AN EXPERIMENTAL OBSERVATION OF FREE JET EXPANSION OF R245FA GAS IN AN REAL ORGANIC RANKINE CYCLE OPERATING CONDITION

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ABSTRACT

R245fa is a dense gas being used widely as an organic Rankine cycle (ORC) working fluid. Real-gas effects should be considered in ORC expanders. Oblique shock and the interaction of shock on the turbine blades showed a deviation between a real gas and an ideal gas according to computational fluid dynamic (CFD) simulations. However, the results have not been validated by experiment due to the lack of the experimental data. In this study, a PIV measurement setup for a supersonic organic vapor jet of R245fa is designed by substituting the turbo-expander of an ORC with a converge-diverge nozzle expanding inside a settling chamber. The expanded R245fa fog inside the settling chamber is utilized as the seeding particles. The PIV results clearly show the underexpanded shock wave trails. Also Mach disk and triple points is observed. A free jet with same conditions shows more stretched structures in comparison with R245fa gas due to lighter molecules weight. The outcomes of this study can help the designer of future ORCs to validate their CFD simulations to lead more robust and accurate design.

1. INTRODUCTION

With more limitations on energy sources and pollution concerns, the recovery of low-grade waste heat is becoming more and more attractive and necessary (Nematollahi and Kim 2017). Currently, the Organic Rankine Cycle (ORC) is the most remarkable heat recovery scheme in both science and industry (Nematollahi et al. 2018). A simple ORC includes two heat exchangers for the evaporator and condenser, a pump, and an expander. Almost all of the components except the expander have been investigated extensively, and there is a long history behind them. The expander might be considered as the most important part of an ORC. There are a number of studies on the expander design procedure and factors such as the expander type, operating conditions, and geometry (Al Jubori et al. 2017, Alshammari et al. 2018, Head et al. 2016, Pang et al. 2017, Papes et al. 2015).

Due to the high cost of experimental work on turbomachinery problems, computational fluid dynamics (CFD) has been used for design and evaluation. The ideal gas law is the simplest form of the equations of state (EoS) used for modeling the thermophysical properties of a fluid. This assumption is mostly acceptable when the working fluid is air or steam. However, in ORC applications with using dense gases, such as R245fa and siloxane MDM, that assumption is not valid. Real-gas effects should be considered in the vicinity of vapor saturation lines or near or beyond the critical point (Matheis et al. 2016, Nili-Ahmadabadi et al. 2018, Petit et al. 2015). In an ORC expander, where the flow regime is supersonic, these effects are more dominant. There have been a number of studies regarding real-gas effects for different flows (Liu et al. 2017, Liu et al. 2018, Sun et al. 2018, Wang et al. 2018). Besides the CFD studies a number of experimental works have been published related to the expander performance. However this studies are useful but they cannot present the detail about the structures of flow. Furthermore, since the organic substances have more complex molecules then their behaviors are different from simple Rankine cycle turbine.

In addition recently several setups have been made for studying the flow structures of organic gases. One of them is TROVA in Politecnico di Milano. This facility is designed for investigation of discontinues flow of MDM inside the converge-diverge (CD) nozzle (Spinelli et al. 2018). In the current condition flow inside the CD nozzle using Schlieren method have been investigated qualitatively (Spinelli et al. 2019). Furthermore a Ludwig test setup with a limited test duration has been presented for investigation of trailing-edge loss in supersonic regime for SF_6, Co_2 and air as working fluids. Other notable facilities related to organic gases are ORCHID (Head et al. 2016) and the one within the NextORC project (White and Sayma 2018) which is being constructed.

To the best of authors knowledge, a closed loop with fully controllable to achieve different condition with unlimited work time for organic vapors has not been constructed. Furthermore, up to date a qualitative experimental results for an organic vapors has not been reported. To fill this gap, an ORC cycle has been modified while a novel test section which is fully visualizable is implemented for investigation of a free jet of R245fa as an organic vapor. Particle image velocimetry (PIV) is utilized for quantitative measurement of velocity field while R245fa fog is considered as seeding particles.

2. EXPERIMENTAL APPARATUS

2.1 ORC for visualization purpose (ORCviP)

An ORC setup has been modified to study the flow structures of a dense gas jet. Figure 1 presents a flow diagram of ORCviP. The test rig includes one main loop for refrigerant where expander is replace with subset loops which will be explained in detail in next part. There are two lateral loops for preparing high and low temperature for ORCviP loop. The hot water loop setup consist of a water boiler with temperature controller with embedded heater with maximum power of 110kW. The heat is provided by a pump to the evaporator for refrigerant. A plate heat exchanger is utilized for changing heat as evaporator. The refrigerant is cooled by condenser which is a plate heat exchanger. Water is used as cooling medium while an air-cooled chiller is operating with temperature controller. Both the hot and cold loops are equipped with mass flow meters and using thereof temperature controllers the loops are fully controllable.

The ORCviP is included a refrigerant pump which has the maximum flow rate of 7.6 liter per minute (LPM) and can provide sufficient pressure for the loop. In addition, the pump equipped with an inverter that can be used to adjust the different pressure in the high pressure side of the ORCviP loop.

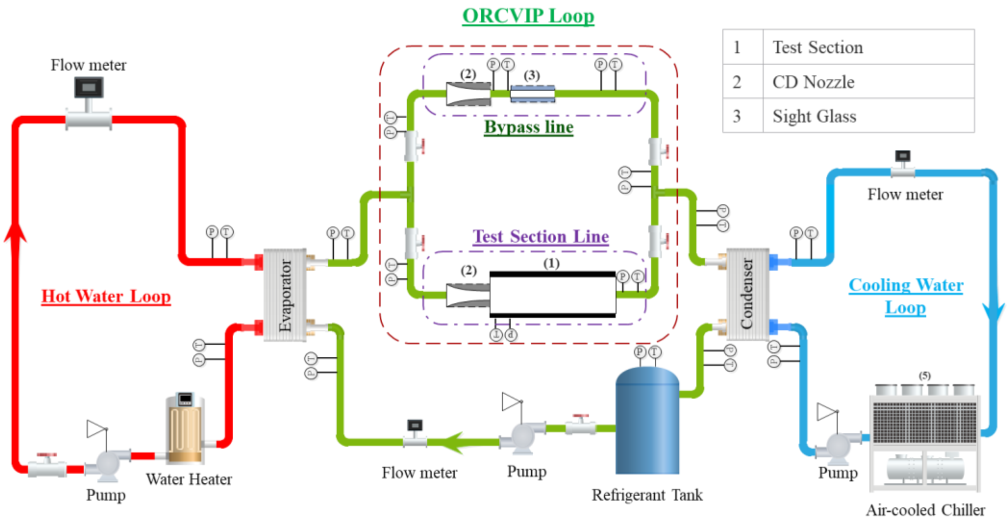


Figure 1: ORCviP cycle schematic

Generally, for all the components the inlet and outlet pressure and temperatures are measured using pressure transducers and k-type thermocouples, respectively. All the signals from measurement devices are connected to the NI data acquisition modules while monitored in real-time and saved by LabVIEW program. Furthermore, NIST Refprop (Lemmon et al. 2002) library is implemented to the LabVIEW program to calculate the cycle parameters such as enthalpies, densities, degree of superheat during the experiment.

As previously mentioned the ORCviP is a modified version of ORC to investigate the dense gas flow characteristics of a jet. The modified part as shown in figure 1 has 2 different lines. Test section line is equipped with a CD nozzle while the outlet is connected directly to a test section which all the four side is visualizable for different experimental method such as schlieren and PIV. However, in the current study two side is used while tempered glass is utilized for visualization side. In the bypass line, same CD nozzle have been used to make enough pressure drop for recirculating the refrigerant inside the cycle.

The test section is designed flexible to test different nozzle in super/subsonic conditions. Since ORCviP worked within an ORC cycle, both superheated and two-phase expansion investigations is achievable. When working fluid flows to the test section line, the ORCviP can be considered as a closed high-speed wind tunnel for organic vapors. T-s diagram and main design characteristics of ORCviP are presented in figure 1 and table 1, respectively. Furthermore, it should be mentioned that regarding to nozzle inlet conditions the compressibility factor is 0.73 which means that real-gas effects should be considered. However, other compressibility factors where real-gas effects are more dominant is achievable with changing, nozzle, refrigerant or even with inlet conditions i.e. pressure and temperature.

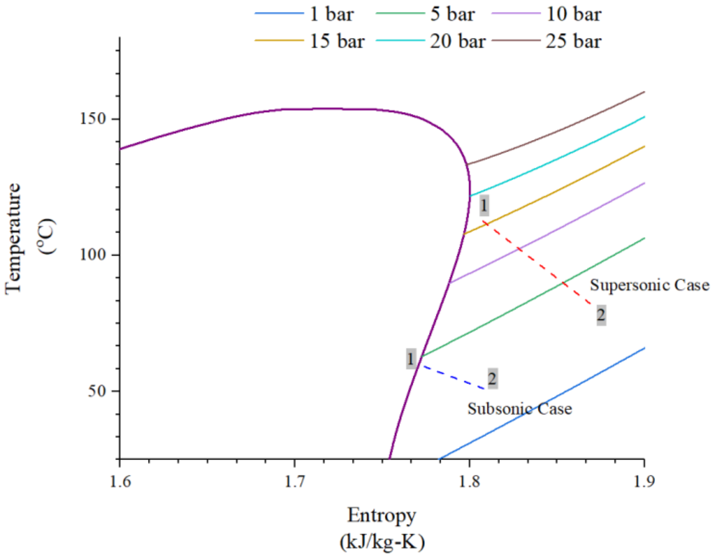


Figure 2: T-s diagram of expansion inside the CD nozzle (1 and 2 refer to nozzle inlet and outlet, respectively)

Table 1: Main characteristics of ORCVIP

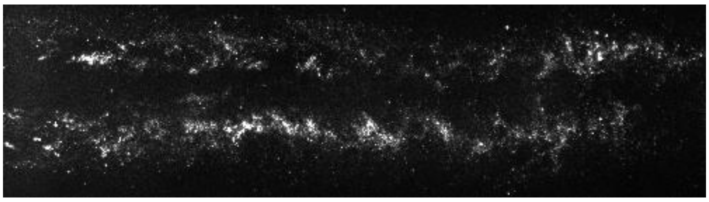
Working fluid	R245fa	
Maximum nozzle inlet Pressure	15.5	bar
Maximum nozzle inlet Temperature	112	°C
Compressibility factor in the nozzle inlet	0.73	
Nozzle inlet superheat degree	3	K
Mass flowrate	0.1	Kg/s
Nozzle pressure ratio (NPR)	5.1	
Nozzle throat area (A^*)	19.6	mm^2
Nozzle outlet area	23.76	mm^2

2.2 PIV setup configuration

Through the years different method PIV have been frequently utilized in sub or supersonic wind tunnels with air as working fluid. But, there have been a few challenges for organic vapors which needs a closed cycle for operation. The most important point except operational challenges is seeding particles, particle generator for PIV measurements. Proper seeding was a crucial issue in the current study.

The most important features of a seeding particle candidates is the ability of following the main flow. Furthermore, since this is a closed cycle, the seeding particles should be compatible with working fluid and ORC. Generally for wind tunnel with air, oils particles are generated by Laskin nozzle. But in such a closed cycle which working fluid is in high temperature and also due to the effects of particles on working fluid, these kind of seeding particles are not useful. Beside of this disadvantage, oil particles can be stuck to the test section and even inside the nozzle which reduce the visibility and even can decrease the performance of nozzle. Therefore, for this kind of closed with special working fluids, the solid particles with fine particle like TiO_2 and Al_2O_3. However, a drawback of solid particles is that the particles can be accumulated inside the cycle which should be frequently cleaned and working fluid should be drained and refilled. Furthermore, solid particle can be harmful for pump and damage it.

Having seen the advantage and disadvantages of solid and liquid particles and following the low superheat degree of nozzle inlet the refrigerant fog is utilized as seeding particles. As it monitored during the experiments for superheat degree lower than 5K there are liquid particles that are invisible to the naked eyes which is suitable for ORC application (Nematollahi, Abadi, Kim and Kim 2018). Since these particles are a part of flows with same flow characteristics, it can be sure that the liquid particles are capable to trace the flow phenomena. As it is mentioned the liquid particles are invisible to the naked eyes but having used a high power laser they can be track by the camera. To the best of authors knowledge using working fluid fog has not been used as seeding particles. A pair of consecutive raw images of PIV measurements is shown in the figure 3 for superheating degree of 3K.



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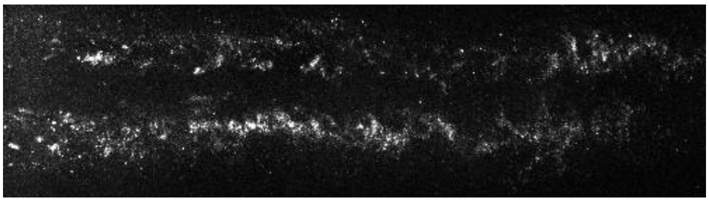

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Figure 3: PIV sample images

A 2D-PIV system was used to observe the flow structures. The PIV system included a PIVCAM 10-15 CCD camera, a double-pulsed Nd-Yag laser with a maximum power of 200 mJ/pulse, a TSI 610032 synchronizer, and a computer. The time difference between two consecutive images for capturing a suitable flow image was 1 μs while the frequency of laser pulse set to 3 Hz indicating the time difference between each double pulses. The resolution of PIV measurement was 1280 by 280 pixels. The size of the interrogation window for the velocity calculation was 32×32 pixels, and 50% overlap was allowed. An in-house software was used for PIV processing, including removing false vectors, ensemble averaging, and additional statistical calculations.

3. EXPERIMENTAL PROCEDIRE

Since ORCviP is a closed loop therefore there are transient conditions before leading to steady-state conditions. During the startup of an ORC the two-phase flow reaches to the expander inlet due to transient conditions. To overcome such a conditions a bypass line is designed with same CD nozzle. In the startup of cycle, the bypass line is opened while the operating conditions of flow is monitored to check the steady state condition. After that the test section line is opened to lead the flow inside the nozzle and PIV measurements will start.

It should be mentioned that however the purpose of the current study is to study the expansion characteristics of a superheated flow, but the expansion of two-phase can be also investigated by opening the test section line before reaching the superheated settings. The expansion of two-phase flow was reported that can be applied to increase the output power (Read et al. 2016).

Furthermore, as previously noted in the current study refrigerant fog is utilized as the seeding particles to visualize the flow. Therefore, the superheat degree was kept constant 3 degrees K during the experiment following table 1.

4. RESULTS AND DISCUSSION

To evaluate the proposed method for seeding particles two case of NPR have been carried out. Two NPR of 2.1 and 5.1 which leads to a subsonic and supersonic regimes are selected for test cases. For calculation of local Mach number the static temperature and mass flowrate of nozzle inlet is used with conservation of energy as shown in the below:

$$T = T_0 - \frac{v^2}{2c_p} \tag{1}$$

Where T_0 is total temperature calculated by nozzle inlet conditions. T is local static temperature and V is local velocity magnitude driven from both radial and axial velocities. Thereafter local Mach number was driven by ratio of local velocity magnitude to the local sound speed. The Mach number contours for low-pressure condition is shown in the figure 4.

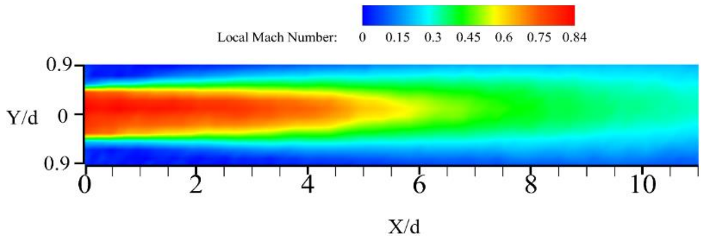


Figure 4: Local Mach number contours for NPR= 2.1

The flow conditions for this case lead to a turbulence subsonic jet where the maximum achieved Mach number is 0.84. As it can be seen almost a symmetrical free jet is evident. While shear layer are clearly separate the inner flow from outer flow. The maximum velocity of jet as it expected occurs near the jet flow while with moving further, the velocity decrease and consequently Mach number decrease. In addition the Mach number distribution for different sections are shown in Fig. 5. The results show that along the X axis the Mach number is decreased and shows the jet will be smoother near to the outer flow.

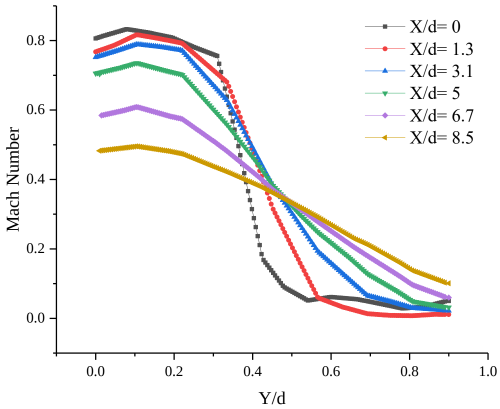


Figure 5: The Mach number distribution along the Y axis for different sections

The ensemble Mach number contour of jet for NPR of 5.1 is shown in the Fig. 6 which is superimposed by streamlines that is an indication of outward direction of the core. Furthermore, the Mach number along the axial direction are shown in the figure 7. As it can be seen the underexpanded jet is evident as immediately after nozzle jet start to grow. In addition free jet boundary that is including the expansion and compression fan is crystal clear for R245fa gas. The detail for velocity vector field around the centerline also is shown in this figure.

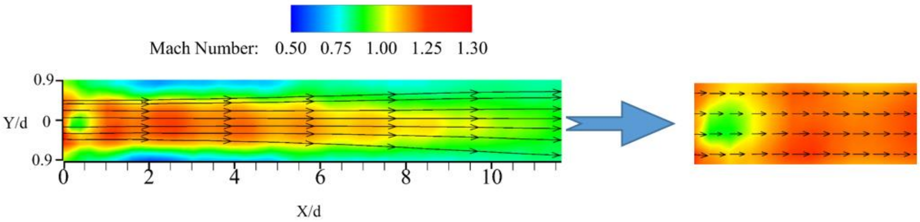


Figure 6: Local Mach Number contour for NPR= 5.1

The flow is directed forward of the jet while accelerate due to expansions waver wave cause the higher velocity in the centerline. Furthermore, a Mach disk and triple point is evident due to under expansion of jet which is visible by difference in colors. Furthermore, the flow leading to the outlet of test section the jet flow passing the shock waves flow decelerate and consequently Mach number decrease to subsonic. However between each shock cell Mach number increase due to expansion of flow until last cells.

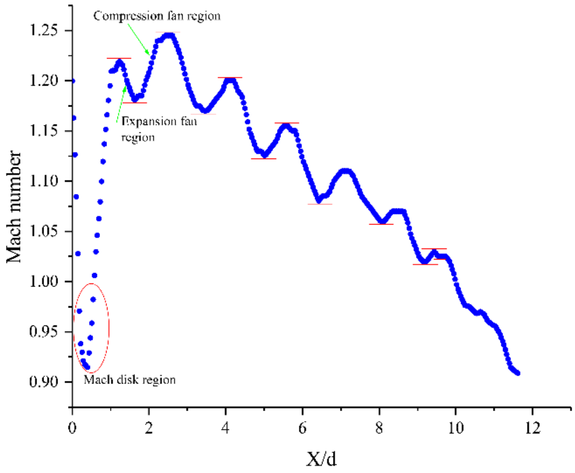
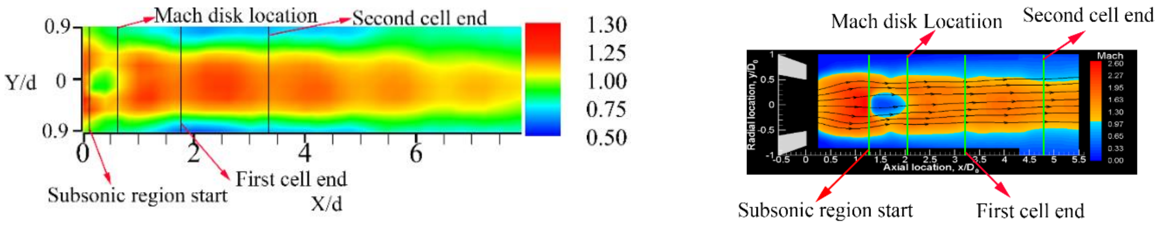


Figure 7: Centerline Mach number distribution

In addition in figure 7 Mach disk region and each compression and expansion region has been marked. Furthermore, as it can be seen the recovery of flow in compression is decreased along the axial direction while the expansion increased that lead to the removing the cell shocks. The flow characteristics of current organic vapor (R245fa gas) is compared with a same free jet of Air which has been reported by Ahumada et al. (Lazo et al.). The nozzle outlet of them was 5.5 mm and NPR= 5.08 which are the same condition with the current study. The flow structures of R245fa gas and air is shown in the figure 8.



a. Current study with R245fa gas

b. Air flow with same parameter (Lazo, Terrazas, Chen and Shu)

Figure 8: Comparison of flow structures in R245fa gas and air

As it can be seen in overall the flow field structures in air is more stretched due its lower molecular weight. The subsonic region is started faster than air in Ra25fa. As a result of the comparison Mach disk location is formed in a lower place for R245fa while it occurs in higher than 1 x/d for air. Also the Mach disk diameter is larger for air. Another feature is shock cell dimension which is smaller in R245fa. Therefore the flow can be rapidly deaccelerate in R245fa gas due to its literal feature of dense molecules. The averaged vorticity contour has been shown in the figure 9. Near the jet outlet the vorticity has the highest value which shear layer separate the core high speed flow from ambient flow. With increasing the axial direction as shear layer become larger and jet goes to be diminish the vorticity become weaker. Furthermore, vorticity pattern can be a fair jet boundaries as it follows the shear layer.

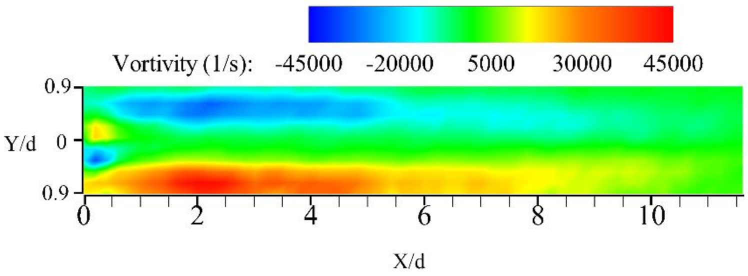


Figure 9: Vorticity distribution for NPR= 5.1

5. CONCLUSIONS

Due to lack of quantitative results for organic vapors a novel measurement setup for a supersonic free jet of an organic vapors was presented. The facility was originally an ORC which was modified for visualization purpose by replacing expander be a C-D nozzle and a test section. R245fa was selected as the working fluid. The tracing particles are one of the important challenges in such an experiments. Therefore in the current an efforts was done to use the main working fluid as tracer particles. The working fluid fog was utilized as the seeding particles while a constant superheating degree of 3K was kept in the inlet nozzle. A nozzle pressure ratios of 2.1 and 5.1 was applied to the nozzle. The features of an underexpanded jet was seen. A Mach disk and cell shocks are evident. The results were compared to a same case with air as working fluid. The comparison showed that flow characteristics of R245fa was occur earlier than air Which is an evidence of the deviation of such flows with conventional flows of air. Therefore in truboexpanders designs where real-gas effects are dominant this deviation should be considered. Current study can help the designer of future ORCs to validate their CFD simulations to lead more robust and accurate design.

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