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Nuclear Power Plants with Super-Powerful High-Temperature Steam Turbine

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Abstract

This paper describes the possibility of creation of 2200 MW turbine for hybrid Nuclear Power Plant (NPP) with external (as to reactor) steam superheating on the base of existing VVER-1000 reactor.
We come with a number of useful outcomes and suggestions for the blueprint of the super-powerful high-temperature steam turbines that might be used in power industry and for increasing the effectiveness of the new turbines produced by the turbine-constructing companies.

Keywords: super-powerful turbines, high-temperature steam turbine, nuclear power plant, nuclear reactor

1 Introduction

The intention develop the efficient super-powerful turbines has long became the priority for all relevant turbine constructing companies in the world. At the same time, the increase of the power of single shaft high-speed turbine up to 1500-1800 MW leads to the problem of accomplishing the last stages of the production of condensing turbine with the blade length of 1500 mm. The prospects for the creation of the blade with these parameters are not obvious, since the problem of its reliability should be solved first. All these make it extremely difficult to ensure the efficiency of the production process at this stage due to the large stitch between the blades at the peripheral section [2, 6, and 16].

At the same time, it can be shown that this problem might be solved even at the existing lengths of the moving blades if one manages to ensure the outlet of steam into condenser passing by the last stage of the Low Pressure Cylinder (LPC).

Such a decision was proposed for the first time by Baumann in 1916 [1]. It was employed in the turbine K-200-130 of LMZ in 1958 with success. Nevertheless, the efficiency of LPC in this case visibly drops, so the Baumann stages were not used any more in the consequent turbines [2, 4].

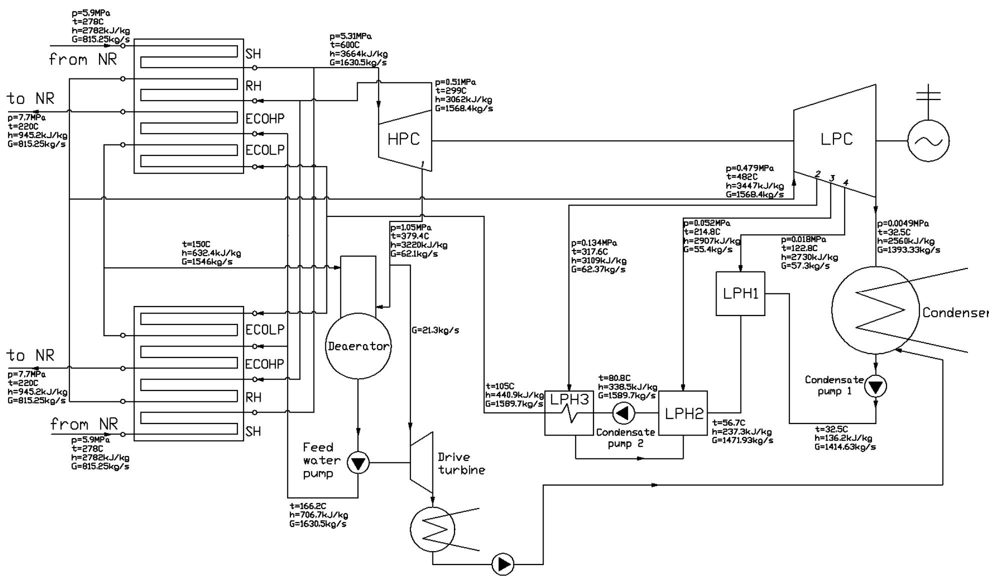
One interesting solution of how to increase the throughput capacity of LPC is presented in two works of Nishnevich et al. and Zaryankin et al. who suggest to using the Baumann like multi-tier turbine [8, 16]. However, due to certain drawbacks this solution has not been implemented in practice [8], even though the idea of the two-level cylinder seems to be rather perspective and is further investigated with regard to the super-powerful turbine for hybrid NPP with VVER-1000 reactor.

2 Thermal balance of hybrid NPP

One of the possible ways how to increase the power of NPP is to use the hybrid units in which the steam that comes out of nuclear reactor (NR) is directed to the external (as to nuclear reactor) superheater that uses the organic fuel energy [5, 11, 13].

If this solution is adopted, not only the drop of enthalpy increases, but also when steam is superheated up to the limiting value of live steam temperatures for modern steam turbine that is equal to 600°C and further reheater of steam up to 480°C, the work of turbine in the area of wet steam might not be necessary [7]. Thus, it is not necessary to use moisture separator-reheaters. The flow diagram of the unit of such hybrid NPP is shown in Figure 1 that follows.

Figure 1: Flow diagram of hybrid NPP with external (as to reactor) steam superheating by the heat of organic fuel combustion



Source: Own results

In this case, the steam after a NR is brought to the two parallel steam superheaters containing four contours (steam super heater (SH), steam reheater (RH), low pressure economizer (LPECO), and a high pressure economizer (HPECO)). In the first contour SH steam, the temperature raises from 278°C up to 600°C and at this temperature steam is coming to the high pressure cylinder (HPC). After the HPC, the steam is coming to the second contour RH of steam superheater where its temperature increases from 299°C to 480°C. Further along the line, the steam goes to LPC after which it is being condensed in the condenser.

Initial heating of condensate to the temperature that equals to 105°C is carried out in three low pressure heaters (LPH) that use the temperature of bled steam from LPH. At this specified temperature the condensate is coming to LPECO of steam superheater, where it is heated up to 150°C and is coming back to deaerator where bled steam from HPC is brought at the pressure of 0,7 MPa and the temperature of 379.4°C. After deaerator, a feedwater passing through a HPECO of steam superheater goes by the feeding pump to a NR at the temperature of 220°C. The accompanying natural gas flow necessary for the external (as to reactor) steam superheating is B_T=55 kg/s [5].

The introduction of the superheater into the flow diagram of the NPP does not bring essential changes to the instruction on its start-up. Here, the main role is played by the high-speed reduction units (HSRU) through which the live steam from steam collectors of a nuclear reactor and the superheater are dumped into the condenser apart from the steam turbine.

In order to protect the superheater surfaces from superheating, the steam after NR proceeds to the first contour of superheater and is further dumped through the high-speed reduction cooling unit (HSRCU) into an inlet line of the reheater which protects its pipes from superheating. The part of the steam from an outlet line of reheater comes into HPC, carrying out its warmth while the residue of steam through HSRU is dumped into the main condenser.

In comparison with the initial flow diagram, the considered diagram does not contain moisture separator-reheater and high pressure heaters, but is complemented by the two external superheaters that use the warmth of natural gas combustion for superheating of the steam. The use of parallel superheaters allows accomplishing their preventive maintenance and repairing without having to shut down the unit, which considerably raises the reliability of hybrid NPP operation.

The basic results of the flow diagram calculations are shown in Table 1 (the parameters of steam and its flow in characteristic points are specified in Figure 1).

As a result of the changes in the initial flow diagram, the steam flow through the last stage of turbine is going to increase by 41% in comparison with the base flow diagram. Moreover, it is necessary either to increase the quantity of the LPC or the length of the blades at the last stages of LPC in order to let it pass. In this case, traditional solutions that include the increase in the number of LPC are cumbersome due to several reasons [2]. For instance, in order to pass additional 41 % of the steam flow, it is necessary to add about 2 new LPC. However, even in this case, the length of shaft of K-1000-60 turbines reaches 63 m and its further increase that takes into account the generator creates an almost impossible puzzle of how to ensure vibration reliability of the rotor. The transition to the two-shaft turbine solves this problem, but at the cost of high additional expenses. Furthermore, the lengths of high-speed K-1000-60- type turbine blades of LMZ reaches 1200 mm and its further increase (as it has been already mentioned), cannot lead to the plausible solution of the problem.

Table 1: Technical parameters of hybrid NPP

No.	Name of the magnitude	Dimension	Magnitude
1	Steam flow after the reactor	kg/s	1630.5
2	Steam flow at low pressure heaters (LPH): LPH 1 LPH 2 LPH 3	kg/s	 57.30 55.40 62.37
3	Steam flow for the drive of the feed water pump	kg/s	21.3
4	Steam flow in LPC	kg/s	1568.4
5	Steam flow through condenser	kg/s	1393.33
6	Live steam temperature	°C	600
7	Steam temperature before LPC	°C	480
8	Power of the feed water pump	MW	16.03
9	Feed water temperature after high pressure economizer	°C	220
10	NPP unit efficiency (gross efficiency)	%	44.25
11	Electrical power of the NPP	MW	2196
12	Heat rate	kJ/kW•hr	8134
13	Existing drop of enthalpy for turbine	kJ/kg	1489

Source: own results

Thereupon, it is expedient to consider the solution providing transition to one-and-a-half exhaust flow on the basis of a Baumann stage. Unfortunately, the well-known multi-level Baumann stages have some serious drawbacks. Some of them have low reliability, are difficult to manufacture, exhibit low efficiency due to the high steam leakages between the levels, demonstrate high turbulence in the flow in the area of dividing shelves, and also yield high additional losses in large axial clearance between the Baumann stage and the last turbine stage. Moreover, in case only one Baumann stage in the flow part of LPC in its upper store is used, the drop of enthalpy equivalent to the drop of enthalpy in two stages of the lower tier is observed. As a result, this group of blades works at lower (in comparison to the optimal) values of the main cinematic parameter u/c_{eq}, where u is circumferential speed and c_{eq} is the speed equivalent to the existing drop of enthalpy for the above-mentioned stage.

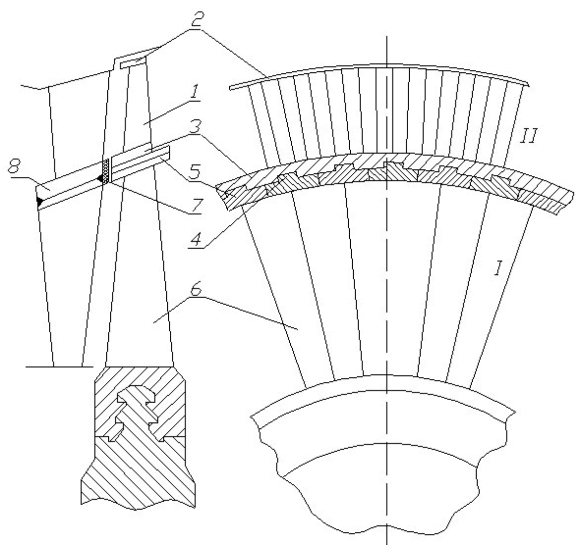
This drawback might be removed by the changes in design of the whole flow part made as two-tier Baumann stages [6, 8]. However, even if this is done, other drawbacks remain. They might be removed or essentially decreased if the upper stores would be designed separately from the blades group of the lower tier [10]. When forming the flow part of upper tier of LPC above the turbine of the lower tier, the multi-level turbine of upper tier should be designed for the same live and final steam parameters as a turbine of lower tier.

3 New two-tier axial stage of condensing steam turbine

In the new two-tier stage (as shown in the Figure 2) the blades assembly of upper level II is made as a separate stage. The moving blades are situated between the rings 2 and 3 and the inner ring is made solid with the longitudinal grooves 4 at the inner surface. The longitudinal lugs enter these grooves of the integral bandage 5 of the moving blades 6 of the lower level I.

In this case, the dismountable connection of upper and lower levels is made, which does not load the blades 6 of the working wheel of lower tier by the additional centrifugal forces, but only transfers them through the lugs at integral bandage the torsional moment produced by the ring blades group of the working wheel of upper level. In fact, the stage of lower level becomes the carrier element for the stage of the upper level

Figure 2: New two-tier stage



Source: Own result

The results of our calculations of durability demonstrate that the most intense element of our design is the ring 3, and that at the circumferential speed exceeding 400 m/s it is impossible to use considered demountable connection of the top tier of a stage with the bottom one.

In accordance with the above, the last two-tier stage of the two-level LPC should have one-piece connection of the top level with the bottom one as it is shown in Figure 2. In this case, the part of the forces from contour 3 is absorbed by the bottom tier blades and the level of both radial and tangential pressure decreases to the values providing durability safety which are equal to 1,65 from a fluidity limit of blade steel.

It should be noted that the durability limit (safety factor) can be essentially raised if the top tier of a considered stage is made from the titan. The technological problem inevitably appears when manufacturing of the driving wheel of the top tier at the creation of a two-tier stage is considered [16].

We suggest two alternatives of the solution for this problem: according to the first alternative, it is supposed to execute the top tier blades together with segments of a ring 3 with the subsequent welding of these segments in a continuous ring 3. In the second alternative, the manufacturing of working two-tier stage blades is done similar to the Baumann stage blades, but on the outer side of the partition separating the blades of bottom tier from the upper one not just one but two blades with smaller chords and smaller steps are considered.

When estimating the dynamic reliability of the offered solution, it is necessary to keep in mind that the presence of additional links (especially in the case with rigid connection of the upper and bottom tiers), and also the presence of a great number of short blades in the upper tier lead to the essential increase in rigidity and frequency of blades of both circles.

Naturally, all mentioned issues demand a further detailed study. Nevertheless, even tentative estimations show the possibility of the creation of a two-tier stage already at the existing technological level.

In order to decrease the overflow of steam between upper and lower tiers the degree of reactiveness in the root area of blades in the upper tier is taken, so that the drop of pressure at both sides of separation wall remains minimal [15, 11].

We run the calculations of a flow part of two-tier LPC with the aim to decrease losses of an overflowing of steam between tiers the variation of reactance degree of the stages of the top and bottom tiers, so that on the one hand differences of pressure in the area of axial clearances between tiers to the minimum are lowered, and on the other hand, the blade efficiency of the stage is kept at the high level.

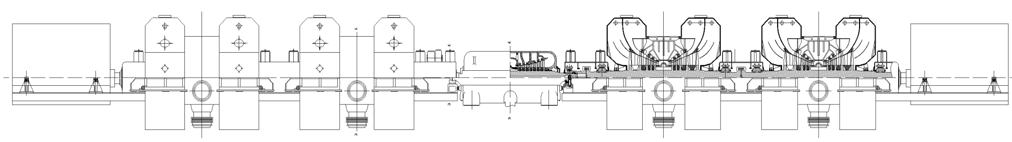
Moreover, in this case all overflows of steam between tiers at first three stages of the upper tier are partially used for power generation, and their decrease is also promoted by the sealing of 7, placed on a partition of nozzle device 8. The connection of the nozzle units of upper and lower levels with each other may be both detachable and non-detachable.

4 Steam turbine for hybrid K-2200-60-3000 NPP

Super-powerful steam turbine for NPP with external (as to reactor) superheating of steam is a tandem unit with one high pressure cylinder and four low pressure cylinders (Figure 3). The live steam parameters before turbine (pressure p_0 and temperature t_0) taking into account the loss of pressure in the external superheater are equal to p_0=5.31 MPa, t_0=600°C. Steam flow G corresponds to the productivity of reactor VVER-1000 and is equal to G=1630.5 kg/s. The pressure in the condenser is the same as in the existing K-1000-60-3000 turbine which is equal to p_k=4.9 kPa.

The turbine has throttling steam distribution. Live steam by four steam pipelines comes to the four stop-control valves. The outlet steam pipelines after valves unit are connected by pairs to two steam pipelines, ensuring steam supply to the flow part of turbine [12, 17].

Figure 3: The longitudinal cross-section of super powerful steam turbine for hybrid NPP with external steam superheating by the heat of organic fuel combustion



Source: Own results

The high pressure cylinder is manufactured as the two-flow unit with nine stages in each flow. Due to the fact that during steam superheating from 278°C up to 600°C its volume rates increase, the lengths of blades of the first stages l_1 happen to be rather big (82 mm). When steam expands in the flow part of HPC from 5.31 MPa to 0.51 MPa, the lengths of blades raise practically linearly. The lengths of moving blades at the last stage of HPC is 630 mm at the average diameter D_9=1.3m. The length of rotor between bearings is 10088 mm.

After HPC, the steam by two pipelines, which is the same as in base turbine K-1000-60-3000 produced by LMZ, comes to four LPC located in pairs from both sides of HPC. The main character of new LPC is that its flow part is made as two-level on the base of the above described two-tier stage. Thus, the flow part of new HPC is the match of 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 length of blades of the last stage is l_z =1145 mm. The turbine of upper level undergoes 4 stages. The length of blades of the last stage of this turbine is 430 mm in the upper tier and 715 mm in the bottom tier. The cylinder has 3 regenerative steam bleedings made from the flow part of upper level.

As a result, if the steam flow through turbine of lower level along the flow part does not change and if it is equal to 102.4 kg/s, then having the steam flow through the first stage of upper level being equal to 90.6 kg/s, only 68.7 kg/s is coming to the condenser. Thus, the monoblock rotor of LPC is based on the external bearings.

The exhaust pipes of all LPC that make the steam bleeding from the last stages of turbine to the condenser are made symmetrical and have the developed diffuser system, ensuring partial reestablishment of the flow kinetic energy that flows from the blades of turbine into potential energy [18]. The length of each LPC between end walls of flanges is 10400 mm. The technical parameters of the new K-2200-60-3000 turbine designed by MPEI-ENTEK and base turbine K-1000-60-3000 of LMZ are shown in Table 2.

The results of our comparison of both turbines are provided in Table 2. They show that the new turbine for hybrid NPP with external steam superheating while ensuring the double increase of power compared to K-1000-60-3000 turbine of LMZ has essentially lower metal consumption at practically the same internal relative efficiency.

Table 2: Technical parameters of K-1000-60-3000 (LMZ) and K-2200-60-3000 (MEI-ENTEK) turbines

No	Parameter	Turbine	
		К-1000-60-3000	**К-2200-60-3000**
1	Nominal power, MW	1074	2196
2	Rotational speed, 1/s	50	50
3	Live steam parameters: Pressure, MPa Temperature, °C	 5.88 274.3	 5.31 600
4	Steam parameters after reheater: Pressure, MPa Temperature, °C	 0.51 260	 0.479 482
5	Number of steam intake for regeneration	8	4
6	Feed water temperature, °C	218	220
7	Nominal temperature of cooling water, °C	20	20
8	Pressure in the condenser, kPa	4.9	4.9
9	Number of stages: HPC LPC	 2x5 2x5	 2x9 2x6
10	Number of steam exhaust	8	8
11	Live steam flow, kg/s	1630.5	1630.5
12	Steam flow into condenser, kg/s	822	1393.33
13	Length of moving blade of the last stage, mm	1200	1150
14	Middle diameter of the last stage, m	2.8	2.9
15	Length of turbine, m	51.6	56.2
16	Internal relative efficiency of LPC, %	84.4	84.1
17	Relative mass of turbine, kg/kW	2.4	~1.6
18	Number of generators	1	2

Source: Own results

When running the estimations of the internal relative efficiency of two-tier LPC of the new turbine for NPP with an external superheater, it is necessary to keep in mind that all stages of this LPC work in the zone of superheated steam and, hence, in comparison with LPC of standard K-1000-60 turbine LMZ losses due to the humidity are absent (at the existing turbine K-1000-60 LMZ factor of losses due to the humidity ζ_m at the third stage is 0.8 %, at the fourth – ζ_m =4,1 % and at the fifth – ζ_m =8,8 %).

However, in two-tier LPC there are additional losses stemming from the overflow of steam between top and bottom tiers. In this case, the overflow of steam from first two stages of the top tier to the bottom tier takes place, and from the fourth and fifth stages of the bottom tier there is a steam leakage to the upper tier.

Thus, the efficiency of the first two stages of the top tier decreases by ζ_l=5,5 % and ζ_l=4,1 %, and the efficiency of last two stages slightly increases. Additional inflow of steam from the top tier raises the efficiency of the bottom tier, since the total inflow of steam from the top circle reaches 6 kg/s, and the leak of steam from the fourth and fifth stages of the bottom tier does not exceed 2.2 kg/s.

As a result, the relative internal efficiency η_{oi} of the two-tier cylinder is 89 %, and ηoi for LPC of K-1000-60 LMZ turbine appears to be 2 % lower. However, the specified values of the efficiency are measured regardless of the steam overflow to regenerative heaters. These selections reduce efficiency of the standard cylinder approximately by 2.6 % and almost by 5 % from the efficiency of two-tier LPC, since 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 LPC. Similar to that, for LPC of K-1000-60 turbines η_{oi}=84.4 % and for two-tier LPC of the new turbine is η_{oi}=84.1 %. An increase in the length of the turbine is then approximately by 4.8 m is due to the essential rise of stages in the high pressure cylinder.

5 Main conclusions

Our results show that the use of steam superheating after the NR up to 600°C with further superheating up to 480°C allows to increase by 70% the existing heat drop for turbine and to ensure its functioning in the areas with superheated and dry steam, which prevents any possible losses due to moisture and erosion wear of blades.

When it comes to using the external steam superheating in NPP, it appears that there is no necessity in moisture separator-reheaters and it seems possible to cut the number of steam intake for its regenerative heating twice.

Moreover, the new super-powerful turbine does not differs much in size from the base K-1000-60-3000 turbine and might also be deployed in the existing turbine.

Overall, the new turbine and the proposed heat balance allows us to increase the designed power of NPP unit on the base of VVER-1000 reactor by two times at relatively moderate capital costs and essentially reduce the period of putting the unit into work in comparison with the construction of the new NPP.

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