New two-tier low pressure turbine for heavy duty steam turbines

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Abstract. Among factors characterising steam turbine units of power plants, a specific metal content which value decreases inversely to turbine power is of substantive importance. In turn, their maximum power depends on the capacity of low pressure turbines. It is traditionally managed to increase either by installation of larger number of low pressure turbines or by lengthening the exhaust blades. It is worth noting that the above-mentioned methods have some technical restrictions by the number of rotors to be connected. Currently some works aimed at solving the stated technical problems appear in the literature for the purpose of increasing the unit power of turbomachines, for example, by using exhaust blades with the length of 1 500 mm and longer. However, it is to be understood that increasing the exhaust area of turbomachine only by lengthening exhaust blades cannot provide a cost-effective and reliable work of the turbine flow part. Here new problems appear: losses rise abruptly due to the stage fan-out, the turbomachine dimensions increase, etc. In this connection, an issue of development of new, technically implementable ways of turbo-units power increase is very acute today.

1. Introduction
An existing tendency of raising of the unit power of turbomachines stipulates the need of increasing the overall exhaust area. The first and the most applied way of raising of the power is lengthening the exhaust blades. This approach is actively developed both in Russian turbine construction industry and worldwide. Today the maximum implemented length of the blade in Russia is 1 200 mm for the exhaust blade mounted at the K-1 200-240 LMZ turbine; a conceptual design of the blade with 1 400 mm length has been performed [1, 2, 3]. Mitsubishi and Hitachi corporations abroad are already performing experimental studies of the longest blade in the world (1544 mm) designed for the full-speed turbine (3 000 rpm). This blade is made of the 13Cr alloy and provides the exhaust area of a single flow of low-pressure cylinder (LPT) equal to 16.5 m² [4, 5].

The second approach is based on application of the so-called “multi-exhaust” of LPT while using already implemented blades of the last moving row. This solution was first proposed by Karl Baumann in 1920. The Baumann exhaust blading is arranged by increasing the height of the penultimate stage and splitting it with a partition (the so-called Baumann stage) which allows for the sharp increase of the capacity of LPT.
The multi-exhaust by Karl Baumann is not the only possible option. In 1978 the CKTI researchers suggested the multi-exhaust arrangement and consequently the increase of the capacity of LPT by splitting and reversing of part of the flow after the penultimate stage [6]. This solution has not become widespread as the reversing of part of the flow is rather difficult to be realised. Also the CKTI proposed to increase the capacity by implementing the two-tier flow part in the LPT which is in fact one of the options of the multi-exhaust arrangement. However, the idea of using multi-tier flow parts in the steam turbines also belongs to Karl Baumann who has patented it in 1916 [7].

Each above-considered option of design of the flow part of the increased-capacity LPT has some difficulties which will be faced inevitably during the practical implementation. The design of full-speed steam turbine based on the LPT with the maximum length of exhaust blades requires to solve a set of important problems: check-out, testing and refinement of the exhaust stage with the maximum length of blades at the LPT brass-board, the decrease of intensification of erosive wear of edges of blades due to the record angular velocities at the periphery, provision of static strength and vibrational reliability of the blade with the maximum length, the decrease of energy loss in the flow part caused by wide aperture angles of meridional bypass and the presence of large inter-stage laps. The way of increasing the capacity by using the multi-exhaust in the flow part of LPT removes a number of problems related to the design of blades of the maximum length. It makes this option quite tempting because the rotor dimensions remain practically unchanged and the exhaust blades of tried-and-true design are used.

However, the above-mentioned flow parts of LPT with multi-exhaust have also their unsolved problems. The practical operating experience for the Baumann stage in the widely known Russian K-200-130 LMZ turbine resulted to decrease of LPT cost-effectiveness by 11 per cent [8] compared to the traditional flow part with uneconomic Baumann stage designed yet in 1960-1970s [9]. This is a rather high price one has to pay for the increase of capacity of LPT. Therefore, the use of Karl Baumann’s design of multi-exhaust for steam turbines of 1 GW power capacity class will require the revision of approaches in design of two-tier penultimate stage. Both Russian and foreign authors are currently engaged in the search and development of such solutions [9, 10, 11, 12, 13]. At the first glance, the multi-exhaust design with reversing of part of the flow seems to be more prospective than the flow part of LPT with the Baumann stage since the second tier of penultimate stage works at the rate of velocities $u/c_f$ close to the optimum values; however, there appear some problems regarding the reversing of the flow and minimisation of energy losses in the flow which are directly related to it. The multi-exhaust design with two-tier flow part has its own challenges as well as all other options, and these issues need to be solved during the practical implementation. These challenges are: the arrangement of the flow in the flow part, the optimum ratio of stages of upper and lower tiers, the system of extraction of relatively large amounts of steam from the upper tier which would not result to essential decrease of cost-effectiveness of post-extraction stages, and also, the design of the most loaded two-tier blade of penultimate stage which would provide the required safety factor and endurance, its manufacturing and competitiveness regarding traditional blades of the maximum length.

In order to settle the most acceptable way of increasing the unit power of full-speed turbines of thermal and nuclear power plants, the comparison of results of both calculations and experimental try-outs is mandatory for each option. It requires the development of research and engineering design works of both LPT where the maximum-length blades are used and the multi-exhaust LPT on the basis of two-tier stages. This work is focused on a direction related to the development and research of structural elements of the flow part of the new two-tier LPT.

2. Flow part of two-tier LPT
As it has been noted above, the implementation of two-tier flow parts, where the upper tier is a blade unit independent from the lower tier and has its own optimum pitches, profiles, values of $u/c_f$ and reactions, is one of solutions aimed to increase the capacity of LPT. A draft of developed LPT with increased capacity is shown in figure 1.
Each flow of the two-tier low pressure cylinder consists of five stages the inlet and the exhaust of which are one-tier whereas the rest three are two-tier. The inlet stage differs from traditional those used in steam turbines by the presence of a special diaphragm which allows for arrangement of independent steam supply for each tier of cylinder. Such flow part assembling provides the optimum values of $u/c_f$ rate for all stages (0.63–0.7). The overall efficiency was 86.5% for the upper tier and 87.3% for the lower. At that, the integrated efficiency of the whole cylinder is 87.15%.

The exhaust nozzle of the two-tier LPT includes two aerodynamically unbound exhaust schemes both for the lower and for the upper tiers; besides, each of them has an axial-radial diffusor mounted with the negative lap relatively to exhaust blades tips and anti-vortex grids mounted at the lateral sides of the nozzle (figure 2).

**Figure 1.** Flow part of two-tier LPT.

**Figure 2.** Exhaust nozzle of two-tier LPT.
The axial-radial diffusor mounted with the negative lap relatively to exhaust blades tips allows to prevent the negative impact on the energy conversion in the diffusor by the full-speed stream which occurs in the peripheral gap of exhaust blades. The anti-vortex grid mounted below the horizontal connector allows to decrease the intensity of concentrated vortices appearing as the flow in the nozzle deflects by $90^\circ$ relatively to the longitudinal axis of turbine. The results of numerical study of developed design of exhaust nozzle are represented in the publication [14]. It is worth mentioning that developed solutions are adaptable for nozzles of traditional on-tier LPT as well. The development of new nozzles for steam turbines with respect to the above-stated recommendations will result both to the increase of cost-effectiveness of steam turbine units due to decreased energy losses in the exhaust system and to the improvement of their reliability due to decreased vibration of the nozzle body and hence, of the rotor of LPT.

A nozzle device of the exhaust stage has also been improved for the developed two-tier LPT. The nozzle device of the exhaust stage of the lower tier of two-tier LPT contains a let-down guide deflector which prevents the jet separation from the peripheral edge of the flow part. Numerical and experimental studies performed for the model of the nozzle device confirmed the effectiveness of the design being provided and demonstrated a great potential of its use both in the new two-tier LPT and in traditional LPTs [15].

3. Two-tier fork-shaped blade
A two-tier fork-shaped blade of the penultimate stage is one of the most crucial components of the flow part of two-tier LPC. The main difference of this blade from the rest two-tier blades is that there are two blades of the upper tier per one feather of the lower tier which determines its heavy loaded state both due to impact of centrifugal loads and on affection of aerodynamic forces of the flow. The developed fork-shaped blade of two-tier stage is shown in figure 3. The design of the blade is solid and indecomposable; it is split by a transverse partition with two blades of the upper tier on its outer surface.

![Figure 3. Two-tier fork-shaped blade and two-tier working wheel of the penultimate stage of LPT.](image)

The results of numerical modelling of the flow through the two-tier blade have demonstrated a high aerodynamic effectiveness of developed profiles. The profile drag coefficient equals to 3.7% for the lower tier and to 2.9% for the upper one. Considering all additional losses, the internal efficiency ratio is 87.6% for the penultimate stage of the lower tier and 77% for the exhaust stage of the upper tier (taking into account losses by the residual velocity).
Calculations performed using the ANSYS software pack intended for computation of metal constructions by finite elements technique have demonstrated that for the two-tier blade of the most loaded wheel which is the wheel of penultimate stage manufactured of the X20Cr13 stainless steel which ultimate tensile strength $\sigma_{UTS} = 710$ MPa, stresses in the unsafe cross-sections of the blade can reach the value of 600–650 MPa. Therefore, a lighter but strong alloy is to be chosen for it, for example, titanium. For the working wheel manufactured of the Ti-6Al-4V titanium alloy which $\sigma_{UTS} = 1200$ MPa, stresses in the unsafe zones of the root section and inter tier tray are 400–450 MPa only which provides almost triple safety factor (figure 4).

**Figure 4.** Stress distribution in the two-tier working wheel which blades are manufactured of the Ti-6Al-4V titanium alloy.

**4. Conclusion**

The developed multi-exhaust LPT based on two-tier stages is free from the limitations of Baumann blading and provides solutions of problems arising due to lengthening of exhaust blades over 1200 mm, not only the stress-strain issues but also aerodynamic challenges related to increased fan-out and aperture angle of the flow part. The application of developed solutions allows for reaching the internal efficiency ratio of the low pressure turbine up to 87.1% which is the same value as for LPT of traditional design.

The noted benefits of two-tier cylinders make the proposed technical solution of key importance for development of high-performance heavy duty steam turbines.

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