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Optimization of Curtis stage in 1 MW steam turbine

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Abstract. When operating at 3000 rpm, small turbines do not require a gear box and the generator does not require complex electronic software. This paper analyses the various geometries of the Curtis stage, comprising two rotor and stator blades with and without an outlet, from the efficiency point of view. Presented are 3D steady viscous flows. The results were compared with the performance of an axial turbine.

1 Introduction

Small steam turbine flow paths can have an axial design with several stages, or can comprise one Curtis or more stages.

Described in [1] is the design and CFD analysis of a Curtis Turbine Stage.

[2] showed a Curtis steam Turbine

[3] presented ways of designing the Curtis stage, nozzle/rotor aerodynamic interaction and the effects on Curtis stage performance

This paper for the first time presents eight variants with full and partial admission for the optimization of a Curtis stage in a 1 MW steam turbine.

2 Boundary conditions

ANSYS CFX was used to calculate steady viscous flow through stator and rotor blades. The number of rotor and stator blades is presented in Tab 1. Design Modeller was used to create the geometries of rotor and stator blades as well as the turbine outlet. TurboGrid was used to prepare the blade and outlet meshes.

In the first model, only one blade in each channel, stator1, rotor1, stator2, rotor2, was analysed. The flow in the interfaces between sator1, rotor1, stator2 and rotor 2 was averaged by Stage (Mixing-Plane). In the next model, all the rotor and stator blades were considered. In these cases, the Frozen rotor interface was used. In this interface, only one relative position of the stator and rotor blade was taken into account. An adiabatic wall condition was assumed.

Table 1. Stator and rotor blades in a Curtis stage

	profile	number of blades
First stator	S9012-A	55
First rotor	R2314-A	141
Second stator	S4525-A	85
Second rotor	R5535-A	197

2.1 Variant one

The calculation of the Curtis stage was done for the full admission in order to see the periodicity of the flow.
The blade length was 20 mm. The profiles of the rotor and stator blades was taken from [4], see Table 1.

Fig. 1 presents the flow through the stage. The supersonic and stall regions are visible.

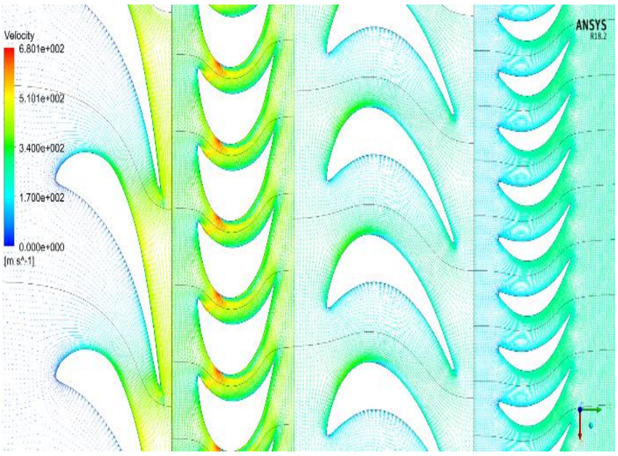

Fig. 1. Velocity field at 0.5 of the stator1 blade length, variant one

According to the CFD calculations, the turbine generated 1.688 MW with a mass flow of 13.98 kg/s (50.33 t/h) and was 74.827% efficient.

2.2 Variant two

In variant two, 1/3 circumference partial admission was analysed.
The number of first stator blades is 17 instead of 55, but the remaining numbers of blades is the same as those presented in Tab 1.

Figs. 2, 3, 4, 5 and 6 the flow through the stage. The supersonic and stall regions are visible.

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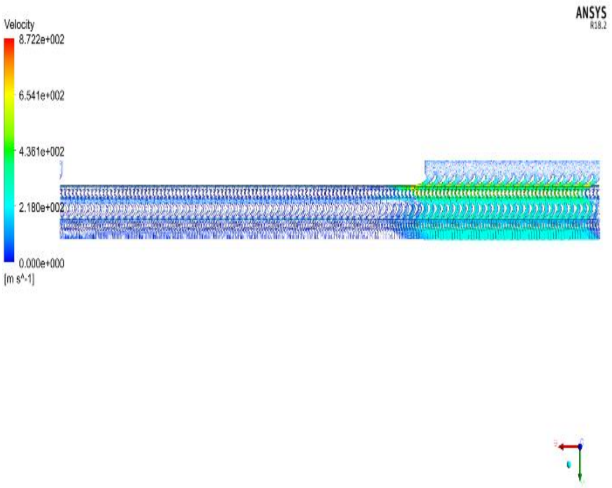

Fig. 2. Velocity field at 0.5 of the stator1 blade length, variant two

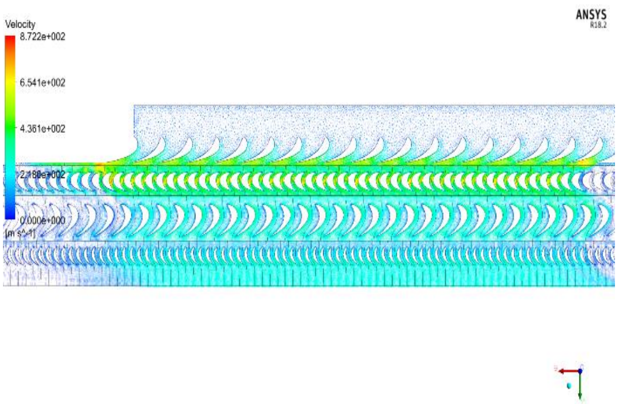

Fig. 3. . Velocity field at 0.5 of the stator1 blade length, variant two

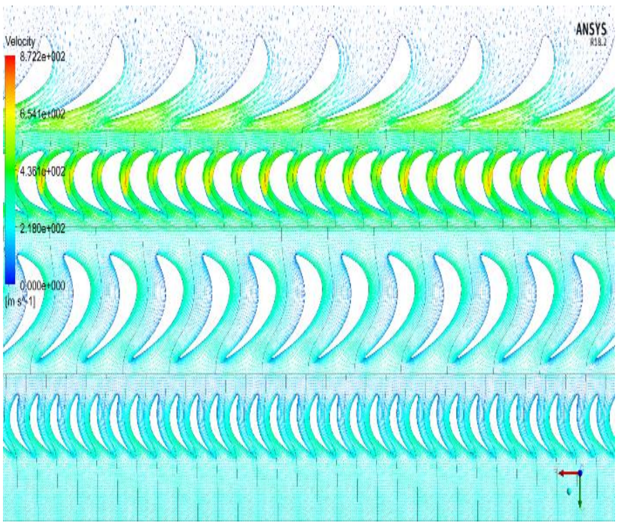

Fig. 4. Pole wektorów prędkości w połowie wysokości łopatek

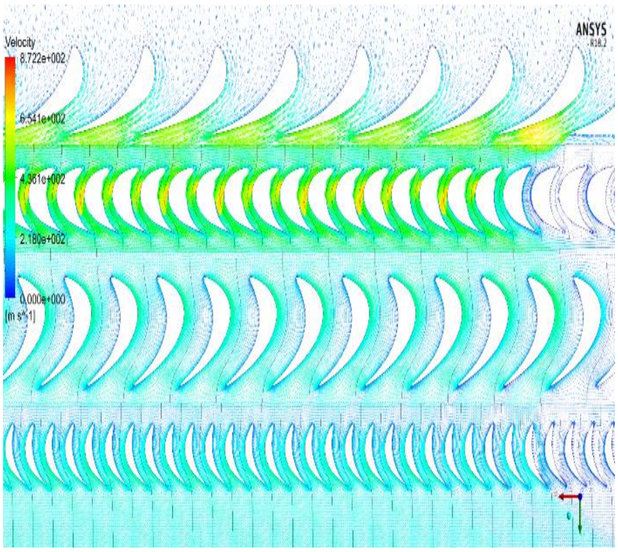

Fig. 5. Velocity field at 0.5 of the stator1 blade length, variant two

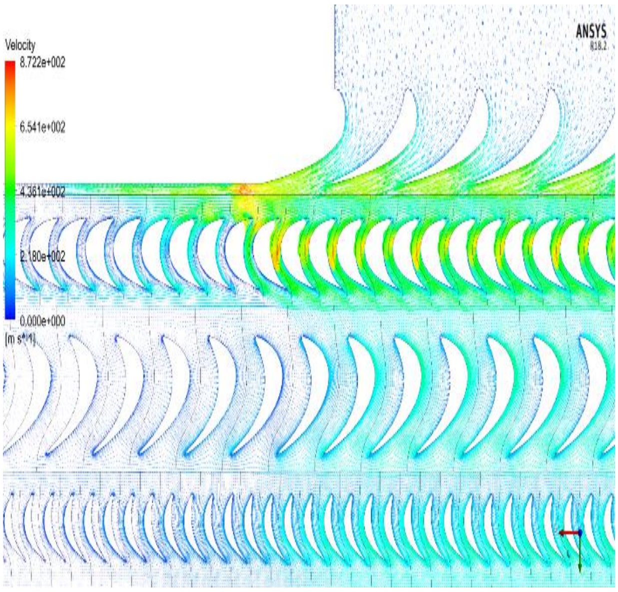

Fig. 6. Velocity field at 0.5 of the stator1 blade length, variant two

In this case, the turbine generated 1,063 MW, with a mass flow of 9.09 kg/s (32.72 t/h) and 72.48 % efficiency. The reduced power, mass flow efficiency were due to the partial admission.

2.3 Variant three

Variant three differed from the second variant with regard to the profile of the first rotor blade. The numbers of rotor and stator blades are shown in Table 2.

Table 2. Stator and rotor blades in a Curtis stage

	profile	number of blades
First stator	S9012-A	17
First rotor	R2117-Bk	141
Second stator	S4525-A	85
Second rotor	R5535-A	197

The modification prevented transonic and supersonic flow through rotor 1, but caused stalling in the stator 2 stage (Fig. 7).

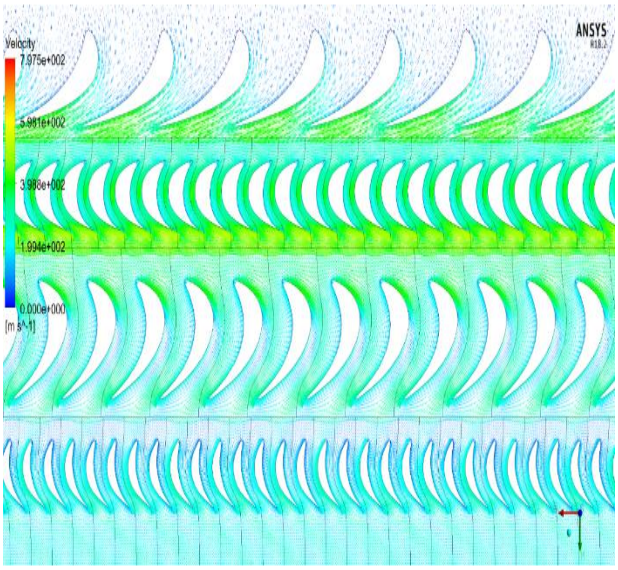

Fig. 7. Velocity field at 0.5 of the stator1 blade length, variant three

In this case, power fell to 0,964 MW, mass flow fell to 8.42 kg/s (30.31 t/h) and efficiency to 70.94 %.

2.4 Variant four

Here, the profile of the stator 2 blades was changed in order to avoid the stalling that occurred in variant three.

Table 3. Stator and rotor blades in a Curtis stage

	profile	number of blades
First stator	S9012-A	17
First rotor	R2117-Bk	141
Second stator	R4629-A	153
Second rotor	R5535-A	197

This measure proved ineffective, and stalling still occurred, as is seen in Fig. 8.

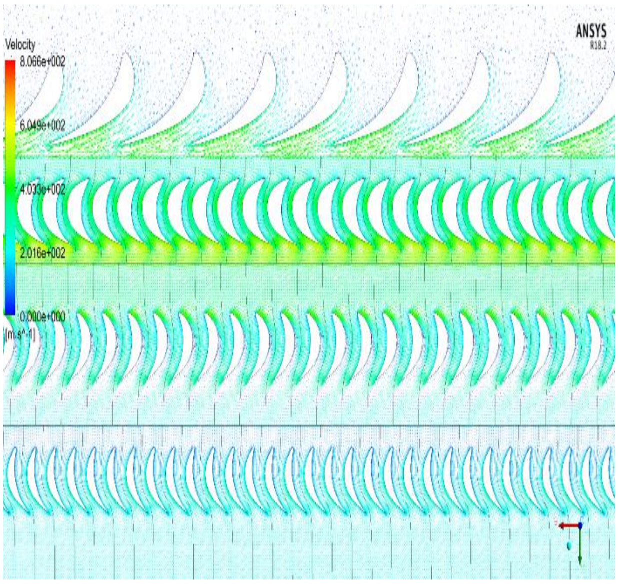

Fig. 8. Velocity field at 0.5 of the stator1 blade length, variant four

Power generation again fell, to 0.958 MW, mass flow increased to 8.50 kg/s (30.6 t/h), but efficiency fell to 68.71 %.

2.5 Variant five

In variant five, the stator 2 blade profile was further altered (Tab. 4), and the inlet of steam now came from two, opposing tubes, and not one, as in the cases of the preceding variants.

Table 4. Stator and rotor blades in a Curtis stage

	profile	number of blades
First stator	S9012-A	16
First rotor	R2117-Bk	141
Second stator	R3525-A	155
Second rotor	R5535-A	197

Figs. 9 and 10 present vector fields. The applied profiles did not prevent stalling, and the application of two opposing inlet tubes increased losses in stator 1.

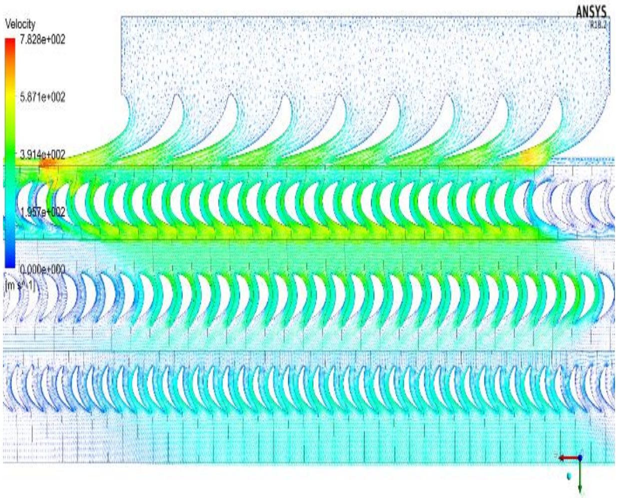

Fig. 9. Velocity field at 0.5 of the stator1 blade length, variant five

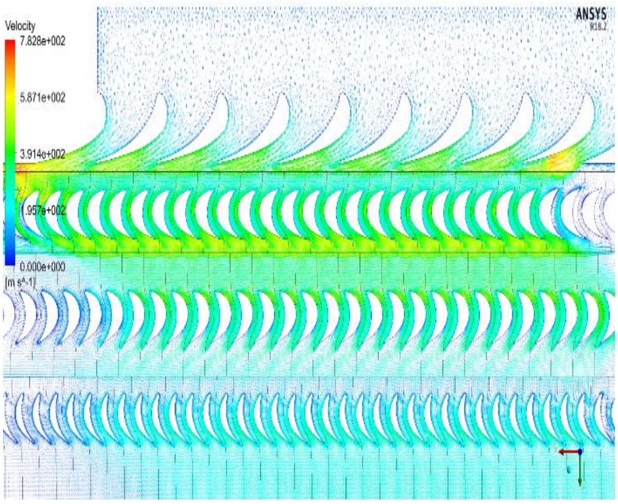

Fig. 10. Velocity field at 0.5 of the stator1 blade length, variant five

In variant five, power generation remained the same as in variant four, 0.958 MW, mass flow increased to 8.66 kg/s (31.18 t/h), but efficiency fell to 68.52 %.

2.6 Variant six

Here, the profiles of all the blades were altered with the exception of those in stator 1 (Tab. 5). These changes were carried out using the polynomial method. The steam entered the turbine the same way as in variants 2, 3 and 4, i.e. without the use of two inlet tubes.

Table 5. Stator and rotor blades in a Curtis stage

	profile	number of blades
First stator	S9012-A	17
First rotor	1818	149
Second stator	3633	234
Second rotor	8731	125

Fig. 11 presents vector fields, where transonic and supersonic flow can be noticed in rotor 1.

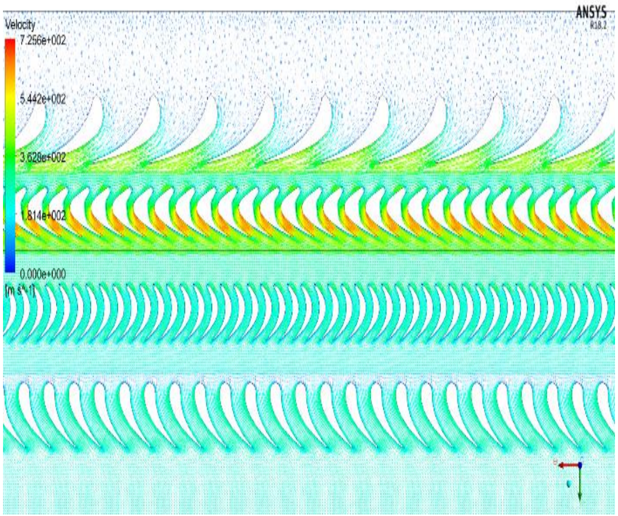

Fig. 11. Velocity field at 0.5 of the stator1 blade length, variant six

In variant six, power generation fell 0.945 MW, mass flow increased to 8.77 kg/s (31.57 t/h) and efficiency fell to 66.74%.

2.7 Variant seven

Here, the profile of the rotor 1 blades was altered, because the shape of the interblade channel in the previous variant resemble the de Laval nozzle (Tab. 6)

Table 6. Stator and rotor blades in a Curtis stage

	profile	number of blades
First stator	S9012-A	17
First rotor	R2117-Bk	141
Second stator	3633	234
Second rotor	8731	125

The altered rotor blade profile prevented transonic and supersonic flow through rotor 1. However, stalling did appear in stator 2. The leading edge of rotor 2 blades could also be improved.

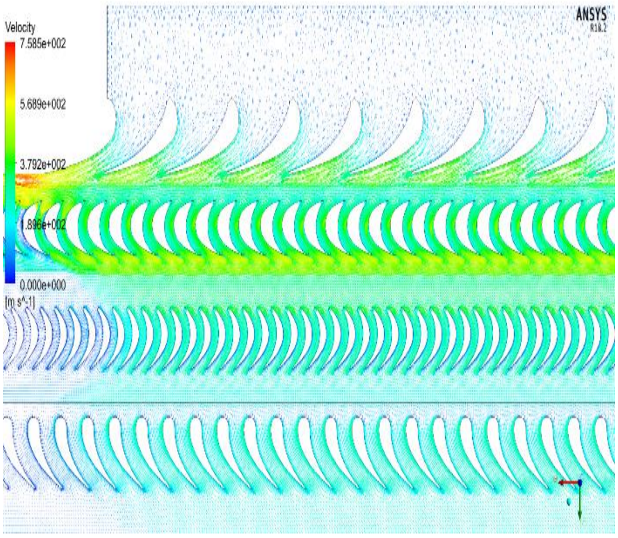

Fig. 12. Velocity field at 0.5 of the stator1 blade length, variant seven

Here, power generation fell to 0.943 MW, mass flow increased to 8.51 kg/s (30.64 t/h), but efficiency increased to 68.75%

2.8 Variant eight

Here, the profile of the rotor 2 blades was modified (Tab. 7).

Table 7. Stator and rotor blades in a Curtis stage

	profile	number of blades
First stator	S9012-A	17
First rotor	R2117-Bk	141
Second stator	3633	234
Second rotor	R5535-A	197

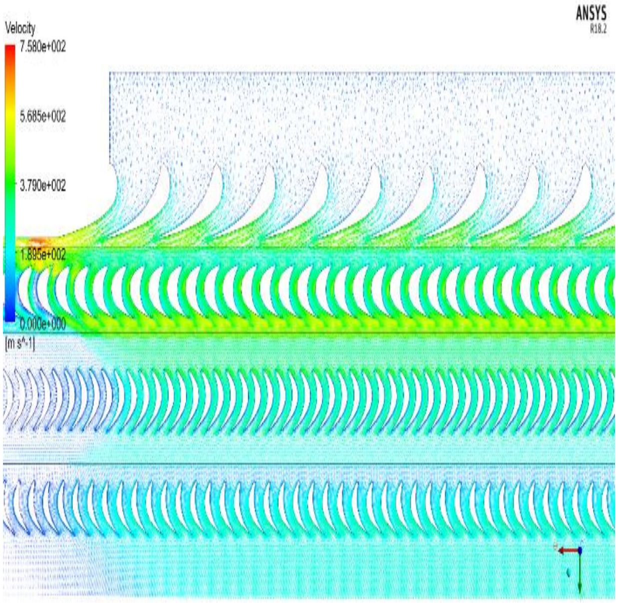

Fig. 13. Velocity field at 0.5 of the stator1 blade length, variant eight

Here, power generation increased to w 0.953 MW, mass flow increased to 8.52 kg/s (30.67 t/h) and efficiency increased to 69.34%.

3 Conclusions

In this paper, for the first time, the geometries of stator and rotor blades in a 1 MW steam turbine Curtis stage were optimized. The most efficient variants for partial admission were variant two, with 1/3 circumference partial admission from one inlet tube and the blade numbers: s1 17, r1 141, s2 85 and r2 197. This gave an efficiency of 72.48 %. This was despite the fact that a standard s2 profile was applied and stalling occurred in r1.

The application of two, opposing inlet tubes deceased efficiency. However, only one such variant was tested and further research would be required. Generally, the efficiency of the Curtis stage is lower than that of typical axial stages.

Optimized flow without transonic and supersonic regions only occurred in variant eight, where half of the blade profiles were modified.

Table 8 presents all the power, mass flow. efficiency and partial admission rate data for all the variants.

Table 8. Power, efficiency, mass flow, partial admission rate of variants one to eight

	Power [MW]	Efficiency [%]	Mass flow [kg/s]	Mass flow [t/h]	Admission
1	1,688	74,82	13,98	50,33	1
2	1,063	72,48	9,09	32,72	1/3
3	0,964	70,94	8,42	30,31	1/3
4	0,958	68,71	8,50	30,60	1/3
5	0,958	68,52	8,66	31,18	2 * 1/6
6	0,945	66,74	8,77	31,57	1/3
7	0,943	68,75	8,51	30,64	1/3
8	0,953	69,34	8,52	30,67	1/3

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