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Methods for flow separation prevention on external contour at high expansion angles of steam turbine flow path

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Abstract

Most thermal and nuclear power plants use a steam turbine to convert steam potential energy into mechanical work on the rotating rotor. To operate the steam turbine at high efficiency, the aerodynamic losses in the flow path must be decreased, especially in a low-pressure turbine (LPT). This study focuses on the problem of flow separation in the area of the external contour, occurring at high expansion angles of the flow path and constituting a principal cause of flow non-uniformity upstream of the nozzle assembly. Under specific flow conditions, the nozzle assembly peripheral area can be blocked by concentrated vortex, resulting in a sharp increase in losses. A numerical study and comparative analysis of two solutions to this problem were conducted. Quantitative evaluation of nozzle blade cascade energy loss reduction showed that the flow suction on the external surface of a wide-angle diffuser is the most effective in the case of removal of 2% of total flow, using holes located in the middle of an annular diffuser. In this case, the loss coefficient of nozzle blade cascade was reduced by 2.1%. Enhancement of LPT flow path, by mounting an aerodynamic deflector in a wide-angle diffuser, led to a 3% decrease in the loss coefficient. The research results lead to the conclusion that energy losses caused by high expansion angles of LPT flow path can be reduced by applying the considered methods to prevent flow separation on the external contour upstream of the nozzle assembly.

Keywords: Low-pressure turbine; External contour; Nozzle assembly; Boundary layer separation; Flow suction; Aerodynamic deflector; Loss coefficient

1. Introduction

Much research in the energy sector focuses on boosting the efficiency of power equipment. Due to the extensive use of steam turbine power plants (STPP) to generate electricity, special attention should be given to upgrading individual parts of STPPs [1, 2]. Flow path aerodynamic efficiency of high-pressure turbine (HPT) and medium-pressure turbine (MPT) of existing steam turbines (ST) is at a high level. Net relative efficiency of HPT reaches 87-88%, and MPT 90-91% [3]. In the meantime, turbine exit losses, steam moisture, high expansion angle of meridional line result in low-pressure turbines (LPT) suffering from relatively poor efficiency, hardly ever exceeding 85% [4–7].

A number of studies have focused on solving problems related to LPT efficiency [8–11]. Specific measures are developed through the study of energy conversion techniques in the system of steam removal to condenser [12, 13], as well as methods to reduce losses resulting from moisture [14–16]. At the same time, scientific literature pays precious little attention to the problem of energy losses resulting from the high expansion angle of LPT flow path.

Flow path high expansion angles (40 .. 45°) are determined by the sharp increase in steam specific volume during the process of expansion. In such case, there is an overlap rise when passing from stage to stage. In turbines K-200-240, K-300-240 the overlap upstream of the last stage reaches 40-50%, and under certain conditions, it becomes a source of substantial energy losses impacting economical operation of the whole stage [9, 10, 17].

The difference in average diameter of adjacent stages causes flow non-uniformity upstream of the nozzle assembly. In addition, there is a heavy radial flow initiation within the blade system. Where there is a small distance between stages and a high expansion angle of the external contour, flow separation in the blade channel may result in stable vortex with its end points based on the walls bounding the channel [18, 19].

In this regard, this work focuses on studying various methods to prevent flow separation on the external contour upstream of nozzle assembly, which is a principal cause of

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Table 1: Main geometrical parameters of nozzle assembly base model with external contour expansion angle of 45°

Characteristics	Unit of measurement	Value
Root diameter	mm	291.0
Average diameter of blade inlet section	mm	341.0
Peripheral diameter of blade inlet section	mm	391.0
Average diameter of blade outlet section	mm	361.0
Peripheral diameter of blade outlet section	mm	431.0
Blade height in blade inlet section	mm	50.00
Blade height in blade outlet section	mm	70.00
Blade chord	mm	38.27
Cascade pitch to average diameter in blade inlet section	mm	26.79
Cascade pitch to root diameter in blade inlet section	mm	22.84
Cascade pitch-chord ratio	-	0.7
Number of blades in nozzle assembly	pcs	40
Outlet section area	cm^2	793.7

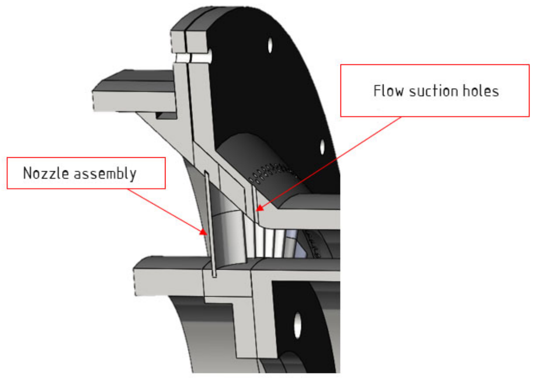

Figure 1: Flow separation prevention by means of flow suction through ring holes

flow non-uniformity in LPT stages. The following methods are considered:

- flow suction on the external surface of a wide-angle diffuser connecting penultimate stage moving blades with last stage nozzle assembly;
- low-pressure turbine flow path enhancement by mounting aerodynamic deflector in a wide-angle diffuser connecting penultimate stage moving blades with last stage nozzle assembly.

This article contains the results of a numerical study of the influence of flow separation preventive actions on flow pattern in a nozzle assembly with an external contour expansion angle of 45°, as well as quantitative evaluation of the effectiveness of the proposed methods.

2. Study subject and methods to prevent flow separation

The study subject is an axisymmetric model of steam turbine nozzle assembly having an annular diffuser mounted upstream with an external contour expansion angle of 45°. Geometrical parameters of the model are listed in Table 1.

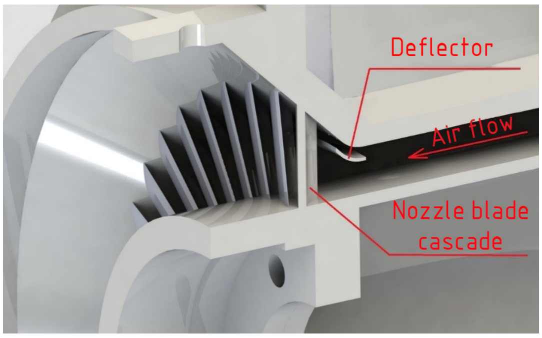

Figure 2: Flow separation prevention by using an aerodynamic deflector

Testing was carried out to investigate methods of flow suction through ring holes (Fig. 1) and use of special aerodynamic deflector mounted in diffuser channel upstream of nozzle assembly (Fig. 2). These are methods to prevent flow separation on the external contour.

Qualitative analysis of the influence of flow suction and an aerodynamic deflector on flow pattern in the diffuser channel was performed using a total pressure diagram.

Nozzle blade cascade energy loss coefficient is used for quantitative evaluation of nozzle assembly efficiency. It is determined using the following formula [20]:

$$\xi = \frac{\left(\frac{p^{out}_{static}}{p^{aver}_{02}}\right)^{\frac{k-1}{k}} - \left(\frac{p^{out}_{static}}{p_{00}}\right)^{\frac{k-1}{k}}}{\left(\frac{p^{out}_{static}}{p_{00}}\right)^{\frac{k-1}{k}}} \tag{1}$$

where p^{out}_{static}- static pressure downstream of nozzle assembly; p_{00}- stagnation pressure upstream of nozzle assembly; p^{aver}_{02}- average total pressure downstream of nozzle assembly; k = 1.4 – air isentropic coefficient.

Average total pressure downstream of nozzle assembly is determined using the formula:

$$p^{aver}_{02} = \frac{\sum_{i=1}^{n} p^{i}_{02}}{n} \tag{2}$$

where p^{i}_{02}—local values of total pressure downstream of nozzle assembly; n—number of points for measuring total pressure local values downstream of nozzle blade cascade.

3. Impact of methods to prevent flow separation on flow pattern in nozzle assembly and its aerodynamic efficiency

Numerical studies were carried out using Ansys CFX program, where Reynolds-averaged Navier-Stokes (RANS) equations are solved. The turbulence model k-omega with scalable wall function was used. Air was a working fluid. Inlet boundary conditions include stagnation pressure and temperature upstream of nozzle assembly. Static pressure downstream of nozzle assembly equal to atmospheric pressure was taken for the outlet boundary condition. These unusual (for LPT) conditions and working fluid were adopted,

Table 2: Quantitative evaluation of flow suction on aerodynamic efficiency of stage nozzle

Characteristics	Without flow suction	With flow suction
Inlet pressure, bar	1.13	
Inlet temperature, °C	50	
Flow suction, %	0	2
Loss coefficient in stage nozzle ξ, %	8.224	6.046

because the results of numerical studies presented in this work precede physical research on an aerodynamic test-bench governed by a regime where the parameters are very close to atmospheric.

The use of flow suction requires the holes to be located appropriately and the flow suction rate optimized. Numerical study results have testified that maximum efficiency of this method can be achieved when the holes are placed near the separation boundary. The influence of flow suction reduces moving from this boundary. A comparison of alternative hole locations at a flow suction rate of 2% and permanent Reynolds number of $3.1 \cdot 10^5$ showed that displacement of the holes from the separation boundary to the mid-point of the external contour results in a 22% drop in suction process efficiency. The results of qualitative evaluation of flow suction on stage nozzle efficiency are presented in Table 2.

Selection of hole locations should be made in light of structural features of the turbine stage and possible problems during production. Further, consideration is given to placing holes in an alternative location in the middle of the external contour.

Evaluation of the impact of the flow suction rate on the nozzle assembly loss coefficient showed that the optimum flow rate is 2%. In addition, the loss coefficient fell by 2.1% compared to the baseline case (without flow suction).

In [21, 22] the problem of flow separation prevention were discussed in the context of seeking to achieve higher diffuser efficiency. The results of physical study of flow suction rate optimization showed that the optimal flow rate through suction holes is 3%. However, the diffuser expansion angle was not specified. The maximum decrease in diffuser loss coefficient obtained during the research was 25% [20].

As the high expansion angle of the meridional line causes flow separation occurring on the external contour, advere effects may be avoided by placing a flow splitter (deflector) directly in the separation zone and locally decreasing the angle [22]. The imposed aerodynamic resistance resulting from edge and profile losses shall be considered as an obvious adverse effect of this technical solution. That is the reason why location and geometrical parameters should be optimized before an aerodynamic deflector is put in place.

Minimum thickness of leading and trailing edges of the deflector shall be provided in order to minimize edge losses (Fig. 3). Otherwise, occasional vortex flow may develop.
As the deflector divides the flow into two constituents, the flow should be unseparated on the diffuser external contour and deflector suction surface. Deflector surfaces should be smooth and sub-angular.

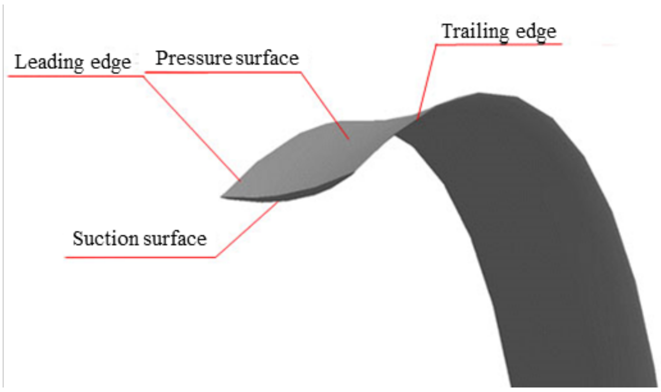

Figure 3: Aerodynamic deflector profile

Deflector length should be sufficient to enable flow redirection to the peripheral area of a diffuser. However, an extended length results in boundary layer growth and increased profile losses.

Axially, deflector location is determined by the separation boundary. The deflector should be located near the boundary to minimize losses. The size of flow non-uniformity as a result of flow separation on the diffuser external contour influences the location of the deflector in the radial axis. The deflector should be installed in a peripheral area. In the meantime, the distance between the external contour and deflector should be sufficient to prevent the connection of boundary layers formed at the surface of the external contour and the pressure surface of the deflector.

When profiling a deflector, it is important to consider the factors involved and to minimize adverse effect on flow pattern wherever possible.

The results of quantitative evaluation of flow separation preventive actions are illustrated by total pressure diagrams in the diffuser flow path (i) without flow suction (Fig. 4 a), (ii) when the suction process is activated (Fig. 4 b) and (iii) when deflector is installed (Fig. 4 c).

Based on the presented total pressure diagrams, no suction condition means that the area of flow separation on the diffuser external contour covers nearly half of the whole conical part of a diffuser (Fig. 4 c, green zone). When flow suction through holes is activated, the area of low total pressure (dead zone) is reduced. The use of an aerodynamic deflector results in the almost complete elimination of the dead zone.

Reduction of flow separation intensity leads to a reduction in flow non-uniformity downstream of the nozzle assembly (Fig. 5) [20].

Compared to the original solution (Fig. 5 a), the use of an aerodynamic deflector (Fig. 5 b) reduced the loss coefficient by 3%, thereby demonstrating the prospects the presented method has in terms of stabilizing working fluid motion. This method has proved itself to be more effective than flow suction in solving the flow separation problem (Fig. 5 c). Moreover, in contrast to flow suction, the aerodynamic deflector excludes loss of flow downstream of the nozzle assembly,

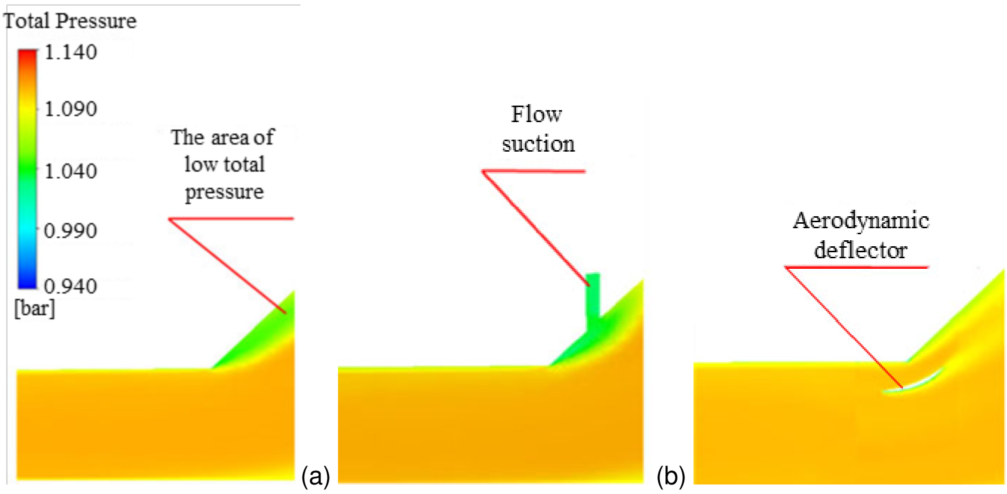

Figure 4: Structural flow analysis in the meridional section of an annular diffuser when using various methods for flow separation prevention; a) without preventive actions of flow separation; b) when suction process is activated; c) when a deflector is installed

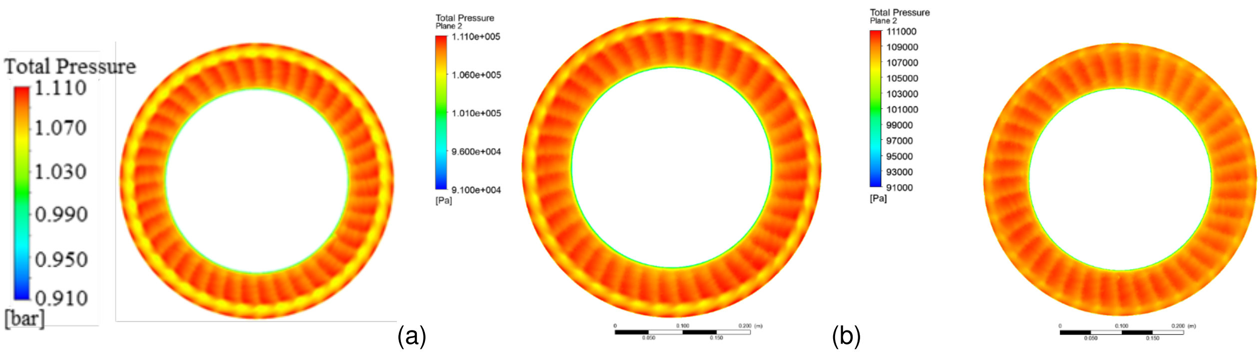

Figure 5: Impact of preventive actions of flow separation on flow pattern downstream of nozzle assembly; a) without preventive actions of flow separation; b) when flow suction is activated; c) when a deflector is installed

ensuring output power production.

4. Conclusions

The results of the numerical study lead to the conclusion that the presented methods for prevention of flow separation on the external contour upstream of the nozzle assembly reduce the energy losses caused by the high expansion angles of LPT flow path.

Structural flow analysis in the meridional section of an annular diffuser revealed a substantial reduction of the low total pressure area by applying measures to prevent flow separation, resulting in flow stabilization upstream of the nozzle assembly.

The method involving flow suction on the external surface of a wide-angle diffuser, connecting the penultimate stage moving blades with the last stage nozzle assembly, is the most effective in the case of removing 2% of total flow, using holes located in the middle of an annular diffuser. In this case, the loss coefficient of the nozzle blade cascade was reduced by 2.1%. Similar results were obtained in previous research work [20] by conducting physical studies of flow separation prevention methods in diffusers, where the optimal flow suction rate was 3%.

Enhancing LPT flow path by mounting an aerodynamic deflector in a wide-angle diffuser, connecting the penultimate stage moving blades with the last stage nozzle assembly, reduces the loss coefficient by 3%, which demonstrates the prospects of the presented method for improving the aerodynamic efficiency of the steam turbine. Moreover, in contrast to flow suction, an aerodynamic deflector excludes loss of flow downstream of the nozzle assembly, ensuring output power production.

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