David Tomás Sánchez Martínez
Lourdes García Rodríguez
(coordinadores)

Proceedings of the 7th International Seminar on ORC Power Systems

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Experiments on Supersonic ORC Nozzles in Linear Cascade Configuration

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ABSTRACT

In organic Rankine cycles (ORCs), the turbo-expander represents a critical component due to the major impact of its efficiency on working fluid selection, cycle layout and overall plant performance and profitability. Also, its design is complicated by large expansion ratios, by the demand of operational flexibility and by the thermo-physical characteristics of the working fluid and non-ideal gas effects. This typically leads to turbines with low number of stages and transonic/supersonic flow regimes. For these reasons, the ORC turbine design relies on advanced aerodynamic models and high-fidelity tools based on computational fluid dynamics (CFD). The verification of high-fidelity tools requires accurate fluid thermodynamic models and experimental data concerning canonical flows, since experiments on non-ideal flows within ORC turbine cascades are still missing in the literature. To fill this gap, a novel experiment has been designed at Politecnico di Milano on an ORC supersonic linear cascade, aimed at characterizing the flow field within the bladed and semi-bladed portion of the channels, at the trailing edge where shock/fan systems arise, and downstream the cascade, by retrieving the pitch-wise total pressure loss distribution. This paper reports the outcomes of an experimental campaign focused on the expansion of hexamathyldisiloxane (MM) within the cascade. Initial commissioning tests were performed using nitrogen at different pressure levels. Finally, the experimental data gathered during a campaign carried out with MM in non-ideal conditions are presented and compared with CFD simulations, allowing to assess real gas effects on the trailing edge shock pattern and pressure distribution through the cascade.

1. INTRODUCTION

In the last decades, ORCs experienced a remarkably increasing appeal, since, in a context of limited resources, it is crucial to exploit efficient technologies for power generation from low/medium enthalpy grade sources. The use of organic fluids instead of water for the Rankine cycle leads to considerable advantages, such as reduced specific enthalpy drops and single-phase expansions, which make this technology one of the most attractive for low-to-medium temperature sources (Colonna et al., 2015). However, complex fluid flows establish within the turbo-expander due to the strong non-ideal behaviour of the working fluids in proximity of the liquid-vapor saturation curve, where the expansion generally takes place. Moreover, the expanders are often designed with a low number of stages, which result in high pressure ratio cascades which leads to transonic and supersonic flows, characterized by complex shock wave patters.

Therefore, the fluid dynamic design of an ORC expander, typically an axial or radial turbine, requires a major attention, also considering that the efficiency of the expander has a crucial impact on the cycle performance and therefore on its overall profitability (Macchi, 2017). In order to successfully design an ORC turbine, several low-fidelity tools were conceived, mainly based on a mean-line method able to compute the thermodynamics and the geometry of each stage at blade mid-span. These methods have proven their value in traditional turbomachinery, where several experimental campaigns where carried out to validate the reliability of the correlations exploited for the losses prediction. The lack of experimental data on ORC turbines in the open literature, though, has often forced to settle for a validation

of mean-line models results through high-fidelity CFD simulations. However, the effectiveness of the latter with organic fluids operating at low compressibility factors is in general established on the use of the state of the art fluid models, while a systematical comparison between simulations and experimental results is still missing. The only experiments documented in literature on the flow of organic fluids are, in fact, providing results for nearly isentropic nozzle expansions or flow around wedge profiles and bluff bodies (Zocca et al., 2019; Reinker et al., 2021). Further data were then provided in (Baumgärtner et al., 2020), which reports a study on an annular turbine cascade but still requiring a numerical estimation of the total pressure downstream the blades.
In order to cover the described literature gap and to attempt a first validation of the CFD simulations results, an experiment was conceived at Politecnico di Milano with the aim of analyzing the flow field across a supersonic turbine linear cascade representative of ORC applications. This paper briefly covers the design of experiment in Section 2. After that, Section 3 reports the main results of the experimental campaign, with a rigorous analysis of the flow field and a comparison between experimental data and CFD simulation results.

2. DESIGN OF THE EXPERIMENT

The campaign was designed to take place within the Test Rig for Organic VApors (TROVA) (Spinelli et al., 2013), a blowdown wind tunnel conceived to work with organic fluids flowing across a stationary test section that replaces the expander. In this specific context, a converging-diverging geometry was selected to represent a supersonic turbine linear cascade for ORC applications, illustrated in Figure 1. A thorough description of the design of the whole test section and of the related instrumentation is pro-

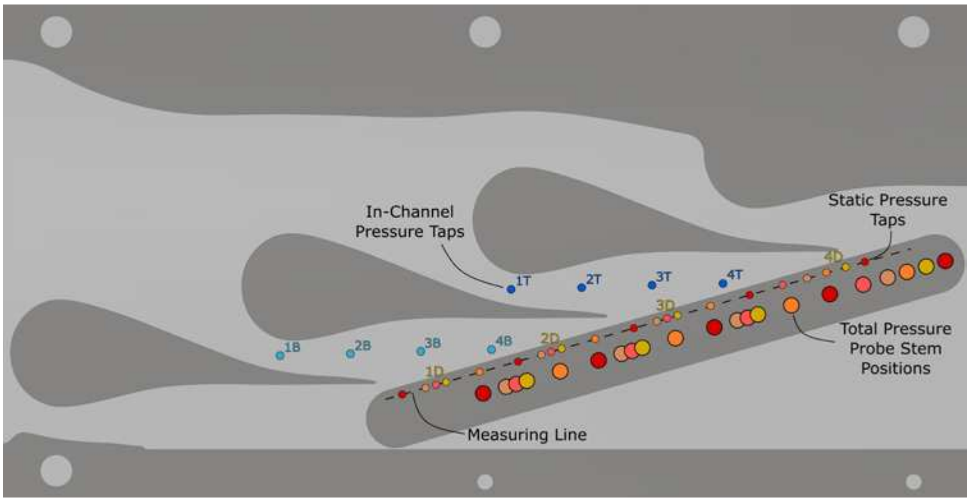

Figure 1: Test section configuration. The static pressure taps are numbered according to their location on the top channel (T), bottom channel (B) or downstream measuring line (D). The circles on the measuring line coincide with the probe head locations

vided in Manfredi et al. (2023), while here are resumed only the main features, essential to point out the cascade characteristics and allow a better understanding of the results outlined in the next sections.
The experiments were designed to be carried out with hexamethyldisiloxane (MM) as working fluid, which is typically considered for medium to high temperature ORC applications and it is particularly convenient for the current investigation, since it exhibits an highly non-ideal thermodynamic behaviour at temperature levels well below the thermal stability limit. As highlighted in Section 1, the main interest of this work is to investigate the flow field of expansions occurring in the non-ideal region. For this reason, the design conditions were fixed at p_{Td} = 25 bar and T_{Td} = 261.5°C, leading to a corresponding compressibility factor of Z_{Td} = 0.31. These conditions were exploited for the whole geometry optimization and as boundary conditions for CFD validations. Nonetheless, as specified later in Section 3, experiments will be mostly carried out at lower pressures, still allowing an assessment of the flow

field at fairly low values of Z, while reducing at the same time issues related to the limited Schlieren measurement range (Conti et al., 2017) and to the test section sealing.
As reported in Figure 1, the linear cascade features three blades and two side-walls, implementing two main central channels, where all the measurements are performed, and two lateral ones. The geometric pitch is of 45 mm and the stagger angle is $\gamma = 75°$. Both inlet and outlet are perfectly axial, meaning that the flow deflection is null, resembling the small deflection of radial machine vanes. The test section, however, aims to be representative also of axial turbines; in fact, the original profile was extracted from Romei et al. (2020), where the flow turning through the cascade is 75°. Here, a null deflection is equivalent to operate the blade with a 75° incidence at the inlet. To withstand such extreme boundary condition and avoid flow detachment, the blade shape was modified, assessing its performance with a CFD validation. The equivalence of the resulting flow field to the one characterizing typical turbine cascades is also proven by the blade pressure distributions reported in Manfredi et al. (2023). The profile was then optimized with the in-house tool FORMA (Persico et al., 2019) to minimize entropy generation. The result is a profile featuring a large curvature radius at the leading edge, which makes it tolerant to significant incidence angle variations while still keeping identical post-throat flow fields and therefore achieving very similar performances, as most of the entropy generation occurs in the supersonic region.
As far as the sidewalls are concerned, they were carefully designed to ensure that periodicity was attained, despite the reduced number of available channels. The lower side-wall is obtained simply by reproducing the pressure side of the blade from the throat to the trailing edge and carving the profile with a sufficiently large curvature radius to avoid any flow detachment at the inlet section. The upper side-wall was instead derived by merging the suction side of the blade to the flow streamline extracted from the numerical simulations previously performed on the optimized blade geometry. Such streamline is depicted in Figure 2 and it can be compared to the upper-wall shape in Figure 1, where the addition of a large fillet is present at the inlet section to avoid separation.

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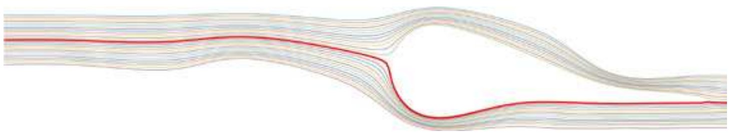


Figure 2: Flow streamline selected for sidewall design

Once the cascade and the sidewalls were defined, a 2D CFD simulation of the flow across the complete test section was carried out to investigate the obtained periodicity. The simulation was performed in design conditions and periodicity was assessed by extracting several quantities, such as entropy and Mach number, from the measuring line and verifying that the peaks of their auto-correlations where spaced by a pitch distance. The auto-correlation assessment pointed out a very good periodicity, as reported in the related plot observable in (Manfredi et al., 2022), concluding the cascade design.
In order to experimentally investigate the flow, several measuring techniques were implemented. Inlet conditions, changing over time due to the blowdown nature of the facility, are measured in a plenum upstream the test section, where the flow can be considered uniform and characterized by a very low kinetic energy. Here a flush-mounted pressure transducer and two termocouples (J and K type) are placed to measure respectively total pressure and temperature. Furthermore, four pressure taps (dark and light blue dots in Figure 1) are inserted in both central channels. They are equispaced between the throat section and the blade trailing edge locus and allow to evaluate the pressure distribution along the expansion, to verify the in-channel periodicity and to assess the agreement with CFD simulations results. Since one of the main scopes of this work is the direct measurement of the cascade performances through the evaluations of losses, downstream the blades a tailored insert was designed to measure both static and total pressure. The former is measured by pressure taps, equivalent to the ones located inside the two main channels. The latter, instead, is obtained by the insertion of a L-shaped total pressure probe accurately designed to achieve a satisfying resolution and sufficient stiffness to avoid unwanted bending of the stem. Each static pressure taps (of 0.3 mm diameter) is connected to a locally mounted absolute

transducer, while the total pressure probe is connected through pneumatic lines to a remote differential transducer. The need of measuring both static and total pressures is due to the inevitable generation of a bowed shock in front of the probe head, due to the supersonic incoming flow. The probe measures, therefore, a post-shock total pressure, but, coupling this information with the static pressure from the relative tap, it is possible to retrieve the pre-shock total pressure solving the balance equations across the shock wave (Manfredi et al., 2023). In order to achieve a distribution of the losses across the two main channels, 21 measuring points (machined on five different inserts) were located along the two pitches, not uniformly spaced to enhance resolution in the wakes, as can be appreciated from Figure 1, where different circle colors designate taps belonging to different inserts.
Lastly, optical visualizations are carried out through a double-passage Schlieren device that allows to observe the flow-field density gradient. This measuring technique is of paramount importance as it allows to study the complex shock pattern established during the test allowing a direct comparison with the flow field obtained through CFD simulations.

3. EXPERIMENTAL CAMPAIGN

This paper covers the first portion of the experimental campaign described in the Section 2, namely the validation of the test concept by exploring the cascade flow field through optical visualizations and static pressure measurements, focusing on the analysis of test repeatability, periodicity and consistency with CFD simulations results. Therefore, the total pressure probe was not inserted and traversed in the frame of this campaign and losses across the cascade were not measured; this is, however, the subject of upcoming tests. Before beginning the experiments carried out with MM, for which the cascade was originally designed, few preliminary tests were performed using nitrogen as working fluid. The aim of these tests, which are way faster to be executed as the plant is filled with nitrogen at ambient temperature, is to asses the experiments results repeatability and check the instrumentation and the acquisition system. Moreover, a first comparison with CFD calculations is relevant as well, since the simulations results with nitrogen in ideal gas conditions can be considered the most reliable ones. Here, we will focus on repeated test carried out with an initial inlet total pressure of 8 bar. 357
Starting with a repeatability analysis on two exemplary tests, in Figure 3 the signals acquired from the 8 in-channels taps are plotted as ratios between the measured static pressure and the upstream total pressure (p_{T0}), highlighting their evolution as function of p_{T0}; notice that, since the total pressure is decreasing during the test due to the emptying of the feeding reservoir, the plots have to be read from right to left. The taps are numbered from the upstream to downstream and divided between upper and lower

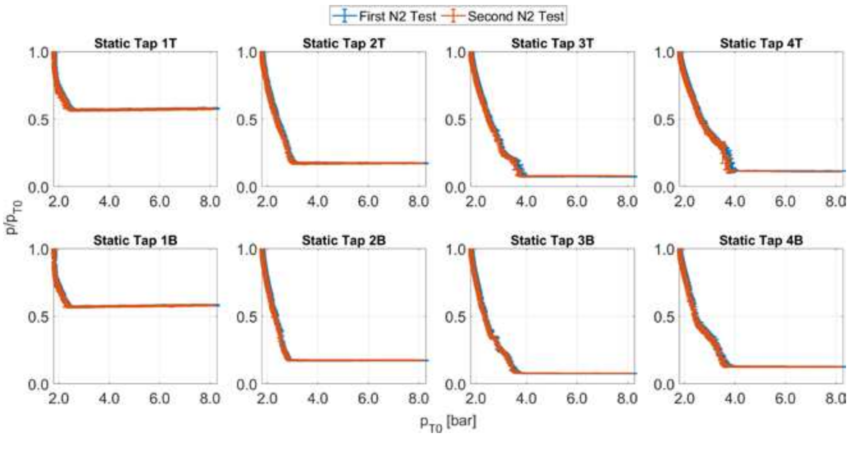
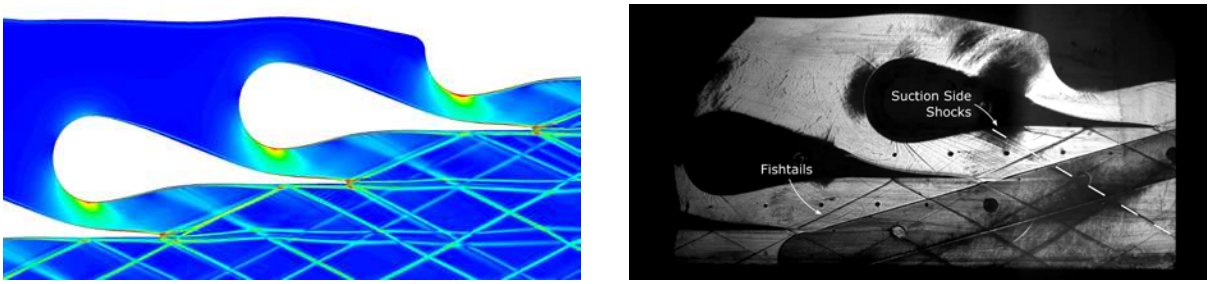


Figure 3: Nitrogen test repeatability analysis. In-channel pressure ratio p/p_{T0} vs upstream total pressure p_{T0}

channel, as specified in Figure 1. As can be clearly appreciated, the two tests generate overlapped results at every measuring point, ensuring an excellent experiment repeatability. In addition, the plots show a perfectly flat trend during the test, which is expected when using nitrogen, since outlet Mach and therefore pressure ratios are only function of the area ratio and the specific heat ratio γ, which is constant for a perfect gas. The steep pressure ratio slope at low values of p_{T0} represents the final portion of the test when the downstream backpressure approaches the upstream total pressure, producing a series of normal shocks entering the cascade channels. Figure 4 illustrates a comparison between the expected flow field obtained from CFD simulation, represented though a contour of the density gradient, and the actual flow field extracted from the Schlieren visualization at the timestep corresponding to p_{T0} = 7 bar. The simulation was performed with a 2D domain, representative of the blade midspan flow field, and the



(a) CFD simulation - Density gradient contour **(b)** Schlieren visualization of the flow field

Figure 4: Flow field comparison between CFD simulation and Schlieren visualization with p_{T0} = 7 bar

mesh was defined through Ansys ICEM, creating a multi-block structured grid featuring approximately 345k cells and a dense o-grid region around the blades and the sidewalls to reach $y^+ \leq 1$, so to achieve a near-wall boundary layer resolution in combination to the selected k-ω SST turbulence model. Due to the nature of the experiment, the level of inflow turbulence was set as low as 1%. The influence of this value on the simulations results, however, is extremely limited, as the Reynolds number is around 10 million, making the flow fully turbulent from the beginning of the blowdown process. Moreover, a no slip boundary condition was imposed to all the walls, which were treated as perfectly smooth without specifying a level of roughness. This is justified by the fact that the endwalls have an irrelevant value of R_a, as the front wall is made of quartz glass, while a lapping process is required on the back wall to achieve a reflection of the light source needed for Schlieren visualizations. Blades and sidewalls are, instead, characterized by a maximum R_a of 0.2 μm, whose only influence would be on the evaluation of the total pressure losses, which is not addressed in the current experiments. The illustrated flow field is characterized by a complex pattern of shocks distinguishable into two main types, namely the blades fishtails originating from the trailing edges and the oblique shocks starting from the suction side of each blade in the region between pressure taps 2 and 3, where the profile curvature changes concavity. Then, since the flow is constrained by either blades or sidewalls, the shocks are reflected and interfere with each other, creating the displayed structures. The comparison between the CFD and the experimental

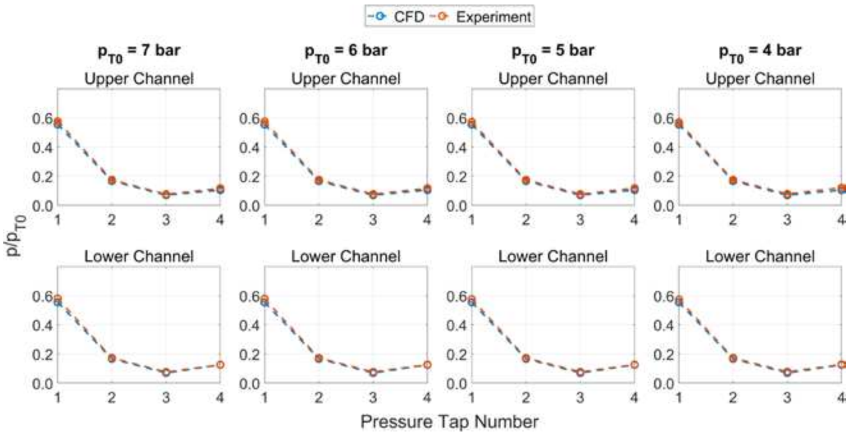


Figure 5: In-channel pressure ratio comparison with CFD - N2 tests

flow field shows an excellent agreement as both the blades fishtails opening angles and the slope of the shockwaves originating from the suction sides are concerned, while small disagreement is present on the reflected shocks, possibly due to a non-perfect numerical prediction of the boundary layer development. This qualitative analysis is confirmed by Figure 5, where the pressure ratios of the in-channel signals are compared to the same quantity extracted from CFD simulation at different values of p_{T0}, always reporting and excellent agreement. It is relevant to underline that, even if a careful assessment of the measurements uncertainties was carried out through the calibration of the instrumentation, the error bars are not reported here, as their amplitude would not be clearly appreciable. However, as an order of magnitude, the value of the error of the pressure ratios is always below 0.6%.
After these encouraging results obtained with nitrogen, a set of experiments using MM as working fluid was carried out. Here, in addition to tests where only the in-channel pressures were measured assessing the cascade periodicity and the test repeatability, experiments were also carried out acquiring the static pressures along the downstream measuring line and specifically at the four positions marked with yellow circles in Figure 1. As far as the thermodynamic conditions are concerned, the initial upstream total pressure was fixed at 13 bar, with a total temperature of 235°C, reaching Z_{T0} = 0.65 and a value of the fundamental derivative of gas dynamics of Γ = 0.619. Focusing on the experiments carried out acquiring

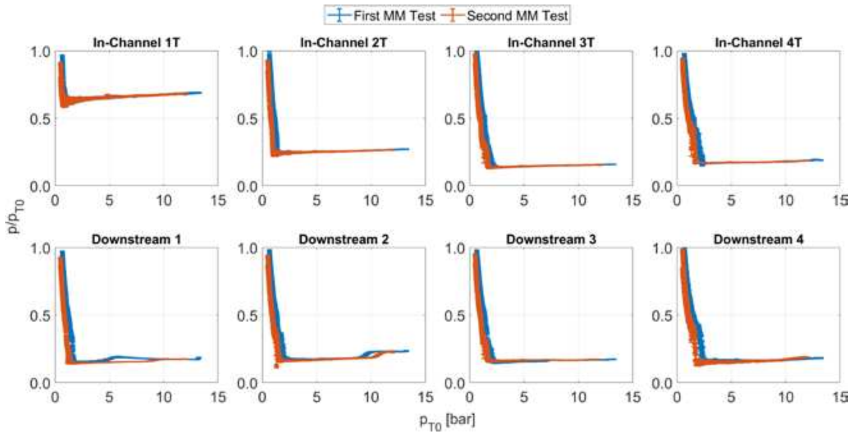
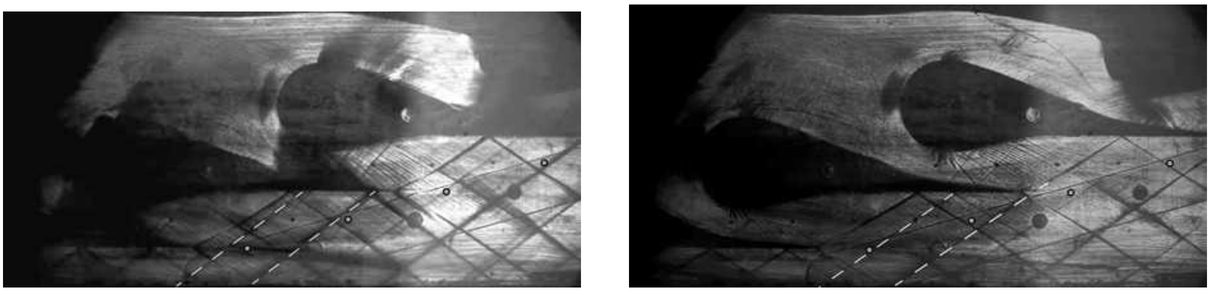


Figure 6: MM test repeatability analysis - Upper blade channel and downstream measuring line

also the downstream pressures, Figure 6 shows, for two exemplary test repetitions, the pressure ratio distribution as function of the upstream p_{T0} along the upper channel taps and the four measuring points downstream the cascade, numbered, with reference to Figure 1, from bottom to top. It can be easily appreciated that also with MM as working fluid, a very good repeatability is attained, especially within the blade channels and in the third and fourth downstream measurement points. The pressure ratios are, correctly, no more constant throughout the blowdown process, since, in non-ideal conditions, the Mach number is also a function of the stagnation conditions and increases as the test proceeds, resulting in a progressive reduction of the fishtail slope and a decreasing trend of p/p_{T0}. The variation from this trend that can be spotted in the first two downstream measuring points (Downstream 1 and 2 in Figure 6), is motivated by the presence of several shockwaves that, after being reflected by the lower sidewall, lie near the pressure taps, increasing the acquired pressure. Along the process p_{T0} decreases and the fishtails angles are reduced, therefore the shocks moves away from the tap location, which suddenly detects a pressure reduction. Such evolution of the flow field can be observed in Figures 7a and 7b, where two frames from the Schlieren visulizations when p_{T0} = 10 bar and p_{T0} = 4 bar are reported. The four pressure taps downstream the cascade are highlighted in yellow, while white dashed lines are superimposed over two shock reflections to better depict the flow field differences in two distinct moments of the experiment and the effect of the shockwaves on the pressures acquired by the measuring points closer to the lower sidewall. This phenomenon explains the peculiar trends reported in Figure 6, and also indicates a non perfect repeatability, as the specific shock pattern and boundary layer evolution are highly sensitive to operating conditions. Nonetheless, the experimental data show a very good agreement with CFD



(a) p_{T0} = 10 bar **(b)** p_{T0} = 4 bar

Figure 7: Schlieren visulizations of the flow field with MM

simulation results. The latter were, as for nitrogen tests, performed through a 2D analysis representative of the midspan section, implementing, via Look-up Tables, state-of-the-art model for MM (Thol et al., 2016), to correctly reproduce the non-ideal thermodynamics of the gas. Figure 8 reports the comparison between the in-channel pressure ratios obtained through experiments and numerical simulations at four different upstream conditions. As can be noticed, the plots corroborate the results discussed so far,

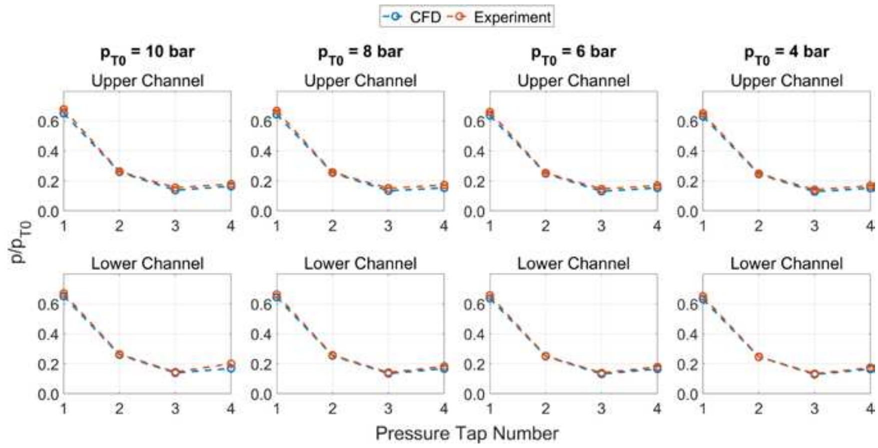


Figure 8: In-channel pressure ratio comparison with CFD - MM tests

showing a very accurate CFD prediction of the experimental data, with the only exception of the fourth pressure tap in the lower channel, that, as observable in Figure 7, is affected by the shock reflection from the lower wall at high upstream total pressures. A similar comparison is also reported in Figure 9,

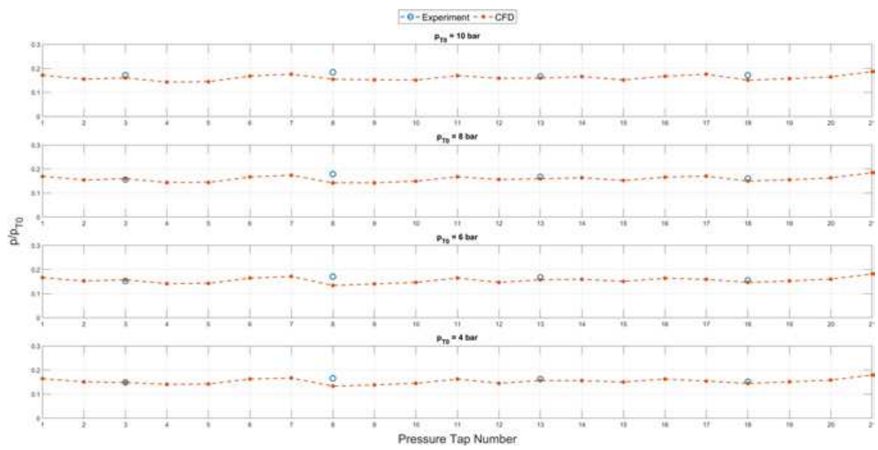


Figure 9: MM tests - Downstream line compared to CFD simulations results

where the pressures acquired in the four downstream taps are compared to the ones expected from CFD simulations.

4. CONCLUSIONS

This paper introduced the first part of an innovative experimental campaign on a supersonic turbine linear cascade for ORC applications, operating with the siloxane MM. A blowdown wind tunnel was exploited as test facility and the test section was carefully designed to include both the cascade and the measuring system. The latter was conceived to acquire the upstream total conditions, to evaluate the static pressure evolution through the blade channels and to compute the total pressure losses across the cascade measuring both downstream static and total pressures. Moreover, for a deeper investigation of the flow field, Schlieren visualizations were performed during each experiment. The design process and the test results assessment were tackled through an extensive exploitation of CFD simulations, which were mostly performed on a 2D domain representative of the midspan section, exploiting state of the art models to characterize the thermodynamics of MM. The aim of the experiments presented in the current paper was to fully characterize the flow field across the cascade, comparing experimental data with CFD simulations results, while leaving the measurement of the cascade losses to the upcoming second part of the investigation. A set of preliminary tests were performed with nitrogen, to assess the instrumentation and carry out a first analysis through experiments which are less time consuming and comparable with simulations based on the ideal gas thermodynamics. Excellent results were found in terms of test repeatability and the comparison between the measured and the CFD simulated flow field showed very good agreement, through both in-channel pressure acquisitions and density gradient visualizations. The main experiments were then carried out with MM as working fluid, exploring expansions processes characterized by initial values of Z_{T0} as low as 0.65. Outcomes similar to the nitrogen test ones were achieved, confirming the excellent test repeatability and the good prediction of the flow field through CFD simulations. One of the main issues highlighted is the effect on the downstream measured quantities of the complex shock pattern that arises from the reflection of shockwaves on the lower sidewall. To reduce the complexity of the flow field, some analysis are currently taking place, considering re-design of the sidewall. In conclusion, the results here reported are considered fully satisfactory and establish a solid basis on which a full campaign for cascade loss characterization is being currently built. 361

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This book contains the compilation of works contributed to the *7th International Seminar on Organic Rankine Cycle Power Systems* (ORC 2023), held in Seville between the 4th and 6th of September 2023. The event was hosted by Universidad de Sevilla on behalf of the Knowledge Centre on Organic Rankine Cycle Technology (KCORC), incorporated in The Netherlands.

The ORC conference, organized biennially, stems as the only conference that is specific to ORC technology, therefore gathering a diverse community whose affiliation spans across all the interested stakeholders, not only in this particular technology but also and in a broader context, in the energy transition. Original equipment manufacturers, professional associations, end-users, investors, policy makers, academics, scientists feel at home at ORC 2023.

The almost 100 proceedings in this book cover a wide variety of topics, from fundamentals to system integration through component design, accounting for thermodynamic performance as well as component design. In addition to this, and as a new track in 2023, works on heat pump technology were also accepted in order to raise awareness of the strong ties between both technologies, specifically in energy storage applications.

This book provides an excellent overview of the current maturity of power systems based on Organic Rankine Cycle technology for applications as diverse as geothermal and waste heat recovery in industry or downstream of other prime movers (e.g., marine applications). It is also an excellent source of information to understand the current challenges faced by the technology, stemming from a very competitive market and increasingly stringent environmental regulations.

The organizers of ORC 2023 hope that the reader finds this work as exciting as the attendees to the conference and, maybe, make the decision to join the 8th edition to the conference in 2025.

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