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CFD analysis of fluid flow in an axial multi-stage partial-admission ORC turbine

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Abstract: Basic operational advantages of the Organic Rankine Cycle (ORC) systems and specific issues of turbines working in these systems are discussed. The strategy for CFD simulation of the considered ORC turbine and the main issues of the numerical model are presented. The method of constructing the 3D CAD geometry as well as discretisation of the flow domain are also shown. Main features of partial admission flow in the multi-stage axial turbine are discussed. The influence of partial admission on the working conditions of the subsequent stage supplied at the full circumference is also described.

Keywords: renewable energy; cogeneration; ORC; partial admission turbine; CFD

1 Introduction

Over the past few years, interest in the utilisation of renewable energy sources has increased. The main reasons are dwindling resources of fossil fuels and also their negative effect on the environment. The European Union issued several directives that enforce a reduction of fossil fuel consumption, carbon dioxide emissions as well as increasing the efficiency of energy conversion processes.

One possibility to increase the energy efficiency of power systems is to apply cogeneration, that is, the simultaneous production of electric power and heat (termed cogeneration of heat and power – CHP). Cogeneration is known to yield an efficiency of primary energy utilisation of up to 90%. The CHP systems work within the range of nominal parameters provided there is a demand for heat. However, during the summer, the heat demand decreases, thus the heat must be dissipated in cooling towers or by other means. In this scenario, the cogeneration efficiency sharply decreases [1, 2].

A promising solution for cogeneration is the Organic Rankine Cycle (ORC) technology [3, 4]. A number of ORC working media exist that could be used instead of water vapour, guaranteeing a high efficiency in a wide range of cycle parameters. This technology is especially suitable for low-power installations, where the cogeneration conditions are much easier to be fulfilled. ORC allows the utilisation of medium-temperature and low-temperature heat. Therefore, it is especially suitable for small biomass-fed units and heat recovery installations.

ORC cycles can work with different types of turbines - from a one-stage radial or radial-axial to multi-stage axial. The flow system that is described in this paper is that of the multi-stage axial-flow turbine prepared for operation at the Institute of Fluid Flow Machinery. The total number of stages is seven and the nominal power is just below 100 kW. The rotational speed of the turbine is 9000 rpm. Silica oil MDM (octamethyltrisiloxane) was chosen as a working medium. This substance is characterised by favourable thermodynamics properties in the medium-temperature range of parameters. The upper temperature and pressure of the cycle are 553.5 K and 1200 kPa. One drawback of this working medium is a large variability of its specific volume as a function of temperature and pressure; the specific volume at the turbine inlet is 0.0081 m^3/kg. The relatively low flow rate for the design value of power results in a low blade height (about 2-4 mm). This is unacceptable due to the growth of endwall and leakage losses. In addition, small blades are difficult to mill. A solution to this problem is partial admission in the first three stages, which enables increasing the blade height. In the considered design, the supply arc increases gradually, from 25% to 50% and to 75% of the full circumference. Partial admission also tends to decrease the stage efficiency, but to a lesser extent if compared to the case of a very low blade height. An additional problem are excessive bending forces and moments. Forces acting on the single rotor blade are also variable in time.

Considering the aforementioned issues, numerical analysis has been conducted to support the turbine design and its commissioning on the test rig. Main results expected from the calculations are force transients con-

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nected with entering and leaving the arc of admission. Numerical simulation can also provide information about distributions of pressure, temperature and Mach number in subsequent turbine stages supplied at the full circumference.

2 Numerical model and CFD analysis

The solver chosen to perform 3D finite volume Computational Fluid Dynamics (CFD) calculations was ANSYS Fluent v15[1]. The applied mesh generator ICEM–CFD also belongs to the ANSYS environment. It enables an easy generation of a fully structural hexahedral mesh. This type of mesh is strongly recommended for CFD computations. The mesh was generated for first four stages of the ORC turbine. The last of them is supplied at the full arc, while the first three have a partial admission. The model contained more than 8,500,000 elements. Since the most important expected results of the calculations are variable forces acting on the rotor blades, the simulation had to be performed in an unsteady (quasi- unsteady) mode. The RANS approach with the $k - \omega$ SST turbulence model were applied. The rotor domains were set as moving domains with interface boundary conditions between the stator and rotor. The pressure-based solver with second-order upwind differencing was used. Pressure boundary conditions were imposed at the inlet and outlet.

The time step for quasi-unsteady calculations was set to 6×10^{-6} s. The computation of one revolution of the rotor (1660 time steps) took about 120 hours of wall time. The computer used to perform the calculations was a desktop with Intel i7 3770 k 3.9 GHz CPU and 32 Gb memory.

During early stages of computation, the ideal gas equation was used to approximate the properties of the working medium. An individual gas constant, viscosity and specific heats (constant values) were evaluated as averages from inlet/outlet conditions. After three revolutions the material model was changed to the NIST Real Gas Model. Using the ideal gas model assures acceleration and convergence of the calculations. On the other hand, the real gas model brings accuracy to the determination of flow parameters.

The CAD geometry was generated in the program Autodesk Inventor. It contains the flow domains for the eight blade rows (four turbine stages). The stator and rotor flow domains are separated by interfacial surfaces for the sake of moving mesh calculations. The geometry was saved in a universal ".step" file format. It was then exported to ICEM–CFD package and discretised. The entire turbine flow domain contains repetitive components, therefore it can be created as a result of replicating the appropriate number of blade-to-blade passages. The whole geometry of the investigated flow domain is shown in Figure 1, whereas mesh details on the metal surfaces are illustrated in Figure 2.

Figure 1: CAD geometry of the full four stages of the 100 kW ORC turbine.

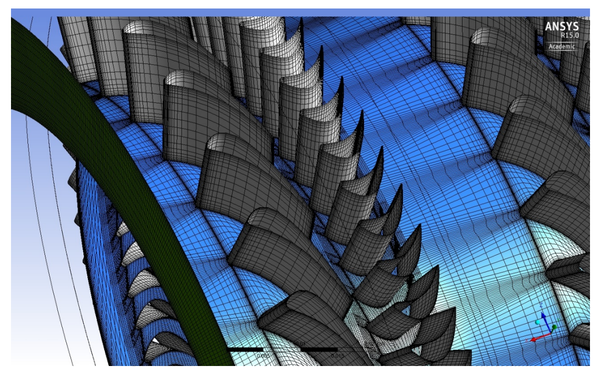

Figure 2: Mesh details at the metal surfaces of the flow channel in the ORC mini turbine.

3 Numerical results

One of the most important features of partial admission flow is an unsteady character of forces acting at the rotor blades. Although stator-rotor interactions typical for full-admission supply are clearly observed, the most significant variations of forces are observed during entering and leaving the arc of admission. Transients of torque (moment of circumferential forces) acting at the rotor blades of

1 ANSYS Customer Portal Support http://support.ansys.com/

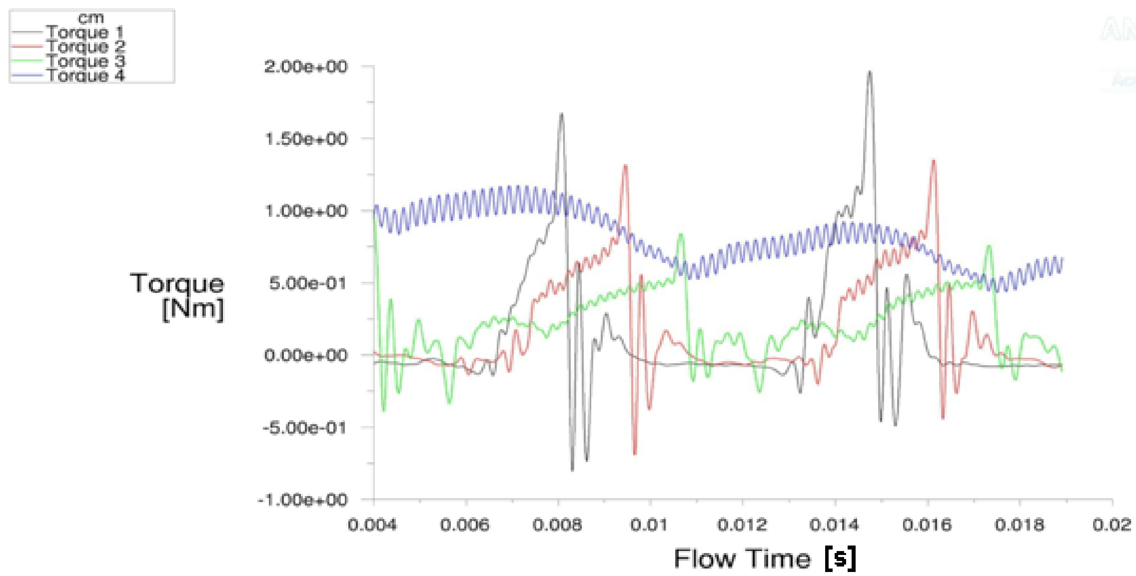

Figure 3: Plot of torque acting at a single rotor blade of subsequent turbine stages – stage 1 (Torque 1, black), stage 2 (Torque 2, red), stage 3 (Torque 3, green), stage 4 (Torque 4, blue – full admission supply).

stages 1-4 (stage 1 to 3 partially supplied, stage 4 supplied at the full circumference) are presented in Figure 3. The torque tends to zero beyond the arc of admission. Within the arc of admission the torque gradually increases and oscillates due to stator-rotor interaction. Particularly abrupt changes of the torque are observed at the end of the admission arc. The calculated torque clearly increases above its mid-arc value before tending to zero, which is caused by the situation of continued supply at the pressure side and stopped supply at the suction side when the rotor blade leaves the arc of admission. The observed torque transients can lead to high-cycle fatigue of the rotor blades.

Partial admission causes variation of flow parameters along the circumference [5–7]. A distinct feature is a region of rapid expansion and very low pressure immediately after the last nozzle, as seen in Figure 4. This phenomenon resembles the effect of vacuum, which occurs when high inertia fluid flows downstream through the blade-to-blade passage and the flow supply is suddenly stopped. Towards this low pressure region, fluid from downstream blade-to-blade passages is directed. Therefore, the region is surrounded by backflow and rotational flow areas (compare Lampart *et al.* [8]).

Another problem with multi-stage partial admission is a necessity of proper positioning of the supply nozzles in subsequent stages. The main-stream fluid that comes out from one stage needs to fit into the next supply arc, so as to prevent additional losses due to possible inflow of

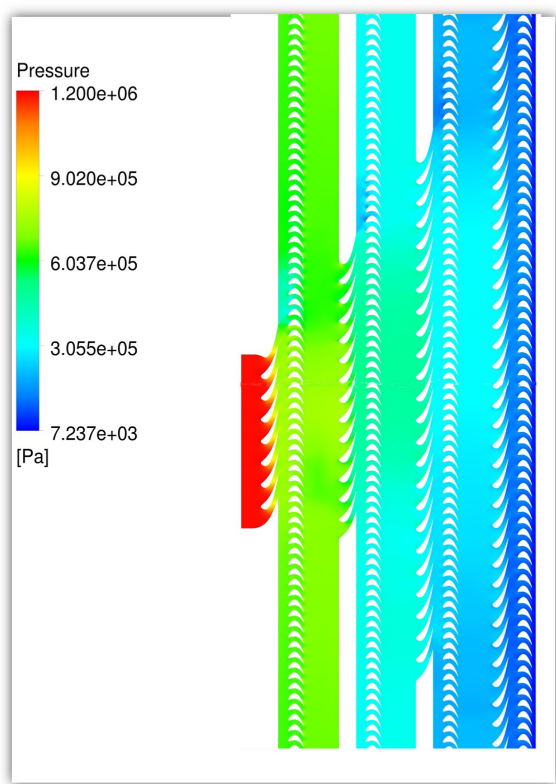

Figure 4: Contours of static pressure at mid-span of the four stages of the ORC turbine.

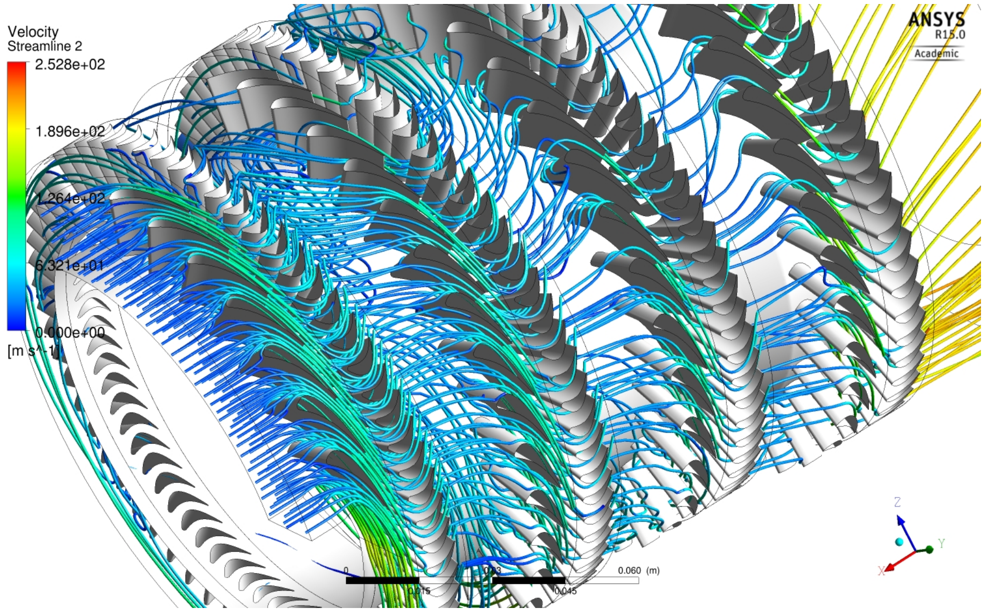

Figure 5: Streamlines coloured by velocity magnitude.

fluid onto the blocked area. In the first approximation, the position of the subsequent nozzles was calculated based on velocity triangles and space between the stages. In the next steps, this position was verified by CFD simulation. The image of streamlines illustrated in Figure 5 shows that the flow through this multi-stage partial admission configuration is smooth.

The blue line in Figure 3 represents the torque acting on the fourth stage. Although the fourth stage is already fully supplied, the torque still exhibits considerable variation due to the non-symmetry of flow parameters along the circumference before the fourth stage. Upon further investigation of all seven stages of the turbine, it will be possible to determine how this circumferential non-uniformity propagates through downstream stages 5 to 7.

Also, the unsteady forces connected with partial admission cannot be eliminated completely. Peak values of forces can be reduced as a result of shape optimization of nozzle blades and wall contours at the end of the supply arc. This will also be a subject of further investigations.

4 Calculation of the efficiency

Flow efficiency of subsequent turbine stages can be calculated as the ratio of the time-averaged stage power obtained from CFD computations to the theoretical power for the isentropic expansion:

$$\xi = \frac{P}{P_{is}} = \frac{P}{GH_{is}} = \frac{M\omega}{GH_{is}}, \tag{1}$$

where: ξ - isentropic efficiency, P - stage power, P_{is} - theoretical power, M - moment of circumferential force (torque) generated on the rotor disk, ω - angular speed of the disk, G - mass flow rate, H_{is} - isentropic enthalpy drop. The isentropic drop of enthalpy can be found from the ideal gas approximation as:

$$H_{is} = c_p T_{in} \left[1 - \left(\frac{p_{ex}}{p_{in}} \right)^{\frac{\kappa-1}{\kappa}} \right], \tag{2}$$

where: c_p – constant pressure specific heat, T_{in} - inlet temperature, p_{in} - inlet static pressure, p_{ex} - outlet static pressure, κ - specific heat ratio.

The calculated efficiency values for stages 1 to 4 are gathered in Table 1. It is found that the flow efficiency of stages with partial admission is around 70%, with the efficiency of stage 4 being close to 80%. The obtained values will be validated by future experimental investigations.

5 Conclusions

Four stages of an axial multi-stage partial-admission ORC turbine were investigated with the help of CFD. Main attention was paid to the effects of partial admission on turbine stage characteristics. Partial admission is a cause of circumferential non-symmetry of flow patterns and unsteady forces acting on the rotor blades of the first three stages. It was found that peak values of blade forces at the moment of leaving the arc of admission significantly exceed mid-arc values, which can lead to high-cycle fatigue of the rotor

Table 1: Efficiency in the four stages of the investigated ORC turbine.

	Stage 1	Stage 2	Stage 3	Stage 4
M [Nm]	8.44	9.92	10.24	21.34
P [kW]	7.95	9.35	9.65	20.11
P_{is} [kW]	12.07	12.74	13.66	25.29
η 65.9%	73.4%	70.6%	79.5%	

blades. The observed unsteadiness also tends to propagate to a fully admitted downstream stage 4. More investigations are needed to determine how far the non-symmetry due to partial admission propagates downstream and how to moderate the effects of partial admission.

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