 600°C. Superheater steam capacity is 1,631 kg/s and its efficiency is 95.4%.
4. The overall size of the superheater is comparable with the overall size of the TGMP-204 boiler with steam capacity 2,650 t/h.
5. The designed superpower steam turbine for a hybrid NPP enables power generation of 2,000 MW in only one turbo-installation.
6. In terms of size, the new super powerful turbine differs little from the standard K-1000-5.9/50 LMZ turbine and may be deployed in the existing turbine building during reconstruction works.
7. Capital costs connected with the changeover to a hybrid NPP do not exceed the capital costs for construction of a new combined cycle power plant with the same power capacity (1,050 MW). In terms of time, changeover to a hybrid NPP is comparable with the construction of a new powerful CCPP.

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