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METHOD OF INCREASING STEAM TURBINE CONTROL STAGE EFFICIENCY

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Abstract. In many cases when the turbine load diverges from the nominal value, the benefit which should result from nozzle governing may be all lost due to a sharp decrease in control stage efficiency. The magnitude of this decrease depends on the aerodynamic characteristics of the cascade profiles, on the conditions of inlet velocity fields forming in the nozzle chests and on the efficiency of the means which cause a decrease in the negative influence of partiality. Different blade profiles and their loss coefficients are presented.

Keywords: Aeroderivative turboengine, coal boiler, combined cycle, cogeneration.

1. Introduction

When analysing the development of large steam turbines we can notice that a long time passes before proposals of new solutions are applied in the industry. For example, methods of raising efficiency proposed 20−30 years ago are only now being applied. This paper discusses the potential of a design which if adopted would bring about a considerable increase in the relative internal efficiency of steam turbines. According to our experience in the modernisation of steam turbines, it is possible to raise turbine effectiveness to theoretical limits under real conditions and at a relatively low investment input.

In recent years, practically all large factories producing steam turbines have been searching intensively for ways of increasing the efficiency of large steam turbines. It is worth looking not only at new solutions but also at the so far unrealised methods of reducing energy losses in blade systems. An overview of known solutions, for example, for blade cascades of a small relative height can be found in [2], [10] and [11].

Many authors, e.g. [4] and [9], give an assessment of efficiency increase possibilities for steam turbines, covering all elements along the entire steam flow path. The asymptotic character of the energy loss reduction process should be taken into account: it is impossible to reduce the losses in cases when they are very low. In other words, attempts at improving efficiency should be made in cases of turbine elements in which energy losses are relatively high.

2. Nozzle governing

Partial steam admission is used in the first stage of turbines with nozzle-group steam flow control, where steam enters the turbine through one or several nozzle groups, Figure 1, depending on the turbine load. Such a stage is termed a control stage. In order to increase the available energy and obtain the proper steam conditions in the space after the control stage, the latter is usually of the impulse type, even when the other stages are of the reaction type. The control stage usually has an increased diameter and it is sometimes made (for older turbines of relatively moderate output) as velocity stages.

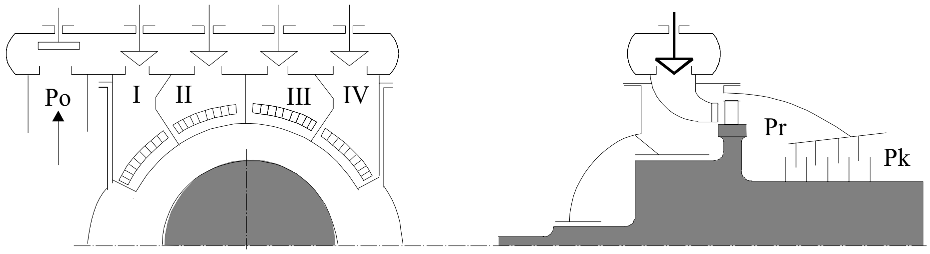

Figure 1. Scheme of nozzle governing

3. Control stage

The control stage is a necessary part of a steam turbine with nozzle governing. The operating conditions of this stage differ significantly from those of the other stages: when the turbine load diverges from the nominal value, two steam jets with different initial pressures appear in the control stage, [7] and [8].

The process for the control stage and its control valves is shown in Figure 2. Two steam flows can be seen there. The first steam flow through the fully open valves enters the segments of the control-stage nozzle row without additional losses. In the second flow, steam is throttled in the partially open valve to a certain intermediate pressure. Both steam flows expand in the control stage to steam pressure p_r.

This means that one part of the stage, where the non-throttled steam jet flows, works at an increased drop of enthalpy while the other part operates at a decreased drop of enthalpy (in comparison with the computational enthalpy drop). Thus in one stage two different operating regimes are realized - with a decreased value and an increased value of basic stage parameter

$$u/c_0 \, ,$$

where u is the blade (circumferential) velocity on the pitch diameter of the bucket wheel and c_0 is the velocity that corresponds to the disposable drop of enthalpy:

$$c_0 = (2H_{01})^{0.5}$$

The total blade efficiency η_{0B} drops significantly when the turbine load decreases.

Internal efficiency η_{0i} drops even more because when the consecutive control valves are being closed, the partiality of the stage decreases very sharply. Our experiments showed that when the partiality of the stage decreases from $\varepsilon = 0.82$ to $\varepsilon = 0.2$ (one control valve open), the relative stage efficiency η_{0i} decreases by 60%. Since the efficiency decreases as a result of a change in the value of u/c_0 during the closing of the consecutive control valves, the stage begins operating in the regime of steam throttling. In other words, the benefit which should stem from nozzle governing may be all lost due to the sharp decrease in the control stage efficiency. The magnitude of this decrease depends on the aerodynamic characteristics of the cascade profiles, on the conditions of inlet velocity fields forming in the nozzle chests and on the efficiency of the means which contribute to a decrease in the negative influence of partiality.

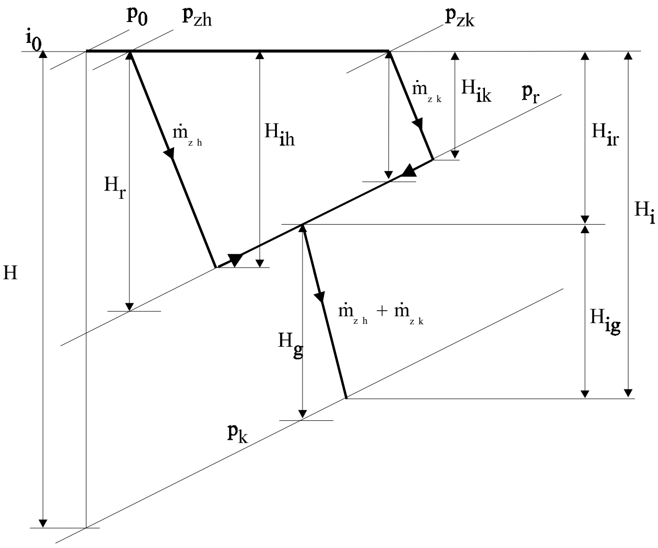

Figure 2. Steam expansion process on h-s axes for steam admission part of turbine with nozzle-group governing

4. Control stage under variable steam flow

A basic operating characteristic of the control stage blade apparatus is a wide range of velocities: from low subsonic velocities up to high supersonic ones, Figure 3. Therefore profiles cascades of the control stage should be multiregime and they should ensure high reliability as regards sharp changes in static and dynamic loads. The first requirement connected with the low reaction of the control stage applies to the turbine nozzle cascade, the second one applies to the bucket cascade where a complex of forces occurs.

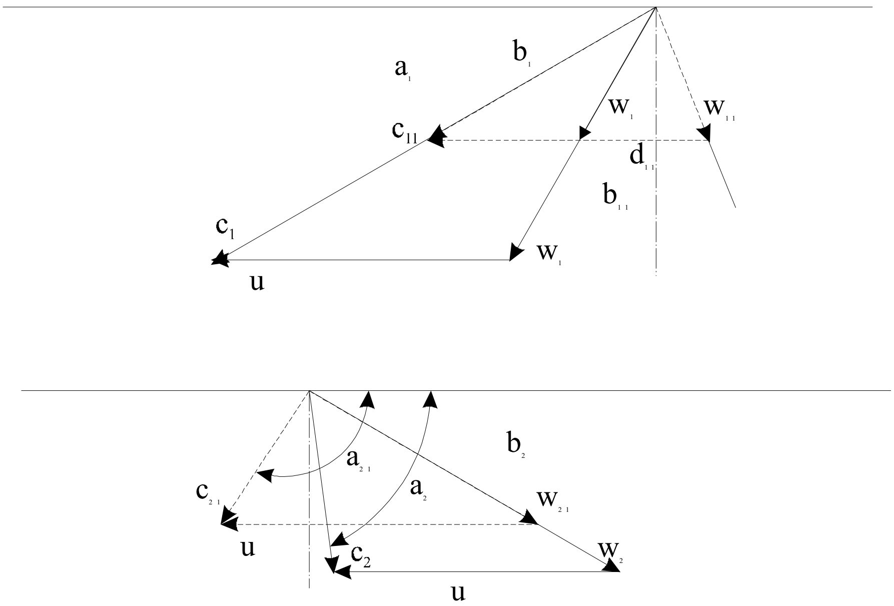

Figure 3. Velocity diagrams for control turbine stage: dashed lines - throttled steam stream, solid lines - non-throttled steam stream

The aerodynamic problems which arise in the cascades are illustrated by a relationship between profile loss coefficient ζ_{pr} and nondimensional velocity at outlet M_{1t} for a converging (line 1 in Figure 4) and diverging (line 2) turbine nozzle cascade. Accelerating cascades ensure a low level of losses $M_{1t} < 0.8-0.9$. The use of divergent cascades is justifiable for $M_{1t} > 1.3 - 1.4$.

When the turbine load decreases, the most characteristic velocity range for non-throttling stream seems to be in a range of $0.8 < M_{1t} < 1.4$ (then a massive increase in energy loss occurs in cascades of both types). That is why new profile cascade designs are needed for the control stage to ensure low losses for both subsonic and supersonic flows and a smooth transition from the former to the latter.

5. Multiregime blade profile

The above condition is fulfilled by profiles with inverse surface curvature of the nozzle blade-suction side at the nozzle exit zone (designed in the 1960s). One of such profiles is shown in Figure 5 and its characteristic is shown in Figure 4 (line 3). It is easy

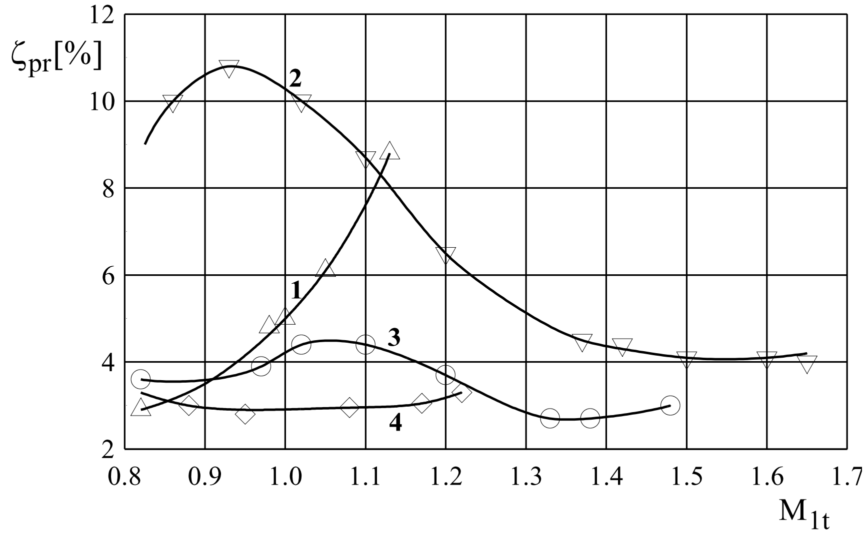

Figure 4. Dependence of profile loss coefficient ζ on Mach number M_{1t} in different airfoil nozzle cascades: 1 - converging blade cascade, 2 - diverging cascade, 3 - cascade with inverse surface curvature of nozzle blade suction-side at nozzle exit zone, 4 - nozzle cascade with longitudinal grooves on convex blade surface

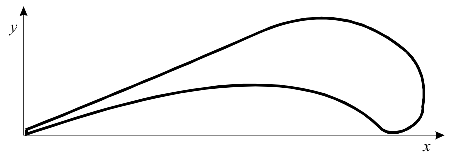

Figure 5. Multiregime blade profile

to see that a nozzle cascade made from such profiles has sufficiently low profile losses in the subsonic, transonic and supersonic ranges. The transition through the nozzle exit zone from the convex to concave surface allows us to avoid stream re-divergence in this section and at the same time to decrease the longitudinal positive pressure gradient in the range of subsonic velocities and to suppress the shock waves in the supersonic range.

6. Multiregime Cascades with Longitudinal Grooves

Cascades built from profiles with longitudinal grooves (rectangular in cross-section) in the nozzle exit zones are even more effective, [3], [5], [6], [12], [14] and [15]. In this design an increase in losses in the transonic area is avoided and sufficiently low level of profile losses can be maintained for the whole tested range of velocities (line 4 in

Figure 4). Similar changes can be made in the shape of bucket cascades designed for the control stage.

Taking into account the above characteristics of the new cascade designs, it would be advantageous to use moving blade profiles with thin leading edges and decreased surface curvature in the nozzle exit zone. Such cascades were designed in the 60s (type $R-\beta_1\beta_2B$ [1]) and their characteristics are compatible with modern requirements.

The presented relationships $\zeta_{pr} = f(M_{1t})$ for the control-stage blade system should be substantially corrected because the control stage receives the jet from the control valves after which the velocity field is characterised by high non-uniformity and a vortex flow occurs for several turbine loads.

The control stage always operates in conditions of a complex inlet velocity field, [16]. As our experiments showed, the losses in the nozzle cascade installed after the standard control valve when the latter is fully open increase by 1.5−2.0% (in comparison with a uniform velocity field) and by 3.0 − 3.5% when the valve is half open. If new valve designs are used, the nozzle cascade losses caused by inlet non-uniformity will not exceed 0.8 − 1.2%, [13].

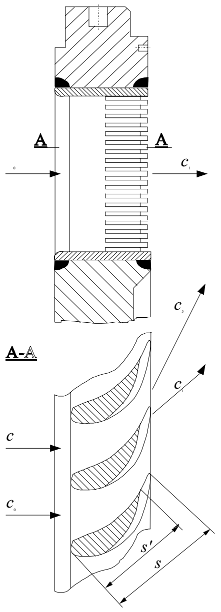

Figure 6. Turbine cascade with longitudinal grooves

7. Summary

This analysis of the operation of control stages shows that because of several negative factors, they operate with relatively low efficiency and may (when the turbine load decreases considerably) operate in the steam throttling regime.

If multiregime profiles are used for control-stage cascades, it is possible to increase the efficiency of the control stage.

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