archives
of thermodynamics
Vol. **42**(2021), No. 1, 97–114
DOI: 10.24425/ather.2021.136949

The influence of stator-rotor interspace overlap of meridional contours on the efficiency of high-pressure steam turbine stages

ANDRII RUSANOV
ROMAN RUSANOV*

The A. N. Pidgorny Institute of Mechanical Engineering Problems
NAS of Ukraine, Dm. Pozharsky 2/10, 61046 Kharkiv, Ukraine

Abstract The results of a systematic study of the influence of meridional contours overlap in the stator-rotor axial interspace of the impulse and reactive type stages of a high-pressure steam turbine on the flow structure and gas-dynamic efficiency of the flow part are introduced. The studied flow parts of the impulse and reactive stages are typical for high-power high-pressure steam turbines. It is shown that the stages that have no overlaps and/or have a smooth shape of meridional contours have the best gas-dynamic efficiency, and the most negative effect on the flow part is caused by the presence of caverns in the stator-rotor interspace. For cases where, due to technological limitations, it is impossible to avoid the presence of caverns and overlaps with a sharp (step-wise) change in the shape of the meridional contours, it is recommended to perform overlaps with positive size of overlap values near the rotor blades.

Keywords: High-pressure steam turbine; Cavern; Overlap; Impulse type stage; Reactive type stage

Nomenclature

b_x	–	blade profile width, m
c_0	–	absolute speed, m/s
D	–	stage diameter, m
D_{mid}	–	average stage diameter, m

*Corresponding Author. Email: roman_rusanov@ipmach.kharkov.ua

D/L	–	blade fanning
h	–	enthalpy, J/kg
h^*	–	enthalpy of stagnant flow, J/kg
L	–	blade height, m
N	–	power, W
Nl	–	number of blades
P	–	static pressure, Pa
P^{*-}	–	total pressure, Pa
Po	–	constant for Tamman equation, Pa
R	–	gas constant, J/K
ro	–	degree of reactivity
T	–	static temperature, K
T^*	–	total temperature, K
t	–	cascade pitch
t/b_x	–	relative blade pitch
u/c_0	–	loading of stages
y^+	–	dimensionless distance from the wall

Subscripts

in	–	at the inlet to the stage
out	–	at the outlet from the stage
iz	–	isentropic value

Greek symbols

α_{1ef}	–	effective stator angle, deg
β_{1ef}	–	effective rotor angle, deg
γ	–	adiabatic index
δ	–	size of overlap, mm
η	–	efficiency, %
ν	–	specific volume, m^3/kg
ξ	–	kinetic energy losses, %
ξ_v	–	losses with outlet speed, %
Ω	–	rotor speed, rpm

1 Introduction

Nowadays, research to find ways and directions for further improvement of power generating equipment, in particular, the ways to increase the gas-dynamic efficiency of the flow parts of high-power steam turbines continues. Along with new design approaches such as reverse twist and complex blade lean [1–3], special profiling of meridional contours [4–6], etc., the well-established, classical principles of selection of the basic geometric and gas-dynamic characteristics of the turbomachines flow parts are used. Those are loading of stages (u/c_0), blade fanning (D/L), relative blade pitch (t/b_x), etc. [7, 8]. Of course, the knowledge and experience accumulated over the years by a large number of researchers are the basis for the creation of new turbines. However, the developers have not yet come to a consensus about some of the approaches. In particular, this concerns the stator-rotor and interstage interspace overlaps of meridional contours.

Initially, overlaps meant a change in the diameter of the meridional contours between the trailing edges of the row, which are located higher upstream (stator or rotor) with the leading edges of the next row (rotor or stator). However, in most flow parts of turbomachines, the meridional contours are made with variable diameters, while there are constructions with and without overlaps. Therefore, it would be more correct for a 'non-monotonic' (abrupt) change in the diameters of the meridional contours in the stator-rotor or interstage interspace to be called the overlap.

Overlaps of meridional contours are used in gas turbines (aircraft engines) [9]. Initially, almost all steam turbines were designed with overlaps both at the inlet to the stator and in the stator-rotor interspace [10–14]. In the last low-pressure (LP) stages, overlaps are used to reduce the negative effect of overbandage leakage [15].

Some steam turbines manufacturers such as Siemens, GE and others, perform most high-pressure and low-pressure stages without overlaps [16, 17]. They motivate this by the fact that at relatively low blade heights, the presence of overlaps negatively affects the flow structure, causing separation flows near the meridional contours. At the same time, Toshiba believes that the presence of overlaps improves the flow structure [18]. Therefore, it can be said that in order to answer the question of the advisability of the stator-rotor and interstage interspace overlaps of meridional contours usage, additional research is required.

The paper presents the results of a numerical study of the influence of stator-rotor interspace overlaps on the flow structure and efficiency of a 300 MW high-pressure (HP) steam turbine stages. Various shapes and sizes of overlaps are considered for two stages: of impulse and reactive type.

2 Mathematical model

Modelling of the 3D spatial flow was performed using the software complex IPMFlow [19], which is a development of the software complexes FlowER and FlowER-U [20]. In this software complex the following elements of the mathematical model are implemented: unsteady Reynolds-averaged Navier–Stokes equations, Menter's two-equation turbulence model

SST (shear stress transport), implicit quasi-monotonic essentially non-oscillatory scheme of increased accuracy. To close the original system of equations, the Tamman equation of state is used [21]. Calculation results obtained with the software package IPMFlow have been extensively tested, even during calculations of the flows in high-power steam turbines [22, 23]. The results have the necessary reliability both by the qualitative structure of the flow and by quantitative assessment of the characteristics of isolated turbine stage and flow parts of turbomachines as a whole. The flow parts of the studied stages were developed using the original method of axial turbines profiling, which is a part of the software package IPMFlow.

3 Results and discussion

Today, both impulse and reactive stages are widely used in high-pressure and medium-pressure steam turbines. Therefore, as an object of research, two types of HP stages of a steam turbine were considered: impulse type (Fig. 1) and reactive type (Fig. 2). It can be seen from the figures that the classic blade shapes in these stages are used for stages of such type. Table 1 shows the main geometric characteristics of the studied stages.

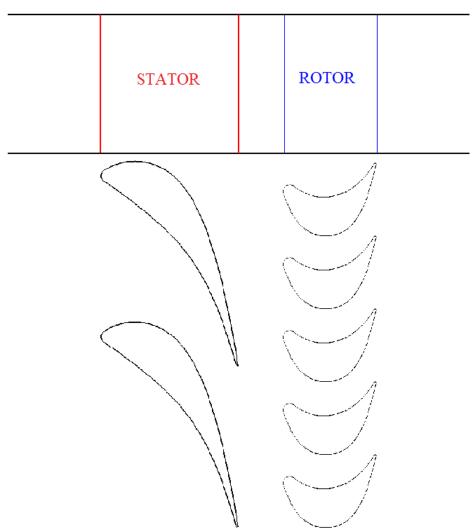


Figure 1: View of the first stage of the impulse type HP steam turbine.

The calculation was performed on a grid with a total number of cells of more than 1.7 million (about 850 thousand cells in one row) using the

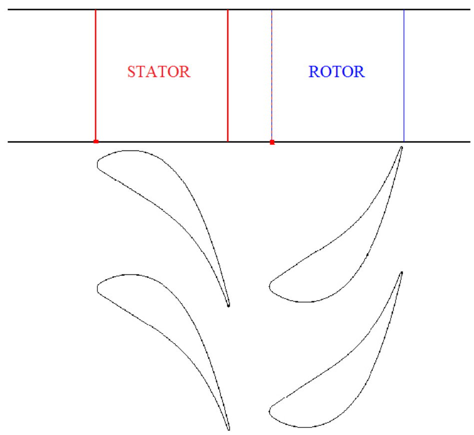


Figure 2: View of the first stage of the reactive type HP steam turbine.

Table 1: The main geometric characteristics of the studied stages.

Stage type	D_{mid}, m	D/L,	b_x stator, m	b_x rotor, m	Nl stator	Nl rotor	α_{1ef}, deg	β_{1ef}, deg
Impulse	0.9	30	0.03	0.02	80	180	13.3028	20.0047
Reactive	0.9	30	0.03	0.03	100	100	18.0040	17.5037

Tamman equation of state. This number of cells is sufficient to describe the near-wall flow, in which the condition $y^+ \leq 1$ (dimensionless distance from the wall) is met. Table 2 shows the values at the boundaries of the computational domain and other parameters necessary to perform gas-dynamic calculations.

Table 2: Initial data for 3D gas-dynamic calculations.

Stage type	P^*_{in}, MPa	P_{out}, MPa	T^*_{in}, K	R, J/kgK	γ	P_0, Pa	Ω, rpm
Impulse	20.2	17.701	788.88	387.38	1.298	–85956.2	3000
Reactive	20.2	18.894	788.88	387.66	1.298	–71439.6	3000

At the boundary conditions indicated in Table 2, close to optimal values of isentropic thermal drops are provided, for which the values (u/c_0) are equal to 0.5 and 0.7 for the impulse and reactive stages, respectively. To facilitate the analysis of the influence of the meridional contours overlaps on the gas-dynamic characteristics of the stage, the calculations were carried out without taking into account the overbandage and interdisc flows [24].

Figures 3–6 show the visualization of the flow, and Table 3 shows the main integral characteristics of the stages of impulse and reactive types, in which there are no overlaps of meridional contours.

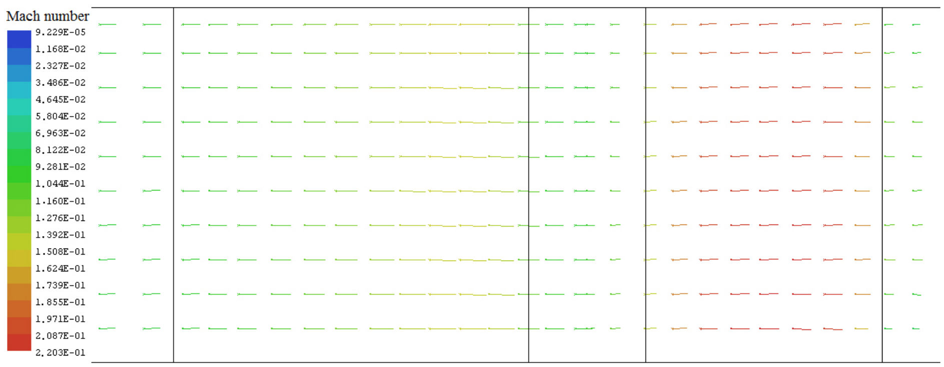
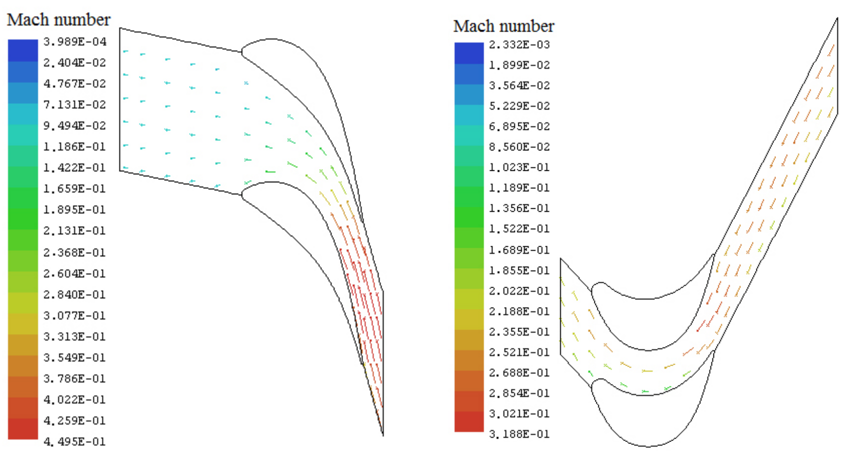


Figure 3: Velocity vectors in the middle meridional section of an impulse type HP stage.



(a) (b)

Figure 4: Velocity vectors in the average tangential section of an impulse type HP stage: (a) stator, (b) rotor.

Table 3: The main integral characteristics of the HP steam turbine stages.

Stage type	η, %	ξ, %	ro	ξ_v, %
Impulse	93.20	7.69	0.12	4.82
Reactive	96.65	5.94	0.50	4.85

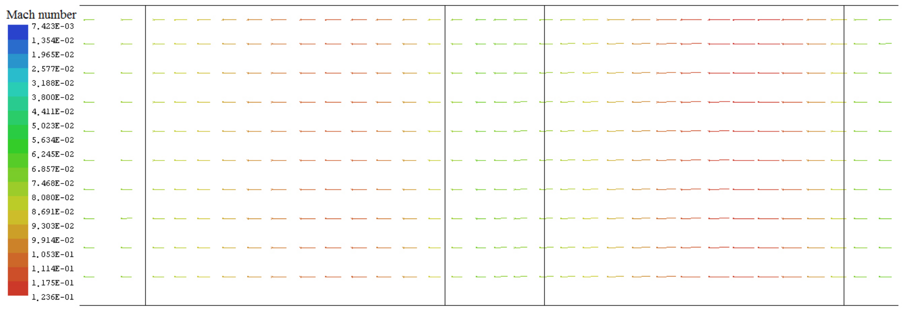
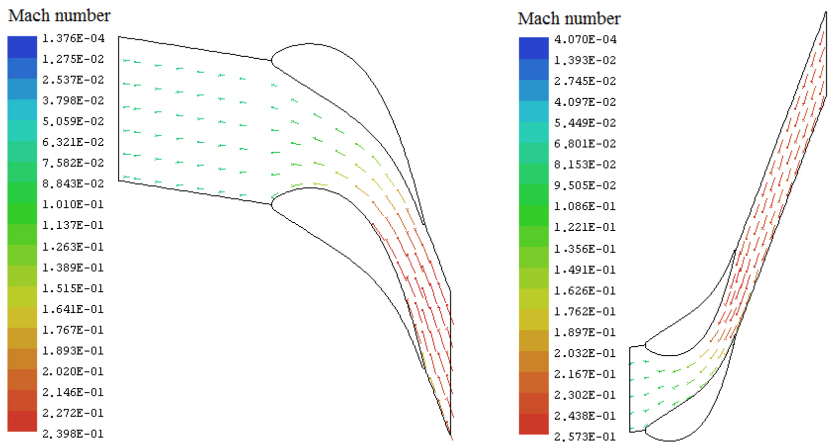


Figure 5: Velocity vectors in the middle meridional section of a reactive type HP stage.



(a) (b)

Figure 6: Velocity vectors in the average tangential section of a reactive type HP stage: a – stator, b – rotor.

The values given in Table 3 are determined as follows:

$$\eta = \frac{h^*_{in} - h^*_{out}}{h^*_{in} - h^*_{iz\,out}}\,, \qquad \xi = \frac{h_{out} - h_{iz\,out}}{h^*_{in} - h_{iz\,out}}\,,$$

$$ro = \frac{h_1 - h_{iz.out}}{h^*_{in} - h_{iz.out}}\,, \qquad \xi_v = \frac{\frac{c^2_{out}}{2}}{h^*_{in} - h_{iz\,out}}\,.$$

From the given results it can be seen that the flow picture in both stage options is favorable, there are no flow separations and high values of gas-dynamic efficiency have been achieved for this type of stages. It is interesting to note that the obtained reactivity values are standard for the corresponding stages. In addition, the reactive type stage exceeds the impulse type stage in terms of efficiency and losses of kinetic energy, which corresponds to the existing concepts.

The studies were carried out for several options of shapes and sizes of overlaps (δ) on the tip and hub shroud (from -3 mm to $+3$ mm):

- option 1 – at the stator outlet (Fig. 7),
- option 2 – at the rotor inlet (Fig. 8),
- option 3 – with a smooth transition between stator and rotor (Fig. 9),
- option 4 – in presence of both overlap and cavern (Fig. 10).

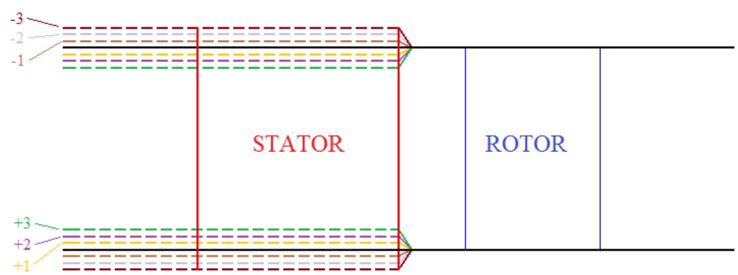


Figure 7: Scheme of option 1 of the meridional contours overlap.

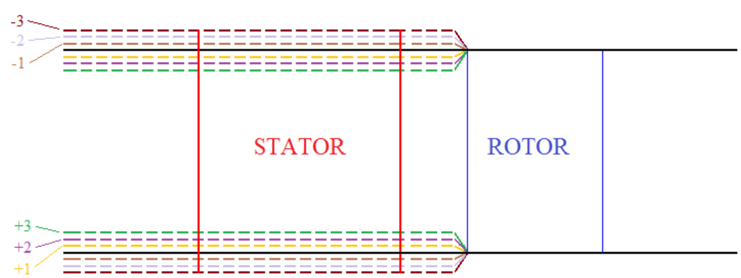


Figure 8: Scheme of option 2 of the meridional contours overlap.

Usually, in real structures, due to technological limitations in the axial stator-rotor interspace, the meridional contours are not continuous surfaces (walls). There are slots on them, and in some cases, there are practically no meridional contours that have a form of solid surfaces in the axial gaps. This type of meridional contours corresponds to option 4.

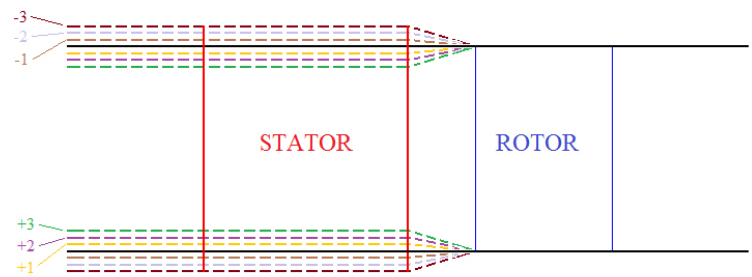


Figure 9: Scheme of option 3 of the meridional contours overlap.

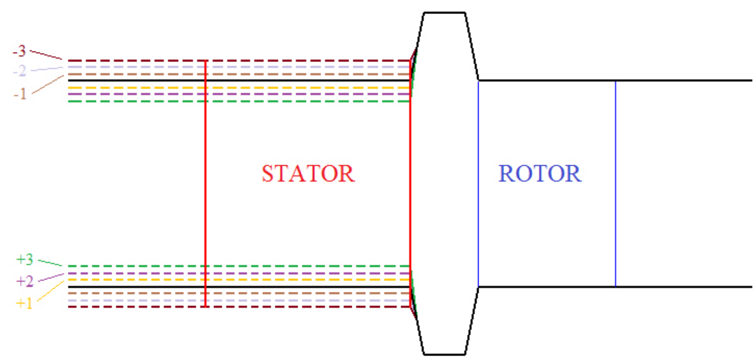
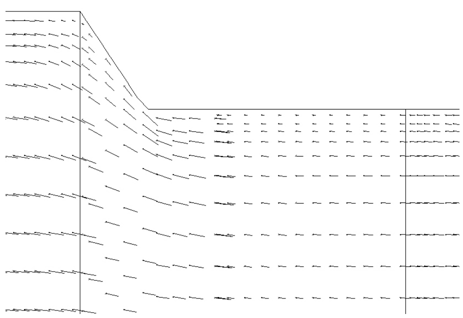


Figure 10: Scheme of option 4 of the meridional contours overlap.

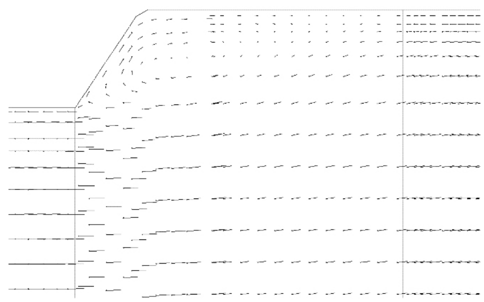
In all options under consideration, with a change in the overlap value δ while maintaining the original profiles, the integral characteristics of the stage, such as flow angles α_1 and β_1, degree of reactivity and, most importantly, the mass flow rate of the working media, will change. The authors are convinced that the study of the effect of overlaps without the mass flow rate preservation is incorrect. Therefore, when varying the value of δ for all overlap options, a slight change in the shape of the stator blade profile (angle α_{1ef} changed), aimed at the mass flow rate preservation, was performed. The permissible deviation of the mass flow rate from the initial value (at $\delta = 0$ mm) was no more than 0.1%.

Figures 11 and 12 show the visualization of the flow in the middle meridional sections in stator-rotor interspace near hub shroud for various overlaps options for the maximum values of δ (± 3 mm).

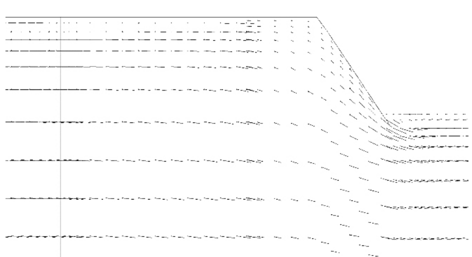
From the given results, the general patterns for the stages of impulse and reactive types can be seen. For overlap options 1 and 2 (abrupt changes in the meridional contours behind the stator and in front of the rotor, respectively), there are circulation zones (flow separations) in places of an abrupt change in the meridional contours shape. For option 3 (a smooth change in the meridional contours), the flow picture is very favorable, the circulation zones (flow separations) in the places where the contours change are almost invisible. For option 4, significant circulation zones (flow separations) are visible in the area of caverns. Moreover, significant circulation (separation) of the flow in caverns is characteristic for any values of δ, including $\delta = 0$.



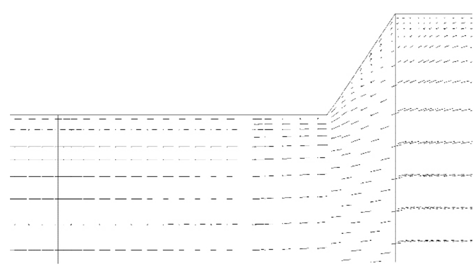
(a) overlap option 1, $\delta = -3$ mm



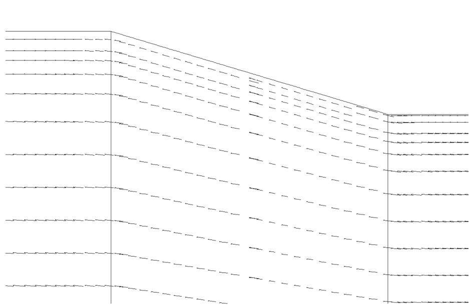
(b) overlap option 1, $\delta = +3$ mm



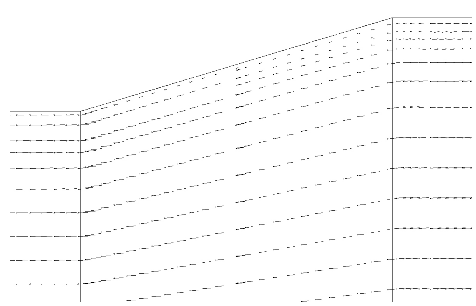
(c) overlap option 2, $\delta = -3$ mm



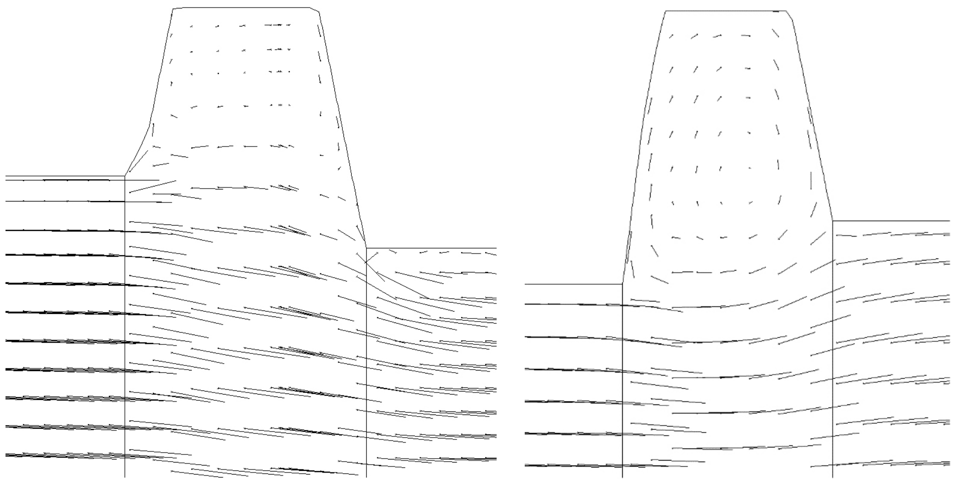
(d) overlap option 2, $\delta = +3$ mm



(e) overlap option 3, $\delta = -3$ mm

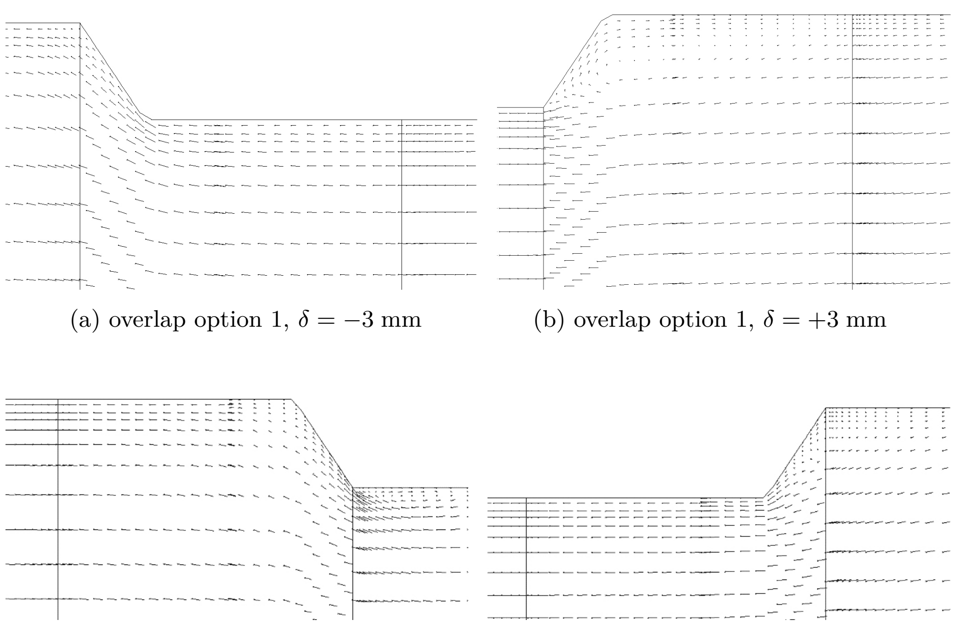


(f) overlap option 3, $\delta = +3$ mm



(g) overlap option 4, $\delta = -3$ mm (h) overlap option 4, $\delta = +3$ mm

Figure 11: Velocity vectors in the middle meridional section in stator-rotor interspace near hub shroud, impulse type stage.



(a) overlap option 1, $\delta = -3$ mm (b) overlap option 1, $\delta = +3$ mm

(c) overlap option 2, $\delta = -3$ mm (d) overlap option 2, $\delta = +3$ mm

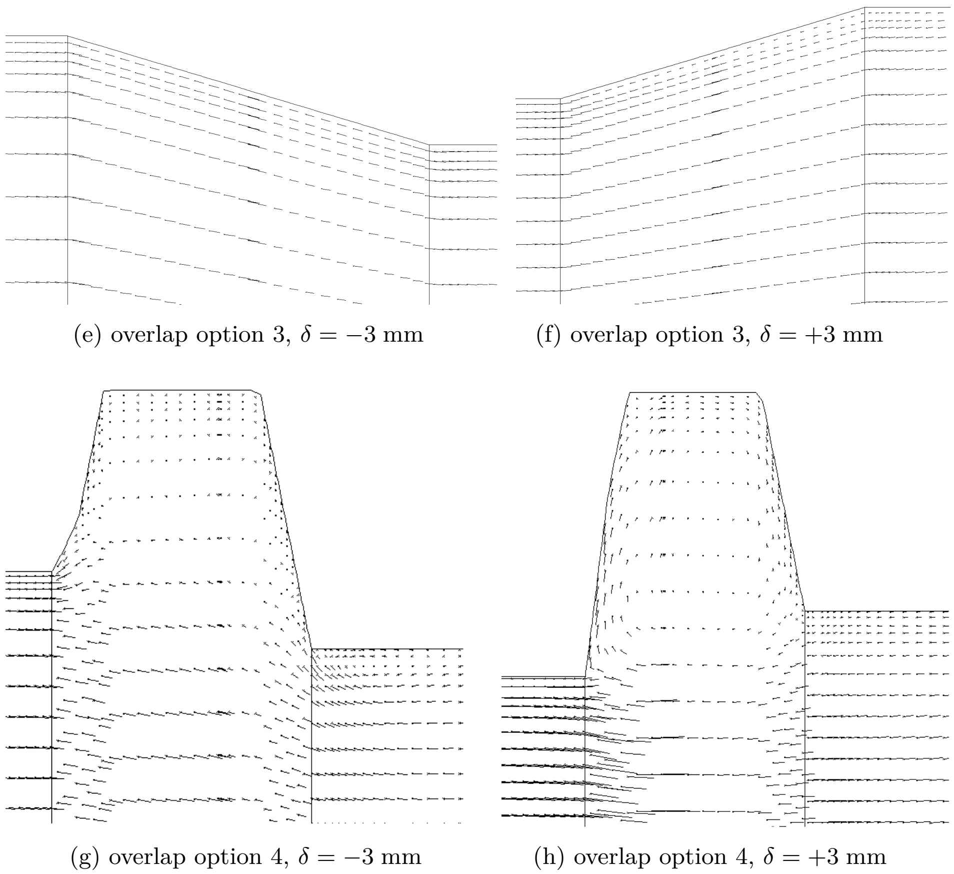


Figure 12: Velocity vectors in the middle meridional section in stator-rotor interspace near hub shroud, reactive type stage.

Table 4 and Figs. 13–16 show the integral characteristics obtained from the results of calculations of the impulse and reactive types of HP steam turbine stages for all options of overlaps and various values of δ.

The presented results show similar patterns for both impulse and reactive type stages. It can be concluded that the best gas-dynamic efficiency is possessed by the stages that do not have overlaps of the meridional contours ($\delta = 0$) and have no caverns. The worst gas-dynamic efficiency is in stages with a cavern (option 4), and its presence (regardless of the value of δ) leads to a significantly greater (by 3–5%), compared to other options, increase in kinetic energy losses and a decrease in efficiency. In the stages with overlap option 3 (smooth change of meridional contours), the

Table 4: Integral characteristics of the HP steam turbine stage for different forms of overlaps.

δ, mm	Impulse type stage				Reactive type stage			
	η, %	ξ, %	ro	ξ_v, %	η, %	ξ, %	ro	ξ_v, %
Overlap option 1								
+3	91.67	10.06	0.14	5.00	95.5	7.64	0.5	4.90
+2	92.38	8.91	0.13	4.89	95.96	6.95	0.5	4.87
+1	92.87	8.11	0.12	4.85	96.45	6.34	0.5	4.86
0	93.2	7.69	0.12	4.82	96.65	5.94	0.5	4.85
–1	93.17	7.87	0.12	4.89	96.47	6.12	0.5	4.88
–2	92.7	8.68	0.12	4.97	95.88	6.91	0.49	4.94
–3	92.21	9.24	0.11	5.14	95.25	7.60	0.48	5.04
Overlap option 2								
+3	92.10	9.18	0.16	5.06	95.84	7.35	0.52	4.96
+2	92.71	8.48	0.14	4.93	96.29	6.53	0.51	4.9
+1	93.12	7.85	0.13	4.83	96.59	6.08	0.54	4.87
0	93.2	7.69	0.12	4.82	96.65	5.94	0.50	4.85
–1	93.16	8.09	0.12	4.94	96.51	6.11	0.49	4.87
–2	92.59	9.01	0.13	5.25	96.2	6.59	0.49	4.92
–3	92.02	9.81	0.15	5.57	95.64	7.23	0.49	5.05
Overlap option 3								
+3	92.61	8.05	0.13	4.77	96.52	6.22	0.51	4.84
+2	92.97	7.79	0.13	4.79	96.63	6.09	0.51	4.84
+1	93.15	7.69	0.12	4.82	96.67	5.97	0.51	4.85
0	93.2	7.69	0.12	4.82	96.65	5.94	0.50	4.85
–1	93.36	7.65	0.12	4.58	96.61	5.96	0.50	4.85
–2	93.36	7.81	0.12	4.89	96.56	6.06	0.49	4.85
–3	93.14	8.22	0.11	4.94	96.5	6.27	0.49	4.86
Overlap option 4								
+3	89.58	10.84	0.19	5.67	93.52	10.81	0.53	5.29
+2	89.55	10.93	0.18	5.68	93.46	10.62	0.53	5.26
+1	89.52	11.02	0.17	5.52	93.36	10.61	0.52	5.27
0	89.33	11.20	0.16	5.51	93.2	10.63	0.51	5.30
–1	89.12	11.42	0.15	5.49	93.04	10.85	0.50	5.33
–2	88.75	11.6	0.14	5.53	92.65	11.04	0.49	5.41
–3	88.22	11.7	0.14	5.58	91.82	11.22	0.47	5.53

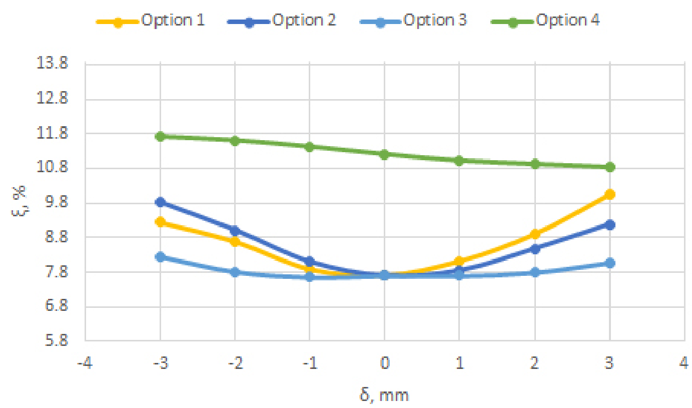


Figure 13: Dependences of kinetic energy losses on the value and type of overlap in the impulse type stage.

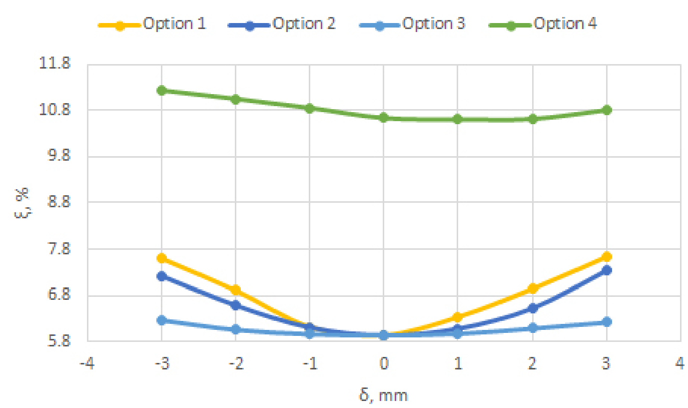


Figure 14: Dependences of kinetic energy losses on the value and type of overlap in the reactive type stage.

influence of value δ is weak and its deviation from 0 mm does not lead to a significant deterioration in the gas-dynamic efficiency of the stages. These conclusions are logical and trivial to some extent, and also correlate well with the approaches to creation of blade-to-blade channels (profiles) of turbines. According to these approaches, it is desirable to provide the most monotonous (smooth) blade surfaces. Based on the foregoing, it is logical to assert that during designing both impulse and reactive type HP stages, it is desirable to ensure the minimum values of the overlaps of the meridional contours in the stator-rotor axial interspace, while the meridional contours themselves should be as smooth as possible.

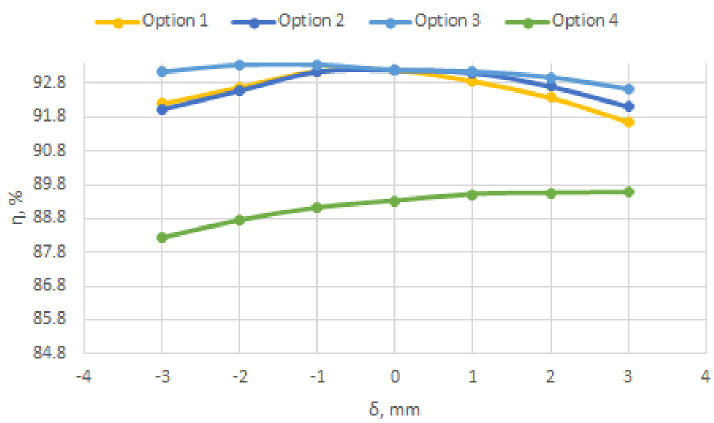


Figure 15: Dependences of efficiency on the value and type of overlap in the impulse type stage.

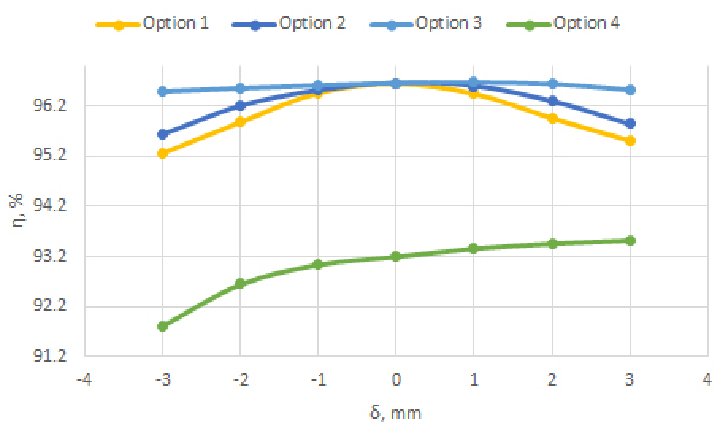


Figure 16: Dependences of efficiency on the value and type of overlap in the reactive type stage.

However, it should be borne in mind that, due to technological limitations, it is not always possible to ensure the implementation of the above recommendations. Therefore, it may be useful to use other regularities obtained from the results of the research. So, it can be seen that for the overlap option 4 (with a cavern), the gas-dynamic efficiency of the stages is approximately the same at positive overlaps values δ. In other words, when the height of the stator blades is less than the rotor's and the jet from the stator 'completely falls' inside the rotor. It is interesting that in constructions where overlaps of meridional contours are used, the positive values of δ mostly are used. It can also be seen that for positive overlaps, option 2 (overlap near rotor) is preferable compared to option 1 (overlap near stator). Thus, if it is completely impossible to avoid caverns and ensure a smooth shape of the meridional contours, it is better to perform overlaps with positive value near the rotor.

4 Conclusions

The results of a systematic study of the effect of meridional contours overlaps in the stator-rotor axial interspace of impulse and reactive types stages of high-pressure steam turbine on the flow structure and gas-dynamic efficiency of flow parts are presented for the first time. It is shown that the best gas-dynamic efficiency is possessed by the stages that have no overlaps and/or have a smooth shape of meridional contours. It has been established that the most negative effect on the flow part is provided by the presence of caverns in the gap between the rows. For cases where, due to technological limitations, it is impossible to avoid the presence of caverns and overlaps with an abrupt (step-wise) change in the shape of the meridional contours, it is recommended to perform overlaps with positive δ values near the rotor blades.

Acknowlegments The authors are grateful to the National Academy of Sciences of Ukraine for funding the research described in this article within the framework of the budgetary theme II-14-20 "Development of methods to increase the efficiency of high-pressure power units through the introduction of steam and gas technologies" under the program aimed to support the development of priority areas of research.

Received 12 November 2020

References

[1] Zhu Y., Luo J., Liu F.: *Influence of blade lean together with blade clocking on the overall aerodynamic performance of a multi-stage turbine.* Aerosp. Sci. Technol. **80**(2018), 329–336.

[2] Tulsidasa D., Shantharaja M.: *Effect of taper and twisted blade in steam turbine.* Int. J. Sci. Technol. Manage. **4**(2015), 1, 319–325.

[3] Lampart P., Gardzilewicz A., Rusanov A., Yershov S.: *The effect of stator blade compound lean and twist on flow characteristics of a turbine stage – numerical study based on 3D NS simulations.* In: Proc. 2nd Symp. on Comp. Technologies for Fluid/Thermal/ Chemical Systems with Industrial Applications, ASME PVP Div. Conf., 1-5 Aug. 1999, Boston, **397**(1999), 195–204.

[4] Benner M.W., Sjolander S.A., Moustapha S.H.: *Influence of leading-edge geometry on profile losses in turbines at off-design incidence: Experimental results and an improved correlation.* J. Turbomach. **119**(1997), 193–200.

[5] Lee J.F.: *Theory and Design of Steam and Gas Turbines.* McGraw-Hill, London 1999.

[6] Oprea I., Negreanu G.: *Research on the long blades of the steam turbine.* In: Proc. Conf.: METIME 2005, 2005.

[7] Stodola A.: *The Steam Turbine and the Future of Heat Engines.* St. Petersburg 1904 (in Russian).

[8] Shcheglyaev A.V.: *Steam turbines. Thermal Process Theory and Turbine Construction.* Vol. 2, (6th Edn.). Energoatomizdat, Moscow 1993 (in Russian).

[9] Kazandzhan P.K., Tikhonov N.D.: *Theory of Aircraft Engines. The Theory of Blade Machines: Part 1. Mechanical Engineering*, Moscow 1995 (in Russian).

[10] Kostyuk A.G.: *Some pressing problems of design and modernization of steam turbines.* Therm. Power Eng. **4**(2005), 16–27 (in Russian).

[11] Ainley D.G.; Mathieson C.R.: *An Examination of the Flow and Pressure Losses in Blade Rows of Axial-Flow Turbines.* Aeronaut. Res. Counc. Rep. Memo. Techn. Rep. 2891, London 1955.

[12] Osipov S.K.: *Computational and experimental study of variants of the LP flow parts in order to increase their throughput.* PhD thesis, National Research University Moscow Energy Institute, Moscow 2019.

[13] Baljé O.: *Turbomachines – A Guide to Design, Selection and Theory.* Wiley & Sons, New York 1981.

[14] Craig H.R.M., Cox H.J.A.: *Performance estimation of axial flow turbines.* P.I. Mech. Eng. **185**(1970), 1, 407–424.

[15] Trukhny A.D.: *Stationary Steam Turbines* (2nd Edn.). Energoatomizdat, Moscow 1990 (in Russian).

[16] Diakunchak I.S., Gaul G.R., McQuiggan G., Southall L.R.: *Siemens Westinghouse Advanced Turbine Systems Program Final Summary.* American Society of Mechanical Engineers. GT–2002–30654, 2002.

[17] Scoretz M., Williams R.: *Industrial Steam Turbine Value Packages.* GE Energy, Atlanta 2008.

[18] Minchener A.: *Developments in China's coal-fired power sector.* IEA Clean Coal Centre., London 2010,

[19] Rusanov A., Rusanov R., Lampart P.: *Designing and updating the flow part of axial and radial-axial turbines through mathematical modelling.* Open Eng. **5**(2015), 399–410.

[20] Yershov S., Rusanov A., Gardzilewicz A., Lampart P.: *Calculations of 3D viscous compressible turbomachinery flows.* In: Proc. 2nd Symp. on Comp. Technologies for Fluid/Thermal/Chemical Systems with Industrial Applications. ASME PVP Division Conf., 1–5 August 1999, Boston, PVP, **397.2**(1999), 143–154.

[21] Godunov S.K., Zabrodin A.V., Ivanov M.Ya. *et al.*: *Numerical Solution of Multidimensional Problems of Gas Dynamics.* Nauka, Moskow 1976 (in Russian).

[22] Rusanov A.V., Lampart P., Pashchenko N.V., Rusanov R.A.: *Modelling 3D steam turbine flow using thermodynamic properties of steam IAPWS-95.* Pol. Marit. Res. **23**(2016), 1(89), 61–67.

[23] Lampart P., Rusanov A., Yershov S., Marcinkowski S., Gardzilewicz A.: *Validation of 3D RANS Solver with a state equation of thermally perfect and calorically imperfect gas on a multi-stage low-pressure steam turbine flow.* J. Fluid. Eng. – T ASME **127**(2005), 83–93.

[24] Lampart P., Yershov S., Rusanov A., Szymaniak M.: *Tip leakage/main flow interaction in multi-stage HP turbines with short-height blading.* In: Proc. ASME Turbo Expo 2004 5 B, 1359–1367.