VISUALIZATION TECHNIQUES FOR SUPERSONIC BLADING DESIGN FOR ORGANIC RANKINE CYCLES

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ABSTRACT

The experimental results based on flow visualization techniques are presented in this paper in order to validate the computational outcomes regarding the real gas effects on the design of supersonic power production turbine for low enthalpy organic Rankine cycle (ORC). The “water table” test rig was built in the premises of the Laboratory of Fluid Mechanics and Turbomachinery of the Aristotle University of Thessaloniki to observe and verify the existence of the developed shock waves at the desirable location inside the blade passages as depicted from CFD results. The blading design for both stator and rotor is performed by applying non-ideal gas models used in Aerospace engineering for supersonic nozzles design for space aircraft applications. For shock wave losses minimization, the “Method of Characteristics” is used. In particular, the stator design was performed by following the “Minimum Length Nozzle” concept for material and manufacturing cost reduction, as well for weight minimization, while the “Vortex Flow Method” was preferred instead of the “Corner Flow Method” for the rotor design since the maximization of the produced power is the key parameter for the current work. The main outcome suggests the working fluid choice must be done with utmost care as it has a significant influence on both ORC thermal efficiency and turbine performance while differentiated blade geometries will occur considering the dominant shock losses. Finally, although the outcomes from the flow visualization experiments shown that the proposed design method seems not to be robust enough to account for the operating variations (off-design operation), the generated shock waves were positioned as indicated by the theoretical analysis. More specifically, the last expansion wave appears to be only 4% further compared to computational outcomes, while no reflection phenomena occurred inside the stator blade passage which means the applied design method is proven to be a dependable tool for the maximization of the produced power.

NOMENCLATURE

Abbreviations

ORC	Organic Rankine Cycle
GWP	Global Warning Potential
ODP	Ozone Depletion Potential
CFD	Computational Fluid Dynamics
MLN	Minimum Length Nozzle

Symbols

c	Flow Velocity
α	Acoustic Speed
V	Average Velocity of Liquid
g	Acceleration of Gravity
L	Dynamic Length
T	Temperature
p	Pressure
ρ	Density
d	Water Depth
M	Mach nr
Fr	Froude nr
t	Time

INTRODUCTION

Over the last decades, a surge in consumption of fossil fuels has led to serious environmental problems such as global warning protection, destruction of ozone layer and atmospheric pollution. For these reasons, an increasing trend in exploitation of low-enthalpy heat sources in the field of power production from waste heat recovery, has gained a renewed interest [1]-[2]. Waste heat is the amount of thermal energy (heat) which is not transformed into useful work during an energy conversion process from a functioning system. Nowadays, an enormous amount of fossil fuels is consumed from these systems in order to cover human needs (figure 1). Out of this energy, more than 65% is wasted, in the form of thermal losses to the atmosphere, with devastating consequences (GWP & ODP) [3]-[5]. The largest part of the total waste heat is coming from power production plants, industrial plants and the transport sector , such as mining industries, oil refineries, steel-glass-cement production plants, kilns, etc.

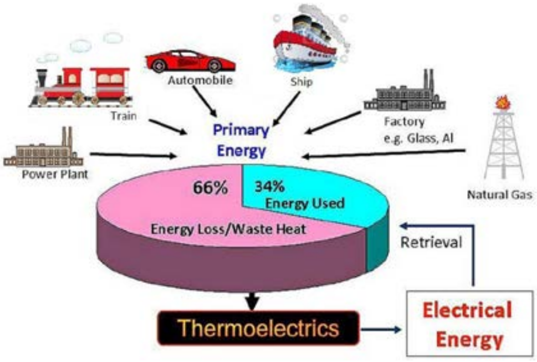


Figure 1. Percentage fossil fuel consumption [Courtesy of SoftinWay]

In order to increase the energy conversion systems efficiency, the “wasted” energy may be captured by another process and can be reused in the same or in different process for heating and/or generating mechanical and electrical power. Waste heat recovery is a common tactic in heavy industries all over the world since decades, but is mainly focused on high temperature heat sources, (above 300ºC), while the low enthalpy heat excess remains unexploitable [6]. For these cases, systems other than the traditional steam Rankine cycle must be developed for efficient exploitation. Towards to this direction, Organic Rankine Cycle systems have proven to be a very promising solution to avoid aggravation of this problem. ORC systems operate with heavy and molecular complex organic substances as the working fluid, which results to completely different design concept of the turbine compared to either standard gas or steam turbine designs [7]-[9]. Also, during dry expansion, these fluids are close to dense gas region (on the right side of the saturation line) where the speed of sound is fairly low. This means that supersonic turbines with high-expansion-ratio must be used to ensure efficient performance (≥75%) of the power production turbine. On the other hand, the designers should be aware of the generated shock and expansion waves within blades passages, because of supersonic conditions, that enhance losses [10]-[14]. For this reason, an experimental test bed was designed and constructed to validate the compressibility phenomena which are developed throughout the supersonic passages inside the ORC turbine by means of flow visualization methods, namely hydraulic jump and oil and dye technique. The developed experimental rig [figure2] consists of a water table apparatus that has the ability to simulate compressible flows and the corresponding shock and expansion waves in combination with the generated vortices as indicated by CFD results. The concept of using a water table for the observation of the compressibility phenomena is based on the hydraulic analogy, which in fact is the analogy between the Mach number of a two-dimensional compressible flow and the hydraulic jump of a water flow with a free surface which is directly connected to Froude number. Preiswerk et al. back to 1940 [15] had proved conclusively that methods of gas dynamic can be applied to water flow with a free surface.

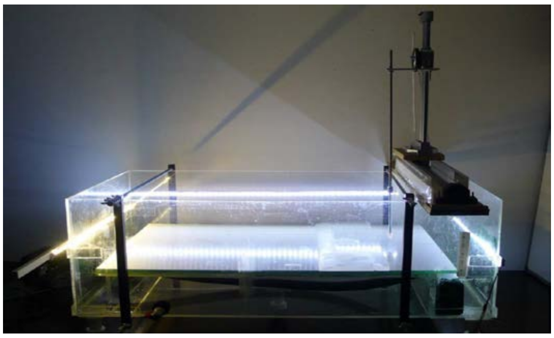


Figure 2.”Water table” experimental setup

THEORETICAL BACKGROUND

The concept of using a water table for the observation of the compressibility phenomena is based on the hydraulic analogy, which in fact is the analogy between the Mach number of a two-dimensional compressible flow and the hydraulic jump of a water flow with a free surface which is directly connected to Froude number [16]-[20]. The water must flow over a smooth horizontal surface which is bounded by vertical rigid geometries which in fact are the supersonic ORC turbine blades as indicated by the design process.

As shown in table 1, the dimensionless Froude number is defined as the ratio between the flow inertia to the gravity and has an analogy to Mach number as follows.

Table 1. Hydraulic analogy similarities

Compressible Flow		Free Surface Flow
Mach number, c/a	⟺	Froude number, $V/\sqrt{g \cdot L}$
Two-dimensional gas flow	⟺	Water flow
Sound speed	⟺	Surface wave speed
Temperature ratio, T/T_0	⟺	Water depth ratio, d/d_0
Pressure ratio, p^2/p_0^2	⟺	Water depth ratio, d/d_0
Density ratio, ρ/ρ_0	⟺	Water depth ratio, d/d_0
Shock wave	⟺	Hydraulic jump

Moreover, there is a strong analogy between shock waves and shock angles in compressible flow and hydraulic jumps. The latter can be described as abrupt changes in water depth such as the bow waves that generated when a vessel travels through water. The angle of these hydraulic jumps is a function of Fr number and it was used in order to calibrate the experiments to the desired speeds [20]-[25] by applying the equation 1 that connects the Mach number and the angle of a bow shock wave (fig. 3).

$$\theta = \sin^{-1}\left(\frac{1}{M_1}\right) \qquad [1]$$

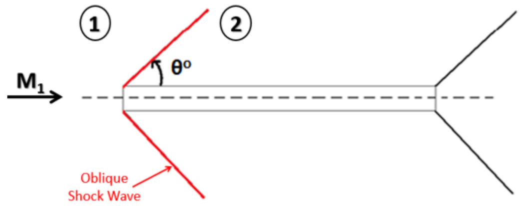


Figure 3. Thin plate for calculation of Mach number

EXPERIMENTAL SETUP

The experimental setup consists of the 1) power supply, 2) hydraulic pump, 3) magnetic flowmeter, 4) water reservoir (discharge side), 5) water reservoir (pressure side), 6) smooth glassy test bed, 7) light source and a wave-height measurement bracket (fig. 4 and 5).

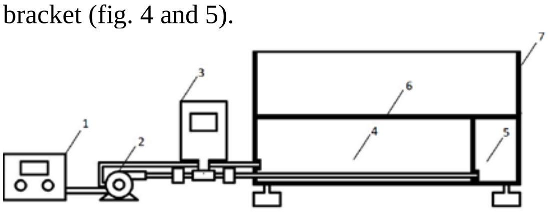


Figure 4. 2D sketch of water table test rig

Figure 5. Final version of water table test rig

For the visualization graphic capturing, a dual mobile camera was used with the following specifications: i) 12 MP, f/1.8, 27mm (wide), 1/2.3", 1.55μm, PDAF, Laser AF, OIS, and ii) 20 MP B/W, f/1.6, 27mm (wide), 1/2.7", PDAF with the ability to record video graphic with 4K@30fps, 1080p@60fps, and a slow motion with up to 32x. Also, for the purposes of the experimental measurements the following parts were constructed by transparent wall sheets:

- A supersonic diamond with length of 100mm and an angle of 30° and a thin plate of 5x100mm (width – length) for the Fr number determination.

Figure 6. Auxiliary parts for Fr number calculation

- The supersonic nozzle geometries that extracted during the design process by applying the "Real Gas" model. This geometry is related to the new-defined working fluid that consists of 30% isobutane – 70% isopentane and was proven to be high efficient and environmental friendly medium in previews publications of the authors [14].

Figure 7. Supersonic nozzle – "Real Gas" model

- The supersonic rotor blade geometry which is also defined by applying the "Real Gas" model for the new mixture of 30% isobutane – 70% isopentane.

Figure 8. Supersonic rotor blade – "Real Gas" model

RESULTS ANALYSIS

In this paper, an experimental setup was built to validate the computational fluid dynamics outcomes that presented in [14]. In particular, the validation process lies in the positioning of the generated shock waves in the produced geometries of a power production ORC turbine. More specifically, the expansion fan inside the divergent section of the supersonic nozzle which was designed by applying the "Minimum Length Nozzle" method and the generated shock waves in a supersonic rotor blades' passage that was designed by applying the "Vortex Flow" method were analysed. For the case of stator blades, two extra polymethyl methacrylate (acrylic glass) parts where stacked upstream the nozzle as inlet guide blades in order to accelerate the flow towards the passage and ensure that no leakages will occur from test bed to reservoirs (fig.9).

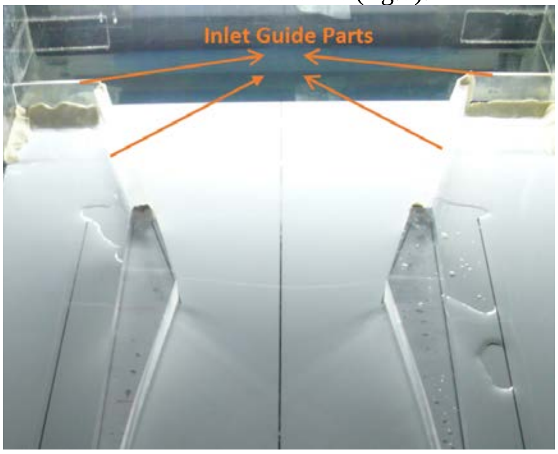


Figure 9. Inlet guide parts from acrylic glass

The top view of the supersonic flow inside the nozzle and the generated waves are presented in figure 10. The curved sonic lines are also depicted in this case at the throat (red lines) and the expansion fan is extended right after (green lines). As shown, the wave formation obeys the analytical design, and the reflection of last expansion wave approaches smoothly the trailing edge of the nozzle. One thing that was not very clear about the experimental results has to do with the shocks that included inside the yellow boxes.

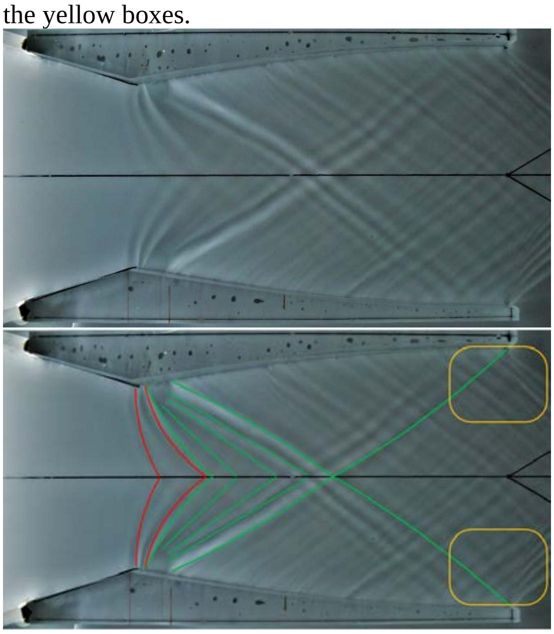


Figure 10. Generated shock waves inside supersonic passage

Having examined the initial results, it was concluded that these waves are the reflections of the expansion waves but after analyzing further the photographic content it was concluded that are shock waves produced by the surface roughness of the wall since they are parallel to these ones that generated earlier.

Moreover, the last intersection node of expansion waves from experimental results almost fits with the theoretical one while the corresponding distance errors is 4% compared to total length of the nozzle (dx) as shown in figure 11.

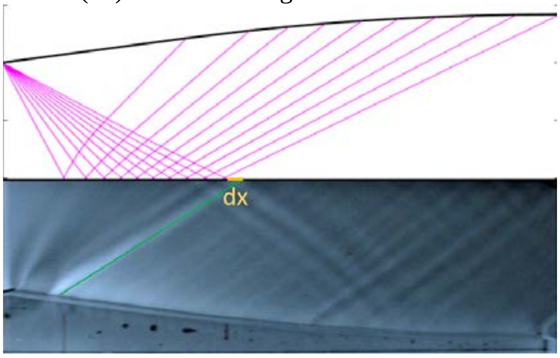


Figure 11. Experimental VS Analytical results for wave formation

Another phenomenon that was observed during the experimental tests due to construction restrictions were the shape of the expansion wave fan. From the theoretical design results the expansion fan starts from a specific point, while in real case this point is extended to few millimeters. This region can be better understood in figure 12, where the expansion fan surface is contained between two hydraulic jumps, the first and the last expansion waves (green lines).

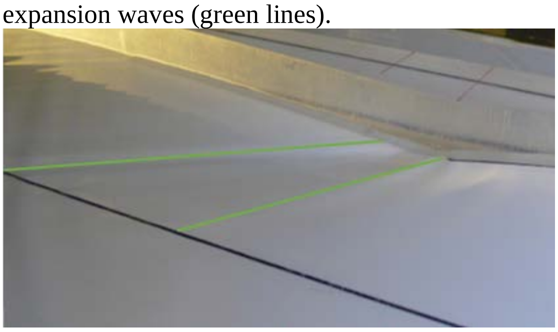


Figure 12. Expansion fan shape

Finally, by taking into consideration the experimental results it was found that both applied models for nozzle design are not robust enough, since it was observed that any small deviation of the mass flow (e.g. off-design conditions) had led to undesired results regarding the wave formation. More particularly, when the mass flow was barely decreased due to leakage issues, the generated shocks appeared more closely to the throat and therefore the reflection waves from the wall were covering useful area (yellow boxes in figure 13) inside the nozzle where it is supposed the undisturbed flow leaves the passage with Fr=2. Of course, these reflections induce extra losses in the flow and the measured Fr number at the exit was lower than the desired one, Fr<2.

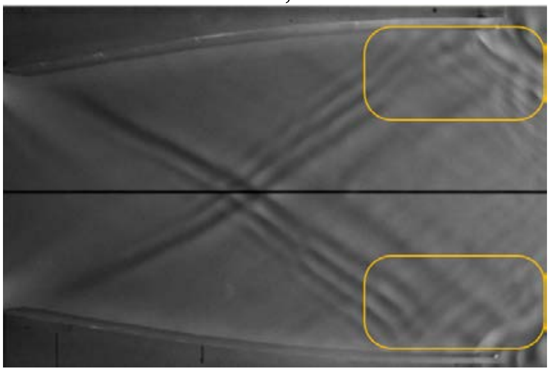


Figure 13. Reflection waves near trailing edge

Having completed the measurements for the supersonic nozzle, the experimental flow visualization technique of dye pigments injection was performed for the rotor blades. The narrow flow passage between rotor blades was the reason that color injection technique was applied, since it was impossible to capture the dominant hydraulic phenomena upstream the 40%~50% of the chord.

The top view of the supersonic rotor cascade is shown in figure 14 where the bow shocks starting from leading edges are clearly depicted as well as their cosines attenuations. Subsequently, as the flow enters the passage there is an overlapping region where the pressure waves intersect with the expansion waves that came from the suction side of the opposite blade (blue region).

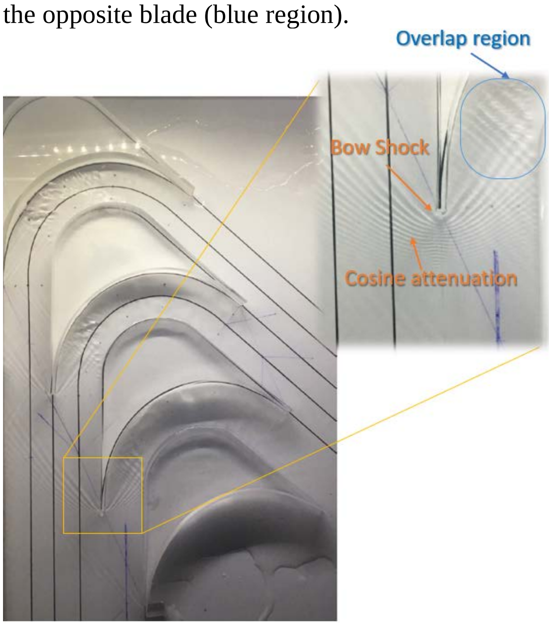


Figure 14. Top view of rotor cascade

As shown in figure 15a, a steep increment of water height at the pressure side close to leading edge validates the CFD results where the local Mach number becomes near zero as depicted in figure 15b.

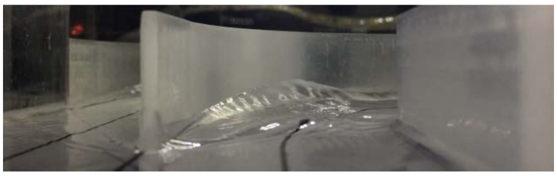


Figure 15a. Water abrupt jump

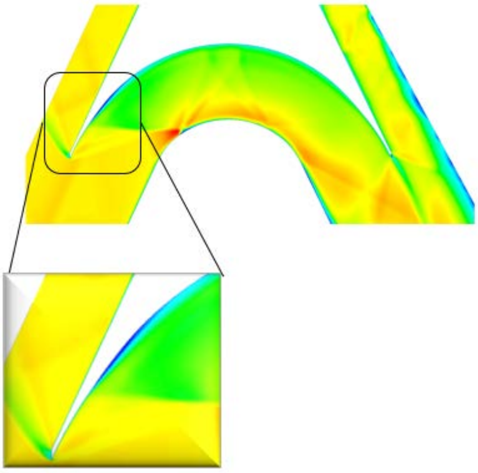
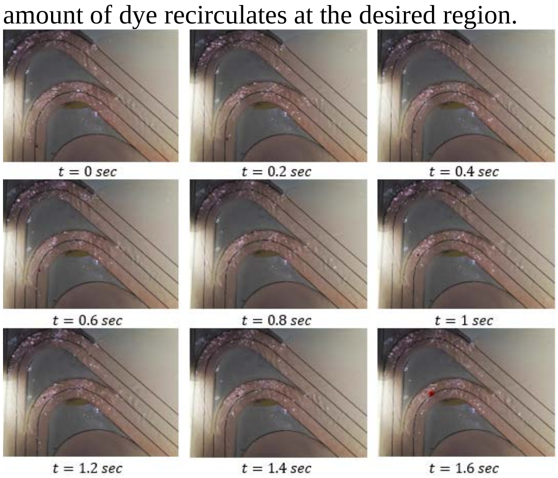


Figure 15b. Mach distribution from CFD results [14]

Finally, the selected “vortex flow method” which aims at the produced power maximization can be verified from the existence of the flow recirculation at the half cord as can be seen in the following figures that constitute a series of captured frames from recorded video during the visualization test of oil and dye injection with a time step of 0.2 seconds. During the visualization tests, the injected diluted dye follows the flow as presented in figure 16 from t = 0 sec to t = 4 sec. The red colored pigment agglomeration enters the passage at the mean line and flows towards the passage without hitting the wall at the suction side, because of the existence of the virtual water block (fig. 15a). This behavior can better understood by observing the frames from t = 1 sec to t = 1.6 sec. Afterwards, the agglomeration exploded due to high pressure at that point and from t = 2.2 sec it is observed that an amount of dye recirculates at the desired region.



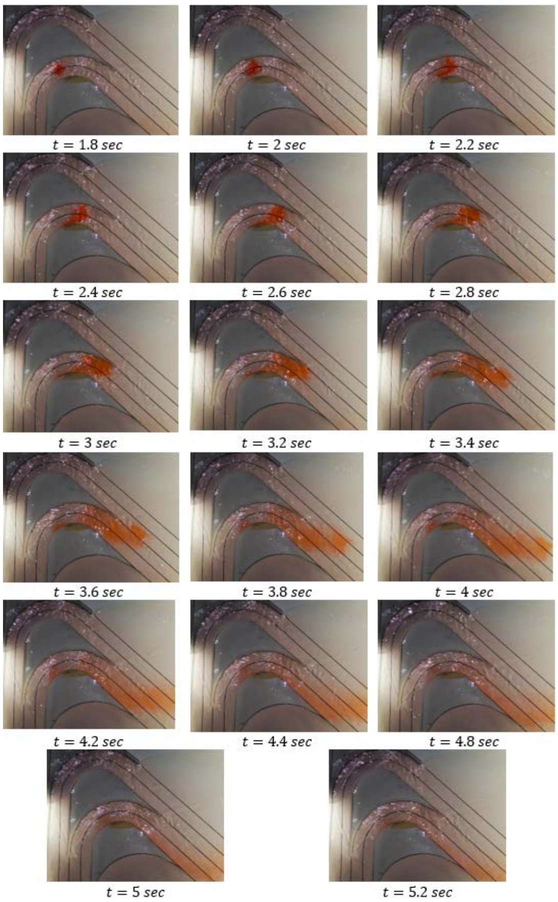


Figure 16. Flow visualization results

CONCLUSIONS

In the present work, a laboratory test facility was developed in order to validate the existence in specific positions of the generated shock waves inside a supersonic turbine blade for organic Rankine cycles. The main outcomes can be summarized as follows:

- The selection of the optimum working fluid depends on the available heat source and is a trade-off between thermodynamic, environmental, safety properties and cost.
- Real gas effects are very dominant close to saturation curve where an ORC usually operates, so they cannot be neglected in the design process of a turbine design.
- The developed design method seems not to be robust enough for off-design operation variations.
- The generated shock waves were positioned as indicated by the theoretical analysis. More specifically, the last expansion wave appears to be only 4% further compared to computational outcomes, while no reflection phenomena occurred inside the stator blade passage which means the applied design method is proven to be a dependable tool for the maximization of the produced power.

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