Computational fluid dynamics analysis of several designs of a Curtis wheel

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Abstract In small steam turbines, sometimes the efficiency is not as important as the cost of manufacturing the turbine. The Curtis wheel is a solution allowing to develop a low output turbine of compact size and with a low number of stages. This paper presents three fully dimensional computational fluid dynamics cases of a Curtis stage with full and partial admission. A 1 MW steam turbine with a Curtis stage have been designed. The fully admitted stage reaches a power of over 3 MW. In order to limit its output power to about 1 MW, the partial admission was applied. Five variants of the Curtis stage partial admission were analyzed. Theoretical relations were used to predict the partial admission losses which were com-pared with a three-dimensional simulations. An analysis of the flow and forces acting on rotor blades was also performed.

Keywords: Steam turbines; Curtis stage; Computational fluid dynamics; Partial admission

1 Introduction

Curtis wheel technology is well known due to its appearance in engineer-ing over one hundred years ago. Its advantages include relatively compact dimensions for a given power compared with other stage designs and the possibility of power regulation with a nozzle. The cost of those advantages is its lower efficiency in comparison to other stage designs and the occurrence of supersonic speeds in the turbine.

The Curtis wheel is often used as the first stage of multistage turbines and as a single stage in low output turbines as well as marine reverse gear turbines. In general, it is applied when the low cost of the turbine is more important than its efficiency.

Although this type of turbine stage has been known for a long time, there are not many publications regarding it besides general information in turbomachinery books. In [1], the authors describe the design process of a Curtis stage wheel. Shown are the preliminary calculations, including velocity triangles and both two- and three-dimensional computational fluid dynamics (CFD) simulations. The initial simulation showed that in the first rotor blade row there were losses due to shocks, but the authors corrected the blade shape and prevented the shocks. The presented simulations were carried out for flow through a single blade. Paper [2] takes into consideration the differences between the characteristics of a Curtis wheel taken from one dimensional calculations and the actual performances of the turbine. Unsteady simulations showed that the cause of an error in performance prediction was mainly due to unsteady interaction between the first stator and the rotor rows. The paper presents results of simulations for only two stator channels and four rotor channels. A general turbomachinery handbook, among other issues, describes the design process and dimensionless characteristics of a Curtis wheel and losses coefficients [3].

There are many more publications on partial admissions in more typical turbine stages. In papers [4,5] the authors analyze axial multi-stage partial-admission ORC turbines. Both turbines include rings to limit ventilation losses. Paper [6] analyzes the influence of inlet pressure and temperature as well as an admission arc and rotational speed on losses due to partial admission. Calculations were performed using CFD methods. In [7] a CFD analysis of quasi three dimensional model with no change of pressure distribution in the radial direction was used to analyze partially admitted air turbine. The calculations were supported by experimental results. The position of admission arcs was also analyzed. An unsteady flow simulation in a 200 MW turbine with partial admission was described in [8]. Analyzed were the unsteady forces acting on control stage rotor blades. In [9] the au-thors analyze inlet geometries for small, partially admitted steam turbine. Paper [10] analyzes the influence of stator-rotor interspace overlap on the efficiency of high pressure steam turbine.

A 1 MW steam turbine with a Curtis stage had to be designed. The fully admitted stage had a power of over 3 MW. In order to limit this power to about 1 MW, partial admission was applied. This paper presents 3D CFD flow analyses of a Curtis wheel with partial and full admission. The influence of a partial-admission arc on efficiency and forces acting on blades was also inspected. Five variants of the Curtis stage with partial admission were analyzed. Curtis wheels can be built with even four rotor rows, but more usually with two. Here only two rows were considered. Three or more rows allow for a Curtis wheel with even more compact dimensions, but this greatly limits its efficiency.

2 Numerical model

The solver chosen for the CFD simulation was Ansys CFX [13, 16]. To simulate the steady viscous flow through the stator and rotor blades, the Reynolds-averaged Navier–Stokes (RANS) approach with the k-ω SST (shear stress transport) turbulence model was applied. Design Modeler [14] was used to create the geometries of rotor and stator blades as well as the turbine outlet, and TurboGrid [15] was used to discretize the blade and outlet geometries. The number of cells in simulations was about 18 million.

In the model, two rotor and two stator blade rows were considered with profiles from [11]. A frozen rotor interface was used between the stator and rotor domains. In this interface, only one relative position of the stator and rotor blade was taken into account. An adiabatic and smooth wall condition was assumed. Total pressure and total temperature were assumed at the inlet and total static pressure at the outlet. The IAPWS IF97 (International Association for the Properties of Water and Steam Industrial Formulation 1997) equation of state was used [17]. The analyzed the rotational speed of the stages was 3000 rpm.

3 Stage with full admission

First, the Curtis wheel was analyzed with full admission. The blades of second row were atypical for this kind of stage. Moreover, the reversing blades were larger than usual and the velocity triangles of second row are also different. The height of the blades was constant throughout the entire stage. The blades and streamlines of the stage with full admission are shown in Fig. 1.

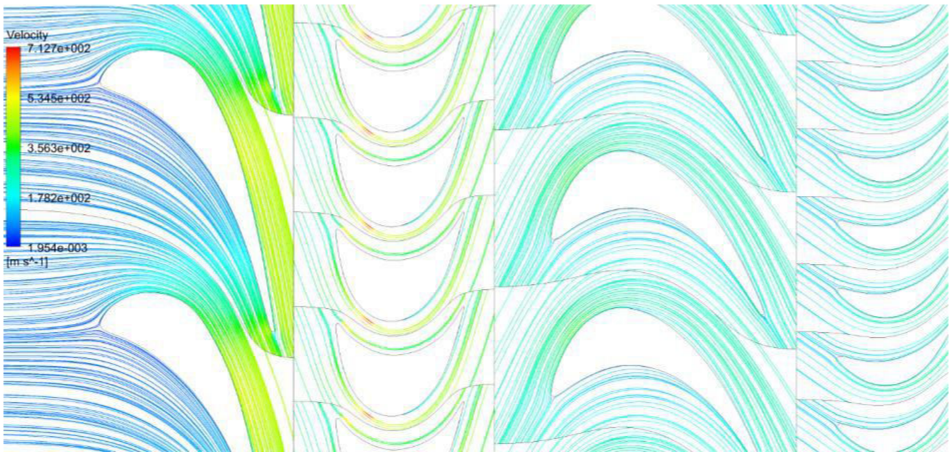

Figure 1: Streamlines in Curtis stage with full admission.

Figure 2 shows that the flow is free of disturbances except the separation of flow in the region of first rotor blade row. A region of high velocity occurs next to this separation. This is caused by the divergence of the channel and the size of blade profiles. Additionally, the angle of attack in this blade row is slightly too small. The degree of reaction of this blading is about

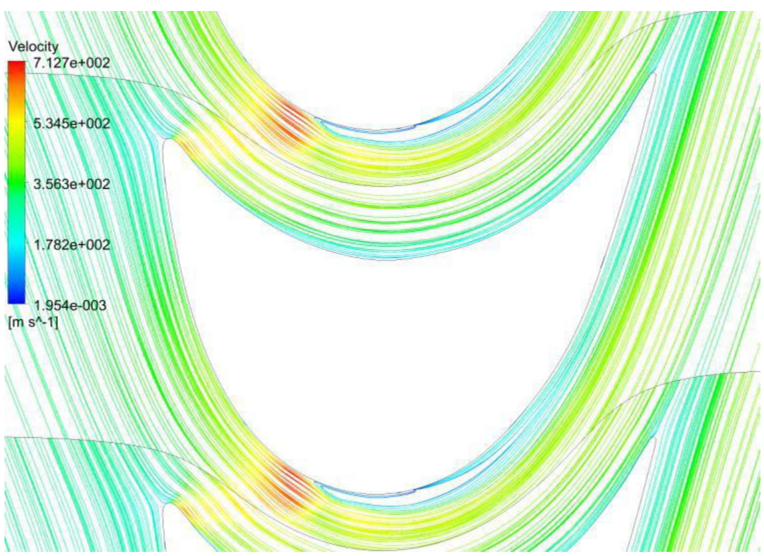

Figure 2: Streamlines in Curtis stage first row rotor with full admission.

0.2. The efficiency of the considered stage with full admission is 75.8%. The power and the mass flow is 3.424 MW and 28 kg/s. The forces acting on rotor blades were also analyzed. In Curtis wheel with full admission, only the axial force was unbalanced. Its value was 11.4 kN.

4 Stage with partial admission

The Cutis stage with full admission reached a power of over 3 MW. In order to limit its power to about 1 MW, partial admission was applied. Five variants were analyzed.

4.1 Variant 1

The blade cross-sections and their length were the same as in the previous section. The admission arc was assumed to be 1/3 of the circumference of the turbine. The blades and streamlines of the stage with partial admis-sion are shown in Fig. 3. Similarly to the simulation of the stage with full admission, the flow in the stage with partial admission was free of distur-bances except for the separation of flow in the region of first rotor blade row, Figs. 2 and 3. In this case, high velocity areas also occurred at the ends of the admission arc and vortices appeared outside it. The efficiency for the turbine 1/3 admission was 72.5%. This value is lower than in the turbine with full admission due to ventilation losses and losses at ends of admission arc. They will be described with greater detail in further sec-

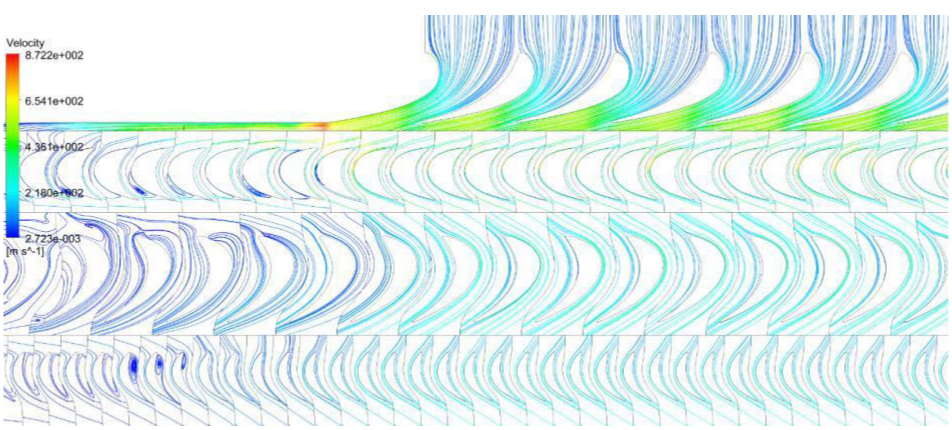

Figure 3: Streamlines in the Curtis stage with partial admission.

tions. The values of power and mass flow were lower than in the Curtis stage with full admission at 1.063 MW and 9.087 kg/s. In addition to an axial force, 2.5 kN, which was lower than in the stage with full admission (11.4 kN), a lateral force (7 kN) also appeared.

4.2 Variant 2

The blading in the second variant was more similar to a typical Curtis stage. The profiles of the first rotor blade and reversing blade row were changed. The profile of the rotor blade row was more adequate to the attack angle and did not create a divergent channel. The profile of reversing blades was more symmetrical than in the previous variant. The blades and streamlines are shown in Fig. 4.

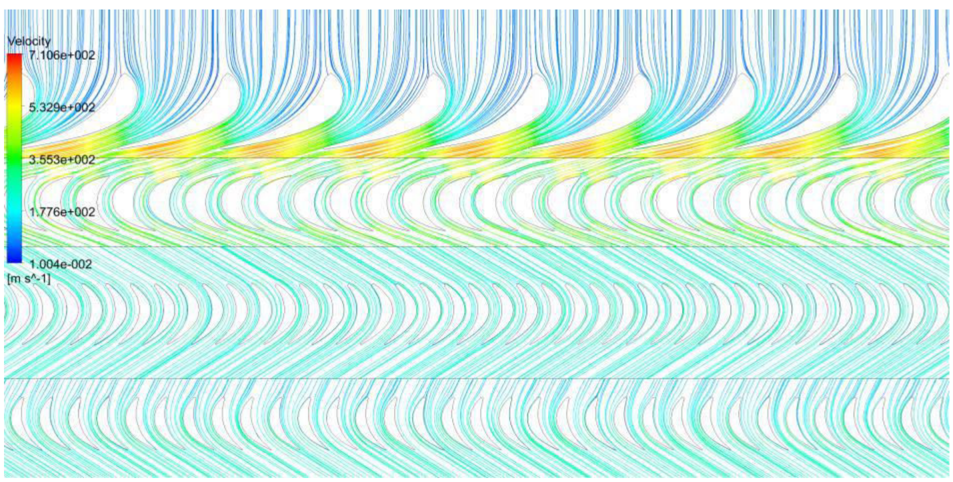

Figure 4: Streamlines in variant 2.

The flow through the stage showed no regions of boundary layer separation, but it was compressed in the first rotor row. The compression occurred due to the convergence of rotor blade flow channels and their supersonic speed. This resulted in a low degree of reaction, 0.10. The flow around the reversing blades was correct, as in the previous variant. In comparison to the pervious variant, efficiency was increased to 74.0%. The power was 1.104 MW and mass flow was 9.238 kg/s. The axial force was 0.8 kN and the lateral force was 7.3 kN. The axial force was lower than for variant 1 (2.5 kN) but lateral force was slightly higher (7 kN).

4.3 Variant 3

In third variant, the blade profiles of stator blade row, first rotor blade row and reversing blade row were changed. The profile of the stator blade row was changed in order to obtain higher velocities. Blades of the first rotor blade row created a converging-diverging channel for adequate transonic flow. The reversing blades were thicker than in variant 2. The 3D CFD velocity triangles corresponded well with the one-dimensional calculations. The mean diameter of the stage was increased and the length of the stator and reversing blades was increased. The stage also had 1/3 of circumference admission. The blades and streamlines are shown in Fig. 5.

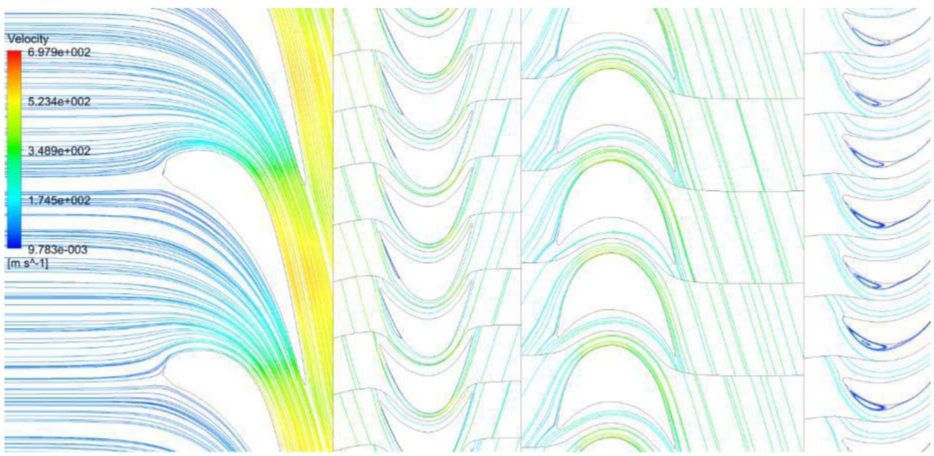

Figure 5: Streamlines in variant 3.

In this variant, vortices appeared near the entry regions of the first and second rotor blade rows. The angles of attack in the reversing blade row and second blade row were not adequate. In second blade row the angle of attack was too high, causing boundary layer separation and vortices near the channel entry. In the first blade rotor blade row the angle of attack was too low, moreover the compression occurred in that blade row. The degree of reaction was about 0.16. The efficiency in this variant was 75.8%. The increase of efficiency in comparison to the previous variants occurred mainly as a result of the change in the turbine mean diameter and not as a result of the changes in blade profiles. The values of power and mass flow were 1210 kW and 9.881 kg/s. The lateral force was 7.2 kN and axial force was 0.6 kN. In contrast to variants 1 and 2, the axial force was directed towards the inlet due to the compression that occurred in first rotor blade row.

4.4 Variant 4

In the fourth variant, the blade profiles in the reversing and first rotor blade rows were changed in comparison with the variant 3 to make them more suitable for near-transonic flow. Figure 6 shows the turbine blades and streamlines. Vortices appeared near the entry to the second rotor blade row as in the previous turbine variant. Here, this also occurs as a result of the angle of attack being too high. In contrast to the previous variant, the angle of attack on the reversing blades was correct. Also the change of the profile of first rotor blade row prevented the occurrence of compression. In this variant, the degree of reaction was higher than in previous variants due to a higher enthalpy drop in the first rotor and reversing blade rows. The degree of reaction was 0.23. The lack of compression behind the stator blade row increased efficiency to 80.1%. The mass flow was 9.828 kg/s and the power was 1271 kW. The values of lateral and axial forces were 7.6 kN and 2.1 kN. The lateral force was higher than that for variant 3 (7.2 N).

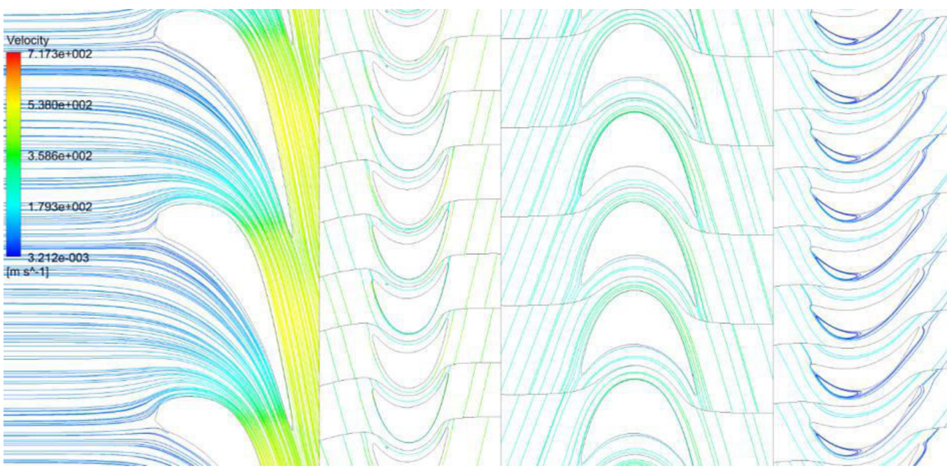

Figure 6: Streamlines in variant 4.

4.5 Variant 5

In the fifth variant, the profile of the second rotor blade row blades was changed to eliminate the vortices that appeared in variants 3 and 4. The blades and the streamlines are shown in Fig. 7. This shows that the angle of attack of this profile is correct, preventing vortices from forming at the entry to the second rotor blade row. Simultaneously, it increased the degree of reaction to 0.26 and efficiency to 82.4%. The mass flow was 9.792 kg/s and the power was 1302.8 kW. The values of lateral and axial forces were 7.7 kN and 3.3 kN, respectively, and therefore higher than in variant 4 (7.6 kN, 2.1 kN). This variant is recommended for 1 MW steam turbine with a Curtis stage.

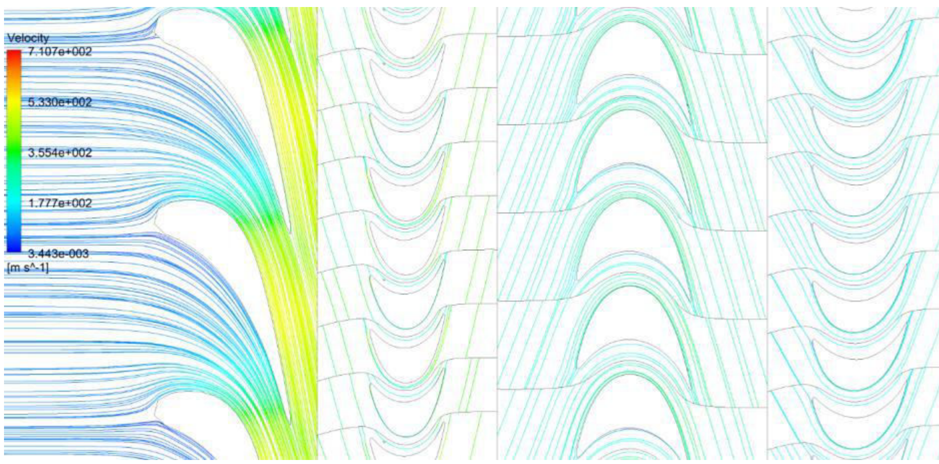

Figure 7: Streamlines in variant 5.

5 Comparison of stages with full and partial admission

In the first variant, the turbine with partial admission was 3.3% less efficient than the turbine with the same geometry but with full admission. This is caused by losses due to ventilation and losses at both ends of the admission arc. The admission arc in partial admission variant 1 covered 1/3 of the turbine circumference. The analysis included the ventilation losses and losses at the ends of the admission arc. Paper [12] presents a number of methods to calculate the losses due to partial admission. Here the relation from [3] is considered:

$$N_V = K_V(1 - \varepsilon)dl_2u^3\rho \,, \tag{1}$$

where: K_V – empirical coefficient of ventilation losses, ε – admission arc, here $\varepsilon = 1/3$, d – diameter of turbine, l_2 – length of rotor blade, u– peripheral velocity, ρ – average density in rotor.

The loss due to this equation is about 76.4 kW. The power of the turbine with full admission multiplied by partial (1/3) admission arc is 1.141 MW. The difference between this value and the power obtained from the 3D CFD simulation of turbine with partial admission is 78 kW. Therefore, Eq. (1) quite precisely estimates losses due to partial admission.

6 Summary and concluding remarks

In this paper, a Curtis wheel with full and partial admission was analyzed using a 3D CFD. The influence of a partial admission arc on the efficiency and forces acting on blades was studied. The purpose was to design a 1 MW steam turbine with a Curtis stage. With full admission this stage reaches a power of over 3 MW. In order to limit it to about 1 MW, partial admission was applied. Five variants were considered.

As was shown, for example in [2], the process of designing of the Curtis stage is complex due to difficulties with estimating the efficiency and flow velocity. During the design process, the differences between the one-dimensional and three-dimensional calculations occurs. In turbines with partial admission, there is additionally the issue of dispersal of flow in suc-cessive rows, which further complicates calculations.

Table 1 presents the turbine flow parameters of the five simulations, including the velocity ratio defined as the ratio of peripheral velocity and isentropic speed. A specific type of blading is required to provide a low degree of reaction of Curtis stage. This can be achieved by using blades that create channels with almost not diverging or converging cross-sections or ones that compress the flow in one of the rows. Both solutions decrease the efficiency by making it easier to form boundary layer separations in the flow. The second approach can even create a negative axial force.

Table 1: Streamlines in Curtis stage with full admission.

Variant	Degree of reaction	Power (MW)	Mass flow (kg/s)	Efficiency (%)	Axial force (kN)	Lateral force (kN)	Blade height	Velocity ratio
1	0.20	1.063	9.087	72.5	2.5	7.0	constant	0.23
2	0.10	1.104	9.238	74.0	0.8	7.3	constant	0.23
3	0.16	1.210	9.881	75.8	–0.6	7.2	variable	0.25
4	0.23	1.271	9.828	80.1	2.1	7.6	variable	0.25
5	0.26	1.303	9.792	82.4	3.3	7.7	variable	0.25

Variant 5 was recommended for further usage. Its degree of reaction is higher than in other variants, but it prevents the boundary layer separation in a wider range of flow conditions. Its efficiency is also higher than in other variants. The highest value of axial force achieved in this variant is a disadvantage, but it is only one of the components of the forces acting on blades.

As has been shown, the turbines with partial admission and a single, two-row Curtis stage, in terms of fluid flow, can be considered for application in small backpressure steam turbines, especially for those using waste heat and in cases where the enthalpy drop is low. There is a possibility to use such turbines without a reduction gear. The efficiency of this solution can be theoretically quite high.

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