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Numerical comparisons of conical and annular-radial diffusers' performance for high-density radial-inflow turbines

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Abstract

Organic Rankine Cycle (ORC) is developed to serve as a leading thermodynamic technique capable of extracting more energy compared to other conventional cycles, benefiting from the use of high-density fluids. The critical component of ORC cycles is the turbo expander, which is fitted with a diffuser at the exit of the rotor to increase pressure recovery and overall efficiency of the turbine. This increase of efficiency can be crucial in improving the efficiency of high-density temperature renewable power cycles. The use of high-density fluids lead to small compact radial-inflow turbines with a high velocity at the exit of the rotor. Such high velocities then enter the diffuser and can negatively impact the recovery process due to losses associated with separation and recirculation. It is thus of paramount importance to better design diffusers for high-density radial-inflow turbines. However, while many studies focused on conical diffusers, they mainly considered ideal gas. One of our previous studies [1], highlighted the different behaviour of high-density fluids in diffusers, thus requiring a more detailed understanding of the flow and design optimization of diffusers for high-density turbines.

In this analysis, R143a, a potential high-density fluid for a radial-inflow turbine, is employed. The suitable type of diffuser is discussed as it is significant to fit the current existing R143a radial inflow turbine to the best possible diffuser geometry. Computational Fluid Dynamics (CFD) is proposed in this study to effectively implement the numerical simulations of conical diffuser and annular-radial diffuser. This paper therefore compares the performance between the preliminary design of a conical diffuser and annular-radial diffuser, matching the conditions from our existing R143a radial-inflow turbine. The numerical results show that the conical diffuser geometry using R143a has difficulties achieving optimal static pressure recovery. For the same conditions, the annular-radial diffuser has higher performance compared to the conical diffuser on pressure recovery. This study further highlights the need to achieve a high performance high-density diffuser design in order to improve overall ORC efficiency, which is a critical to further develop renewable power solutions.

Introduction

The increase of the consumption of finite energy resources and the greenhouse gas emissions makes renewable energies become more attractive to generate electricity. The renewable energies including biomass, solar, ocean thermal energy and geothermal can transfer their energy into electricity by employing high-density turbines [2]. The Organic Rankine Cycle (ORC) is considered to be a leading technology for energy conversion [3], which can be used in renewable energy applications. In ORC, turbo expanders and diffusers are the key components to convert the energy into electricity [2]. Lots of investigations were conducted for ORC turbo expanders like typical work [3, 4] , while ORC diffusers are easily neglected. Diffusers are positioned at the downstream of turbo expanders, aiming to recover exhaust kinetic energy as static pressure and thereby increase the whole ORC efficiency.

A suitable diffuser to fit the radial-inflow turbo expander is significant to maximum the whole turbine efficiency. Conical diffusers are widely employed to connect the downstream of turbo expanders [4] as they have a simple geometry. Originally, the main investigations focused on experimental studies [4-6]. Based on Klein's experimental results of ideal gas conical diffusers [4], turbulence and swirl affect the performance. Baghdadi et al. [5] systematically investigated the relationship between the flow regime and the swirl number. The near-wall separation and centerline recirculation as critical aspects affecting ideal gas conical diffusers performance are investigated in detailed by Clausen et al. [6]. Some typical numerical studies on the swirling ideal gas ERCOFTAC conical diffusers have investigated the complex flow characteristics [7, 8]. However, these investigations mentioned consider ideal gas as the working fluid, which fails to comprehensively represent the high-density fluid in low-grade temperature ORC. Recently, From et al. [1] compared the detail fluid behavior characteristics between ideal gas and high-density fluid in the ERCOFTAC conical diffuser. However, the overall performance of high-density diffuser had not been investigated by From et al. [1]. In addition, based on the experimental investigation by Abir and Whitfield [9], the flow characteristic of conical diffusers are unstable, while the curved annular diffuser and the radial diffuser presented more stable flow conditions. Due to the lack of experiments with high-density fluid to compare the performance of these diffusers, it is interesting to conduct the numerical study to compare the conical diffuser and annular-radial diffuser using high-density fluid. Recently, Keep et al. [10] had a constrained preliminary design for an annular-radial diffuser to fit their existing supercritical CO_2 turbine. However, in their study, the inlet swirl angle was set to zero, which is does not represent the real flow direction out of the turbo expander rotor. In previous studies, diffusers were investigated independently from the whole turbine and did not include the turbo expander. So far, to the best of the authors' knowledge, in current numerical tools, it is quite difficult to set accurately the diffusers' inlet boundary conditions which correspond to the outlet flow of the turbo expanders to conduct numerical studies on diffusers. The influence of inlet boundary conditions are known to affect the flow in diffusers and as such, in this study, our proposed R143a radial-inflow turbo expander [11] is built as the inlet part of the diffuser.

To sum up, these conical diffusers and annular-radial diffusers experimental and numerical studies cover the flow under ideal gas regime. Limited understanding has been established regarding the way flow characteristics of these two typical diffusers employing high-density fluid affect the efficiency of ORC turbines and thus further influence the overall efficiency of the low-grade temperature ORC.

The purpose of this paper is therefore to numerically compare the performance between the preliminary design of a conical diffuser and an annular-radial diffuser, fitting the conditions from our current existing 400kW R143a radial-inflow turbine.

Methodology

Thanks to the capability of Computational Fluid Dynamics (CFD) solver to model high-density fluids [12], it is used in this study to evaluate the performance of two different types of diffusers. The numerical simulations have been conducted by employing the ANSYS CFX package based on the Finite Volume Method to perform steady-state 3D viscous simulations [13]. Reynolds-Averaged Navier Stokes (RANS) equations for viscous compressible flows were applied. Harinck et al. [14] conducted the simulation of a supersonic ORC turbine stator, and they compared the $k-\omega$ and $k-\epsilon$ turbulence models. Very minor differences between the two turbulence models were observed to affect the flow characteristic. Thus, continuing from Sauret and Gu [11], the standard $k-\epsilon$ turbulence model with scalable wall function was chosen, associated with a first order numerical scheme for the turbulence variables for robustness consideration. Convergence is achieved once the Root Mean Squared (RMS) residuals for mass, momentum, and turbulence variables approach the residual target of 1×10^{-6}.

In order to investigate the effect of the high-density fluid properties on the whole turbine performance, the cubic EOS of Peng-Robinson (PR) [15] which is known for its good balance between simplicity and accuracy especially near the critical point, is chosen.

Preliminary design of diffusers

The inlet dimensions of the two diffusers are constrained by the outlet of the upstream R143a turbo expander detailed in [11].

The preliminary conical diffuser geometry is built based on the geometric similarity of From et al. [1] to fit existing R143a radial-inflow turbo expander. The sketch of the conical diffuser is presented in Figure 1. We denote *red colour* point as S_c, which corresponds to a streamwise location = 0.7 along the diffusing wall.

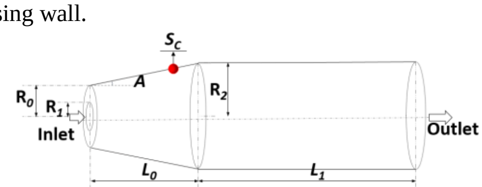

Figure 1. Sketch of conical diffuser.

Using the geometric similarity principle, the original diffuser [1] was scaled down. The geometric parameters for the preliminary conical diffuser design are presented in Table 1.

Table 1. Geometric parameters of the conical diffuser.

Name	Symbol	Value
Inlet outer radius	R_0	46.1 mm
Inlet inner radius	R_1	14.1mm
Outlet Radius	R_2	77.6 mm
Diffuser Length	L_0	180 mm
Extension Length	L_1	360.1 mm
Half Cone Angle	A	10°

The annular-radial diffuser is created according to the theory description from [10, 16]. Moller [17] demonstrated an annular-radial diffuser design method for the bend with no change in passage region along the flow path, which is a key study to combine axial and radial diffuser. In Moller's experiment using ideal gas, the non-dimensional width h/d is 0.1-0.2 and the optimal deterministic analysis value is 0.143. Due to lack of experimental study using high-density fluid, in this study, the h/d is set 0.143 for the preliminary design of annular-radial diffuser. The h is demonstrated in Figure 2. The d is calculated by Equation (1).

$$d = 2\sqrt{r_s^2 - r_h^2} \tag{1}$$

We denote *magenta colour* and *blue colour* points as S_{a-s1} and S_{a-s2}, which corresponds to the locations at shroud are streamwise 0.22 and 0.5 respectively. The *green colour* point is denoted as S_{a-h} corresponding to the streamwise 0.13 along the hub. The sketch of annular-radial diffuser is presented in Figure 2. Based on the inlet dimension constraints from the existing R143a radial-inflow turbo expander, the optimal diffuser dimensions for r_s, r_h, L, r, r_0, and h are constrained by the equations given in [17].

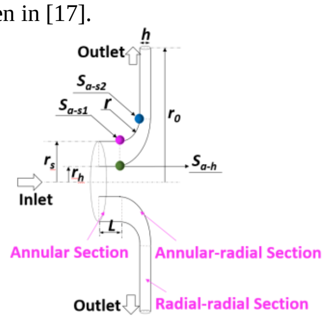

Figure 2. Sketch of annular-radial diffuser.

The geometric parameters of the preliminary design of annular-radial diffuser are presented in Table 2 where $\alpha_1 = h/d$.

Table 2. Geometric parameters of the annular-radial diffuser.

Name	Symbol	Value(mm)
Shroud radius	r_s	46.1
Hub radius	r_h	14.1
Inlet axial length	L	15
Transition radius	r	26.9
Outlet radius	r_0	120
Radial passage scaling factor	α_1	0.143
Radial Passage width	h	13.1

Performance of diffusers is typically described by the pressure rise coefficient, C_p is defined in Equation (2).

$$C_p = \frac{P_{s\,out} - P_{s\,in}}{P_{t\,in} - P_{s\,in}} \tag{2}$$

Modelling

Mesh

A structured three-dimensional hexahedron O-H grid for the turbo expander with a total grid number of 1,359,907 nodes is used. The validation and grid independence of the CFD results associated with the turbo expander design have been conducted by Sauret and Gu [11] against the meanline analysis with results showing good agreement between both the CFD results and the meanline analysis.

An O-H grid for both the conical diffuser and the annular-radial diffuser is generated. The grid independence study is conducted employing refinement ratio 1.2 as shown in Table 3. The nominal mesh sizing is employed in this study for both diffusers. The pressure recovery coefficient C_p is monitored for both diffusers, and the nominal mesh is shown to be converged.

Table 3. Grid study of isentropic static enthalpy at exit of diffusers.

	Conical diffuser	Annular-radial diffuser
Mesh	C_p	C_p
Coarse	0.7266	0.7533
Nominal	0.7269	0.7536
Fine	0.7268	0.7536

Due to modelling the whole turbine, the periodic boundary condition is built so that only one passage is modelled for expanders including stator, rotor, and for both diffusers geometries as well. The mesh of one passage for both diffusers is presented in Figure 3.

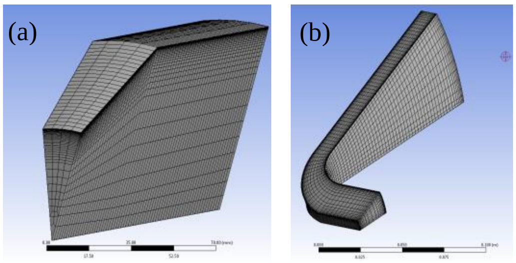

Figure 3. One slide passage mesh for (a) conical diffuser (b) annular-radial diffuser.

The nearest grid point from the wall is 7×10^{-6}m, which satisfies the requirement of $y^+ < 2$.

Boundary conditions

In this study, as the whole turbine is modelled, the main boundary conditions of the 400kW-R143a ORC radial-inflow turbo expander designed by Sauret and Gu [11] are listed as: inlet mass flow rate of 17.24 $kg.s^{-1}$, total inlet temperature of 413K, outlet pressure of diffuser 1.835 MPa, rotational speed of the rotor 24,250 RPM, total blade number of stator 19, and total blade number of rotor 16. The wall is set to a no-slip condition. All detailed geometric and design conditions are provided in [11] and not fully repeated here.

Results

The Mach number range through annular-radial diffuser and conical diffuser are 1×10^{-15}- 0.3798 and 1×10^{-15}- 0.4762 respectively. The Reynold Number range for annular-radial diffuser and conical diffuser are 1.09×10^{6}- 4.66×10^{7} and 1.36×10^{7}- 4.67×10^{7} respectively.

The total-to-static efficiency and flow fields of the whole R143a radial-inflow turbine including turbo expander and diffusers are calculated. The total-to-static efficiencies ($\eta_{T-S} = \frac{h_{T_{in}} - h_{T_{out}}}{h_{T_{in}} - h_{S_{is\,out}}}$) are presented in Table 4.

Table 4. Total-to-static efficiency η_{T-S} for the whole turbines using different diffusers.

Diffuser type	η_{T-S}
Conical diffuser	0.8738
Annular-radial diffuser	0.9038

Overall efficiency is improved by approximately 3.4% using the annular-radial diffuser compared to the conical diffuser.

Table 5. The pressure recovery coefficient C_p for both diffusers.

Diffuser type	C_p
Conical diffuser	0.7269
Annular-radial diffuser	0.7536

Overall pressure recovery coefficient has approximately 3.7% improvement employing the annular-radial diffuser compared to the conical diffuser as presented in Table 5, which explains the increase of the overall whole ORC turbine efficiency.

Further Uncertainty Quantification analysis for turbo-expander performance using different EOS as proposed in [11] have been investigated and recently submitted for review. It showed that PR EOS is not the most sensitive to uncertain parameters and as such the superiority of the annular-radial diffuser is expected to still hold under uncertainties. Further design optimisation may be needed to improve those results even further.

In order to better understand the flow characteristics of the two diffusers, the velocity streamlines at the periodic plane for both diffusers are presented in Figure 4 and Figure *5*.

Based on Figure 4, a small near-wall separation marked in *Red Rectangle* happens, which is located near the outlet of the diffuser. Furthermore, there is a recirculation at the inlet centreline of the conical diffuser (*Purple Rectangle)*.

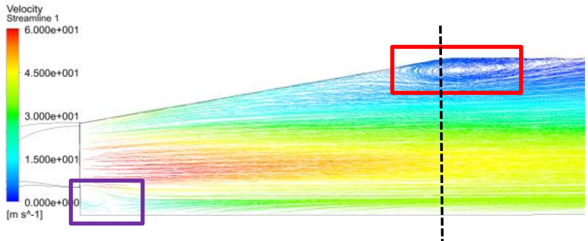

Figure 4. The velocity streamline of the conical diffuser.

Compared to the conical diffuser, neither obvious separation nor recirculation is observed in the annular-radial diffuser according to Figure 5 (a) and closer view of dash box for Vector Figure 5 (b).

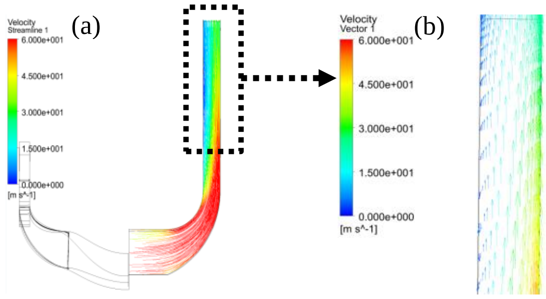

Figure 5. The velocity streamline of the annular-radial diffuser. (a) Overall view. (b) Closer view for the dash box for Vector.

In order to investigate the flow phenomenon regarding the near-wall separation, the characteristics of boundary layer along the wall of the diffusers are evaluated by the skin friction coefficient (C_f), as shown in Figure 6 for the conical diffuser and in Figure 7 and Figure 8 for the annular-radial diffuser.

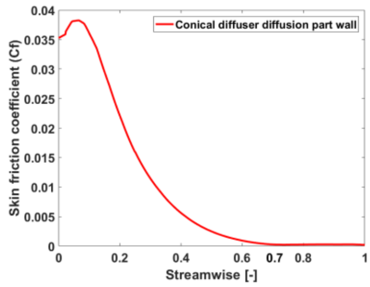

Figure 6. Skin friction coefficient of conical diffuser.

Based on Figure 6, from approximately streamwise 0.7 (point S_c in Figure 1), the skin friction coefficient is zero for the conical diffuser. These results have good agreement with Figure 4 in *Red Rectangle* region, which means it is starting to generate the near-wall separation in this region.

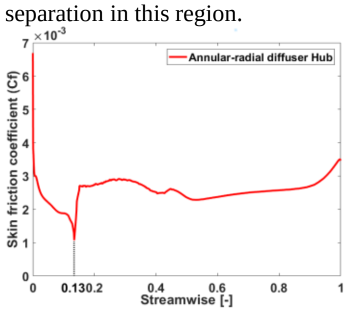

Figure 7. Skin friction coefficient of annular-radial diffuser hub.

As presented in Figure 7, there is an obvious drop of the skin friction coefficient at the annular-radial diffuser hub at approximately streamwise 0.13, at the beginning of the bending (point S_{a-h} in Figure 2). The geometry changes from straight to bending, which results in a change of the flow direction, and thus the velocity reducing at the turning region.

As demonstrated in Figure 8, a skin friction coefficient peak occurs at streamwise 0.22 (S_{a-s1} point in Figure 2), which indicates that the near-wall separation is difficult to be generated in this region. However, from approximately streamwise 0.5 located from the annular-radial section to radial-radial section (S_{a-s2} point in Figure 2), the skin friction coefficient is low but much higher than zero. These results show that the near-wall separation more easily happens in the radial-radial section than in the annular and annular-radial sections for annular-radial diffuser. No obvious near-wall separation occurs in this annular-radial diffuser.

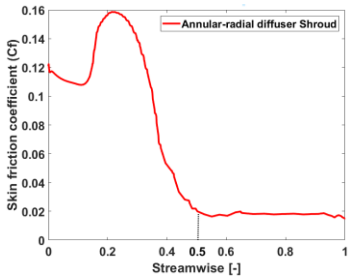

Figure 8. Skin friction coefficient of annular-radial diffuser shroud.

In summary, these results agree well with the experimental results in [9]. The diffuser performance improves when curving the passage from the flow cone angle to the radial direction. The curved radial direction passage better converts the high kinetic energy from upstream rotor into static pressure than straight direction does. Moreover, the annular-radial diffuser effectively avoid the recirculation at the centerline generated in the conical diffuser. The conical diffuser also needs very long extension to achieve static pressure recovery, which may be a space limitation for the whole turbine layout.

Conclusions

Comparing the total-to-static efficiency of the whole turbine by fitted two diffusers, the annular-radial diffuser design produces favourable results compared to conical diffuser. The total-to-static efficiency and pressure recovery obtained with the annular-radial diffuser are approximately 3.4% and 3.7% higher than the conical diffuser, respectively.

Based on these preliminary designs of these two types of diffusers, the annular-radial diffuser seems slightly more favourable than the conical diffuser to fit our current R143a radial-inflow turbo expander. The appropriate choice of diffuser is critical to improve the whole turbine efficiency and thus to improve overall ORC efficiency, which is significant to further develop renewable energy sector, and would thus require further detailed investigations.

Acknowledgments

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