Ventilation modes of operation and their representation at the power characteristics of turbine stages and compartments

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Abstract. The article proposes an analysis of the main approaches in the theory of ventilation processes applied to the correct determination of ventilation losses occurring in the stages and compartments of TPP steam turbines in operating modes with low volumetric flow rates in a low-pressure cylinder. The features of the flow of ventilation processes in the low-pressure flow parts of CHP steam turbines and methods of their study are presented. New physical and mathematical models for calculating the ventilation power losses in the flow part of the turbine are considered. The universal generalized mathematical dependence for a high-precision estimation of the ventilation power losses of the turbine compartments is substantiated, taking into account the whole variety of parameters determining the level of these losses. On its basis, the authors have created mathematical models for calculating several types of CHP steam turbines for rapid assessment and accounting of technical and economic indicators of turbine operation all the possible range of operating modes. The basis of the new calculation models is adequate power and flow rate characteristics of the turbine stages and compartments, so the computational results correlate well with the experimental data, allowing to analyze a wide range of operating modes.

Keywords: CHP steam turbines, low-pressure cylinder, ventilation processes theory, mathematical relation.

1. Introduction
Recently, there has been great interest in the study of the variable modes of operation of certain stages and sections of steam turbines. This primarily relates to the study of modes with the lower, compared with the nominal level, values of the volumetric flow rates. These modes are typical primarily for the stages of low-pressure section (LPS), the intermediate compartment and the pre-selection compartment of CHP steam turbines, but they can also occur in the last stages of condensation turbines when the electrical load decreases or the vacuum in the condenser deteriorates [1, 2, 3]. The use of low-flow modes of operation has improved the turbine plants efficiency due to reducing heat losses in a cold source and increasing electricity generation based on the heat supplied (organizing regulated heating steam extractions, heating of make-up water or delivery water in condensers, etc.) [4, 5, 6]. In order to identify the energy effect of their implementation, it is necessary to have a clear understanding of the general patterns of the processes occurring in the flow sections of the turbine stages and compartments under variable operating conditions, as well as to use reliable generalization of experimental data in the form of power and flow rate characteristics of turbine stages. It is important to choose an adequate assessment of ventilation power losses in these stages since their value can be very significant and decisive, especially when conducting optimization studies. Therefore, the research is relevant for a wide range of steam flows and backpressure levels.
1.1. The aim of the research
The study's aim is to identify the most effective methods for determining ventilation losses of power in the stages and compartments of the axial turbomachines and to determine the effect of these losses on the power characteristics and indicators of variable operating modes of heat and power plants in order to solve problems of increasing the CHP energy efficiency.

1.2. Setting research objectives
It is known that the working conditions of the cogeneration turbine compartments (especially low-pressure sections - LPS) are variables due to the presence of adjustable steam extractions. For the turbine stage the low flow rate modes, when the volumetric flow rate of the steam does not exceed 20% of its nominal value, are the most interesting in the theoretical and important in practical terms. In this regard, the research objectives are:
1) analysis of existing approaches to calculating the ventilation energy losses in turbine stages and compartments, identifying the advantages and disadvantages of various approaches for their determination, general patterns of processes occurring in the flow part under deeply variable operating modes, and as a result – the choice of generalized power and flow rate characteristics of turbine stages and compartments for the research;
2) conducting detailed computational studies, description of the energy performance of the CHP by mathematical modeling methods using the obtained energy characteristics of steam turbines, comparing the results with data from industrial tests.

2. Methodology of the research
Ventilation modes of the turbine compartments and stages are the least studied today. For this reason, various empirical generalizations are widespread. Most of them determine the energy losses in individual turbine stages in a no-flow mode and are based on the results of model studies. The working conditions of the model stages in low-flow modes are noticeably different from the real ones, which makes it difficult for an assessment to be reliable using the specified empirical formulas of the actual characteristics of the full-scale stages.

For a long time, starting from the first half of the last century and up to the present, low-flow rate regimes have attracted the attention of researchers, and a sufficient number of approaches and models have been accumulated to describe the ventilation processes connected with them. The most widely used are mathematical dependencies for estimating ventilation losses of power in the steam turbines stages of thermal power plants, made by scientists of the Leningrad Metal Plant (LMZ), Ural Turbine Plant (UTZ), the company English Electric (EE) and others. Most of them are based on the model proposed by Aurel Stodola (1859–1942) [7], according to which the ventilation currents of the working fluid on an inactive arc arise due to gas capture by the edges of the blades. The gas flow rate is proportional to the peripheral speed, and the pressure is determined by the Euler equation for the specific work. Ventilation losses in this case are proportional to the average impeller diameter, the height of the blades, the gas density and the cube of peripheral speed. The calculation results of such losses by different dependencies differ significantly when comparing them with experimental data; the values of standard deviations vary greatly in no-flow regimes in a wide range (from 7.5 to 176% [8]). Agreement between the experimental and calculated values of ventilation energy losses is observed in steam turbines of small and medium power. At the same time, an agreement with the experimental data at different pressures in the condenser is provided by the calculation of ventilation losses using the universal mathematical dependencies of I. Usachev and V. Neuimin [9], but their area of application is limited mainly by no-flow modes of powerful turbines.

Some of the research results made at VyatSU are presented in this paper. Well-known theoretical concepts of technical thermodynamics, the theory of heat and mass transfer, gas dynamics, the theory of turbomachines and mathematical modeling of heat and power plants, numerical and physical experiments and proven techniques of technical and economic research were used to solve these problems. However, the authors have used a different approach as the basis to the generalization of experimental data. Their mathematical model is described below.
The model is based on (as a first approximation) the calculation method for the average diameter, since the calculation of turbine stages in the framework of the one-dimensional theory has independent significance regardless of the development of more accurate methods based on the two-dimensional lattice theory and the axisymmetric model of spatial calculation. The compartment is calculated for a given geometry of the flow part. The source data are either the state of the steam in front of the compartment and the pressure behind it, or the state of the steam behind the compartment and the mass flow rate [10-12].

In contrast to the known methods, the developed mathematical model provides the possibility of varying operational and constructive parameters, as well as loss factors in stage gratings. Moreover, the authors have proposed a unified method of calculating all the stages of the considered turbine compartment.

The methodological approach is based on the use of the volumetric flow rate of steam \( (Gv_2) \) as an argument, where \( G \) is mass flow rate, \( v_2 \) is the specific volume of steam behind the stage (compartment). The experience of theoretical and experimental studies of the flow parts of turbomachines have shown that the volumetric flow rate \( Gv_2 \) or its return value \( (Gv_2)^1 \) are the arguments from which heat drops, efficiency and power of stages can be represented in the form of graphical and analytical dependences in the most convenient and informative form. The specially developed methods of full-scale studies, which was used to determine these characteristics, were described in detail in [13]. In particular, one of the methods for determining the throughput of a low-pressure sliding grid (SG LPS) was direct measurement of the mass flow rates of the turbine (either through the main steam valve bypass and the steam injection organs, or via an additional steam line to the intermediate stage of the turbine) with fully closed SG LPS. Experiments were carried out on a pre-heated turbine, with a generator disconnected from the network (due to low mass flow rates, the rotor speed is below the nominal value), with regenerative and district heaters disconnected, as well as with closed drains from the flow section and steam lines to the condenser. Under these conditions, the steam consumption in the LPS through the sliding grid differs from the leakage through the turbine seals measured by the value determined by calculation.

Compared with traditional balance tests, the developed technique is characterized by higher accuracy, which does not depend on steam humidity and non-uniformity of its parameters in LPS stages, significantly less laboriousness and allows to significantly reduce the cost of steam turbines research [14].

3. The results of calculation studies and their comparison with experimental data

When reducing the volumetric flow rate of steam through the stage lower than the idle volumetric flow rate \( (Gv_{2cr}) \), the stage goes into power consumption mode, at which its actual heat drop \( h \) becomes negative [15, 16]. At the same time, the average static pressure behind the stage \( p_2 \) becomes higher than the pressure before the stage \( p_0 \), i.e. the stage begins to inject the working fluid similarly to a ventilator. In this case, the modes are distinguished when the power consumed by the step \( N=N_i \) ceases to depend on the mass flow rate of the working fluid through the stage, but depends only on its specific volume \( v_2 \) at the exit of the step. For such "clear ventilation" modes \( (Gv_2)<(Gv_{2cr}) \), (index "cr" refers to the steam outflow mode, when ventilation losses cease to depend on the volumetric flow rate of steam as it decreases), the effect of "clear ventilation" is observed with a decrease in consumption, up to a zero value \( (Gv_2)=0 \). From this, it is obvious that \( (Gv_2)<(Gv_{2cr}) \). The most typical ventilation modes of operation are for the LPS stages, as well as the intermediate compartment stages (between heating steam extractions) of cogeneration steam turbines, as well as the last stages of other types of turbines in low-flow modes [17].

The LPS stages of cogeneration steam turbines pass into the indicated modes when the SG LPSs are covered or closed, which ensures coverage of a given heating load while minimizing losses in a cold source (condenser) [18]. For the final stages of these turbines, which have greater fidelity, the power characteristics in ventilation modes also depend on the design of the exhaust branch pipe.

The parameter characterizing the stage in terms of ventilation losses is the coefficient of specific losses in the clear ventilation mode, which for a given stage or compartment at a synchronous frequency of rotation \( n \) is defined as
\[ C = N_v \nu_2, \text{ W} \cdot \text{m}^3/\text{kg} \]  

(1)

where \( N_v = -N_i \) is the value of losses in the mode of clean ventilation of a stage or compartment, W; \( \nu_2 \) is the specific volume of steam behind the stage or compartment, m\(^3\)/kg.

For the stage (compartment) of the turbine with given geometrical characteristics, the power \( N_v \) and, consequently, the magnitude of the coefficient \( C \) are directly proportional to the third power of the rotor speed [13].

An important pattern found in experimental studies of different stages of natural turbines is the constancy of the ratio \((G\nu_2)_r/(G\nu_2)_{ao} \approx 0.67\). If the compartment consists of several stages, this ratio will be less than 0.67. It will depend on the number of steps in the compartment and on the ratio of the geometric dimensions of the stages of the compartment.

The fact that the value of \( N_v \) is unchanged at constant density of the working medium and the frequency of rotation is explained by the presence of the step self-ventilation effect. This effect is expressed in the fact that the stage of great fidelity at \((G\nu_2) < (G\nu_2)_r\) begins with the decrease in the main flow rate and increasingly sucks the working fluid from the space after the stage (countercurrent to the flow of the mainstream direction). At the same time, the flow of steam or gas actually circulating through the impeller remains approximately constant, and this leads to the invariance of power consumption for such circulation. The effect of self-ventilation is widely used to organize the cooling of the flow path of the stage to remove the energy of ventilation losses [12, 13].

The power characteristics of the turbine compartments and stages are constructed as the dependence of the internal power of \( N_i \) or the actual heat drop \( h_i = N_i/G \) on various arguments. The latter ones are used the pressure behind the compartment \( p_2 \), the disposable heat drop of the compartment \( h_{ao} \), the volumetric flow rate of the working fluid after the compartment or stage \( G\nu_2 \) and the reciprocal of this volumetric flow rate \((G\nu_2)^{-1}\). Fig. 1 shows the generalized power characteristics of the LPS of a number of domestic cogeneration steam turbines, made in the form of \( N_i\nu_2/C = f((G\nu_2)_r/(G\nu_2)_{ao})\).

The applied method of studying the mathematical model of physical processes allowed us to obtain the result in graphic and analytical form. According to these graphs, a complete, detailed, step-by-step comparison and analysis of various modes was made, and the corresponding conclusions were given [12, 13].

![Figure 1](image.png)  

**Figure 1.** Generalized power characteristics of LPS in operating modes with energy consumption: 1, 2, 3, 4 - LPS of turbines PT-60-12.7, PT-135-12.7, T-50-12.7, T-180-12.7, respectively.

All of the above is confirmed by experimental data obtained from industrial tests. As an example, Fig. 2 presents a comparison of the results of full-scale tests of the turbine T-110-12.7 in modes with single-stage and two-stage heating of delivery water [19].
As it can be seen from the example, the discrepancy between the calculated and experimental data lies within the accuracy of the entire calculation and does not exceed 1%. It proves a high level of generalization of the dependencies used in a wide range of mode changes.

4. Conclusion

1) Detailed calculations and a comparison of their results with the available experimental data allowed us to identify a number of regularities and substantiate the type of generalized integral energy characteristics of the steam turbines stages and compartments during operation with low volumetric flow rates. These characteristics can be used in the development of adequate mathematical models and the study of variable modes of turbine installations.

2) Based on the new dependencies, we obtained the results of detailed calculations for estimating the ventilation power losses in low-flow regimes and showed their agreement (the discrepancy is less than 1%, which is within the accuracy of the entire calculation) with the data of industrial tests.

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