

Study on the Scroll Compressors Used in the Air and Hydrogen Cycles of FCVs by CFD Modeling

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ABSTRACT

Fuel cell vehicles (FCVs) have become a research hotspot because of the continuous increase in transportation needs, energy needs, and environmental issues. However, several challenges must be overcome to be competitive with conventional vehicles. The performance of air and hydrogen cycles depends on compressors. It is a key issue to guarantee the efficiency and reliability of FCVs. In this paper, the working conditions of hydrogen and air scroll compressors in FCVs were described in details. 3D transient CFD numerical simulations with dynamic meshing of the air scroll compressor and the hydrogen compressor/pump were presented. The performance of scroll compressors in various working conditions was studied including different fluid, rotating speed, pressure ratio and axial clearances. The simulated results were validated experimentally. The results show that the large air demand is a challenge for the scroll-type air compressor to apply in FCVs. The scroll compressor is a good way to recycle the unreacted hydrogen in FCVs. However, method should be taken to solve the leakage issue through the axial clearance and radial clearance. The axial clearance has a significant influence on the hydrogen compressor, which dropped from 95.12% without axial clearance to 70.00% with 0.04 mm axial clearance.

1. INTRODUCTION

New energy vehicles have gained extensive attention worldwide due to the continuous increase in transportation needs, energy need, and environment issues^[1]. The fuel-cell vehicles (FCVs) have become a research hotspot because they are recognized as zero-emission vehicles. They use hydrogen and produce only water and heat^[2]. The world's leading automobile manufacturers such as Toyota, Honda, Hyundai, Ford, Shanghai Volkswagen, etc., have engaged in the development of their own FCVs. For many automobile manufacturers, the timetable of launching their commercial FCVs is set to be before 2025. FCVs are also taken as a suitable solution for environment pollution to China, "Made in China 2025 strategy" emphasized the plan of developing FCVs. Obviously, the FCV is one of the most potential vehicles in the future guaranteed by the development of related technologies.

The proton exchange membrane (PEM) fuel cell, as an energy power device, is the key component of FCVs, and its performance directly impacts on stability, reliability and durability of FCVs. The air supply system and the hydrogen supply system must be applied to satisfy PEM requirements. The air supply system is to supply continuous oxygen for fuel cells by an air compressor. Even though inlet hydrogen can achieve enough power from high-pressure hydrogen tanks to feed in, a hydrogen compressor or an ejector is still required to recirculate unreacted hydrogen. It is because the actual flow of hydrogen should be 1.1-1.5 times the consumption of hydrogen to achieve high fuel utilization and efficiency of fuel cells^[3]. Due to the inflexible flow rate of ejectors, the hydrogen compressor is recommended to recycle unreacted hydrogen in FCVs. In December 2014, Toyota released the first commercial fuel cell vehicle named Mirai using a compressor in hydrogen supply system^[4]. Figure 1 shows the fuel cell system in FCVs with hydrogen and air compressors. Hydrogen from high-pressure tanks feeds in and comes through PEM to react with oxygen. Then water is generated and discharged. The unreacted hydrogen is recycled by the hydrogen compressor.

The traditional types of air compressors cannot be directly employed in PEM. There are special requirements of FCVs: 1) relatively low flow rate with high pressure ratio compared to other air supply systems, pressure ratio is usually among 1.3-3.2 bar and volume flowrate is about 95.75 Nm³·h for a 100 kW fuel cell system, 2) oil-free, 3) high efficiency, 4) low noise level, 5) low weight and volume. The hydrogen compressor in FCVs must be applied with the same requests except point one. And it works under this condition: 1) low flow rate with low pressure ratio,

pressure ratio is usually among 1.1-2.0 bar and volume flowrate is about $17.6 \text{ Nm}^3\cdot\text{h}$ for a 100 kW fuel cell system when hydrogen reflux ratio is 2.0. Comparing with other types of compressors, the scroll-type compressor is one of the most promising compressor for FCVs. The reasons are as follows, first the scroll compressor provides wide flexible flow range and tune pressure ratio without oil lubrication. It guarantees the performance and stability of FCVs in various working conditions. Second, the operating efficiency exceeds the traditional piston compressor particularly under low mass flow condition. Its efficiency can typically achieve 85% higher than a typical piston compressor which is 65%^[5]. Third, the scroll compressors have low noise and vibration, and it provides comfort and safety for FCVs.

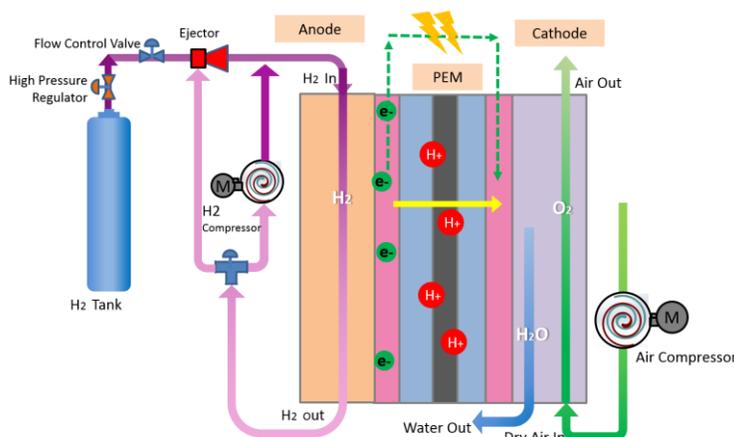


Figure 1: Fuel cell system in FCVs with the hydrogen and air compressors

Previous studies mainly focused on performances of scroll compressors used in refrigeration systems or air conditioners. When scroll compressors are applied in FCVs, there are challenges need to be overcome especially for the scroll-type hydrogen compressor. The gas leakages through radial clearance and axial clearance may vary widely and influence the overall performance. This paper presents a CFD method to study performances of the scroll-type hydrogen and air compressors in FCVs,

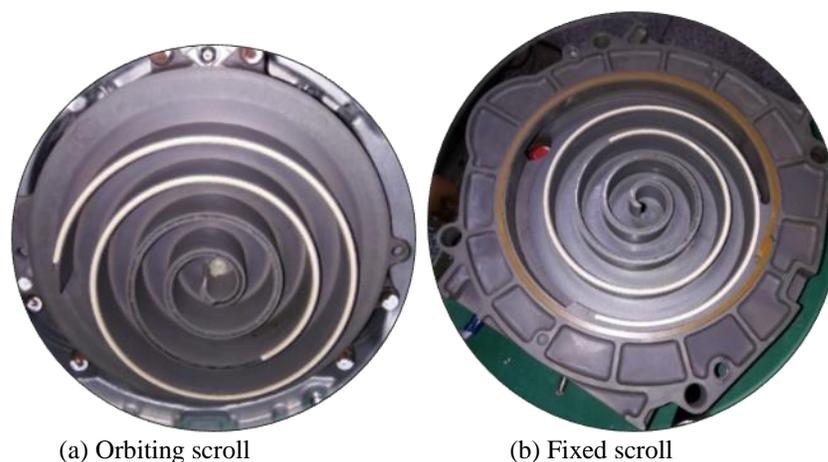
2. MATHEMATICAL MODEL

2.1 Geometric Model of Scroll Compressors

In this study, the reverse engineering method^[6] through 3D scanning was used to design a scroll-type air compressor and a hydrogen compressor based on a real oil-free air scroll compressor. The images of the compressors are as shown in Fig. 2. The 3D representation of a real air scroll was obtained including the actual geometric features of the scroll profile. Table 1 shows the designed parameters for the scroll-type hydrogen and air compressors in details.

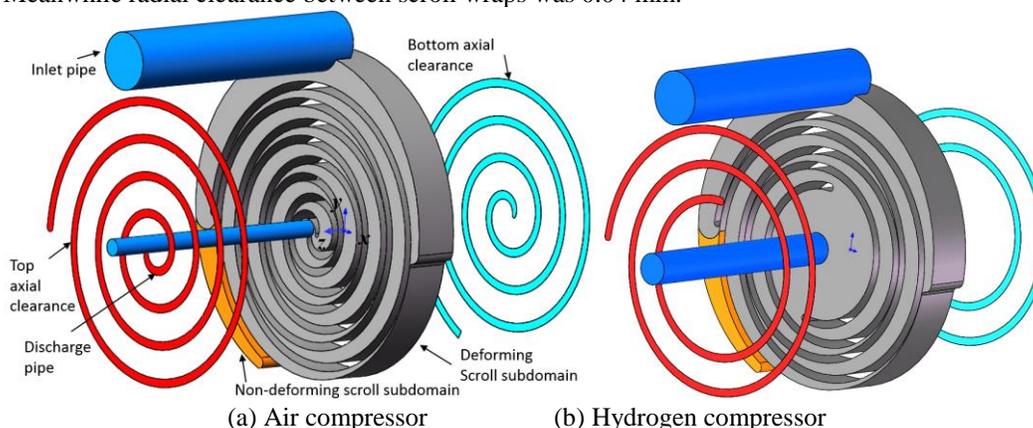
Table 1: Main parameters of the scroll-type compressors in this study

Parameters	Value
Pitch of scroll involute / mm	17.40
Thickness of scroll wrap / mm	4.0
Height of scroll wrap / mm	23.30
Number of circles	2.25 for H ₂ compressor, 4.25 for air compressor
Basic circle radius / mm	2.77
Orbiting radius / mm	4.71
Theoretical suction volume / mL	84.00
Rotational direction	clockwise



(a) Orbiting scroll (b) Fixed scroll
Figure 2: Oil-free scroll compressor in this study

Based on the analysis of the geometric model, the calculation region of scroll fluid field is plotted out as shown in Fig. 3. The fluid domain of a scroll-type compressor was decomposed into two domains: the deforming scroll subdomain that moves with the orbiting scroll, and non-deforming subdomains that include the top and bottom axial clearances, inlet pipe, discharge pipe, and the non-deforming scroll subdomain. The sizes of fluid domains in working chambers are at 10 mm level, while the sizes of radial and axial clearances are just at 0.01 mm level. There are two main types of clearances: radial clearance leading to tangential leakage and the top and bottom axial clearance leading to radial leakage. Due to the great challenge of generating high-quality grid in multi-scale fluid domains, Previous researchers have either neglected the axial clearances^[7] or adopted a larger size than the actual clearance^[8]. To ensure accuracy, it is necessary to consider the clearances in the model, especially when the scroll-type hydrogen compressor is applied. In this paper, different axial clearances of 0 mm, 0.02 mm and 0.04 mm were adopted. Meanwhile radial clearance between scroll wraps was 0.04 mm.



(a) Air compressor (b) Hydrogen compressor
Figure 3: Fluid domains of the scroll-type compressors

2.2 Mesh Generation

The key to simulate a scroll compressor working process by CFD is the generation of dynamic mesh, especially applying sufficient density mesh in leakage clearances with size in the micrometer level in the narrower areas to ensure simulation accuracy. At the same time, the mesh quality should be kept at a reasonable level to ensure high speed of computation. First, the structured grid is generated in the x-y plane. Then, the 2D mesh is stretched along the z-axis (height direction) to form a 3D mesh. Figure 4 shows the details of the structured 2D mesh in the x-y plane and in height direction. The number of layers in the radial clearance is as many as in the working chamber, which is 20 in this case. And 24-layer grids were generated in the height direction.

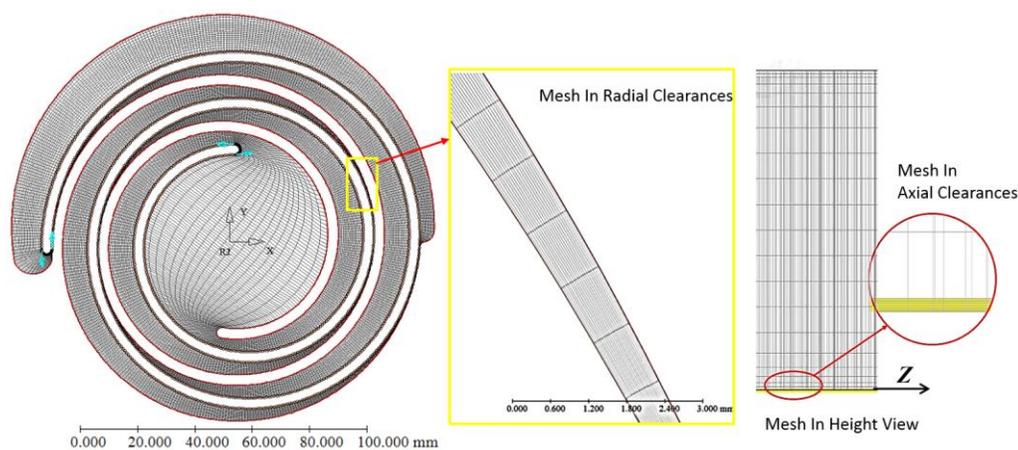


Figure 4: Structured mesh in the scroll compressor

2.2 Simulation Method

The inlet conditions were set as 1.0 bar and 293.15 K, and the outlet pressure was set according to the pressure ratio. Table 2 presents 18 simulated operating conditions of the scroll-type hydrogen and air compressors include different working fluids, axial and radial clearances, rotating speeds, and pressure ratios. As the rotating speed of the scroll compressor is relatively high, heat transfer cannot occur rapidly, and hence the working process was assumed to be an adiabatic process.

Table 2: the details of simulation conditions

Case	Fluid	Radial Clearance mm	Axial Clearance mm	Pressure Ratio	Rotating speed $r \cdot \text{min}^{-1}$
1	H ₂	0.04	0	1.3	3000
2	H ₂	0.04	0.02	1.3	3000
3	H ₂	0.04	0.04	1.3	3000
4	H ₂	0.04	0.04	1.3	4500
5	H ₂	0.04	0.04	1.3	6000
3.1	Air	0.04	0.04	1.3	3000
4.1	Air	0.04	0.04	1.3	4500
5.1	Air	0.04	0.04	1.3	6000
6	H ₂	0.04	0.04	1.4	3000
7	H ₂	0.04	0.04	1.4	4500
8	H ₂	0.04	0.04	1.4	6000
9	H ₂	0.04	0.04	1.6	3000
10	H ₂	0.04	0.04	1.6	4500
11	H ₂	0.04	0.04	1.6	6000
12	H ₂	0.04	0.02	1.3	4500
13	H ₂	0.02	0.02	1.3	4500
14	H ₂	0.02	0.04	1.3	4500
16	Air	0	0.04	4	1889
17	Air	0	0.04	4	2008
18	Air	0	0.04	4	2258

With regards to turbulence modeling, the shear stress transport $k-\omega$ (SST $k-\omega$) model was used in the present study. This model is widely used in aerospace and rotary machinery fields. The SST model can predict the effects of strong streamline curvatures and adverse pressure gradients that could occur in the radial clearances^[9].

3. EXPERIMENTAL VALIDATION

Experiments of an oil-free air scroll compressor shown in Fig. 5 were carried out to validate simulation results of case 16-18.

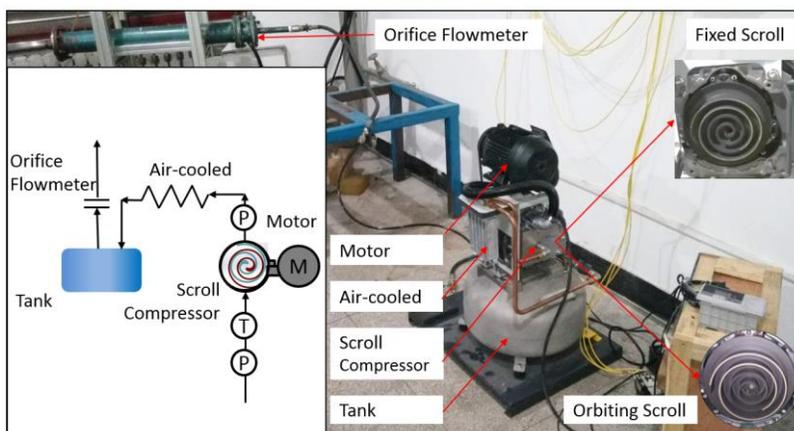


Figure 5: Test-rig of the oil-free scroll compressor

The model without axial clearance was used, because sealing strips were applied in the actual scroll compressor. The pressure ratio was 4.0, and the value of radial clearance was 0.04 mm. Volumetric efficiency was used to analyze the leakage level. Dividing the actual flow by the theoretical value will yield a value which, taken as a percent, indicates volumetric efficiency. The results in Fig. 6 indicated that the simulated variation tendency of volumetric efficiency was the same as the experiments. The maximum deviation between the simulated and experimental results was 9.0% on volumetric efficiency. For the compressor, the radial leakage would still happen even though there are sealing strips, so the simulated volumetric efficiency will be a little higher than the test results. From an engineering perspective, the simulation results can satisfy practical requirements.

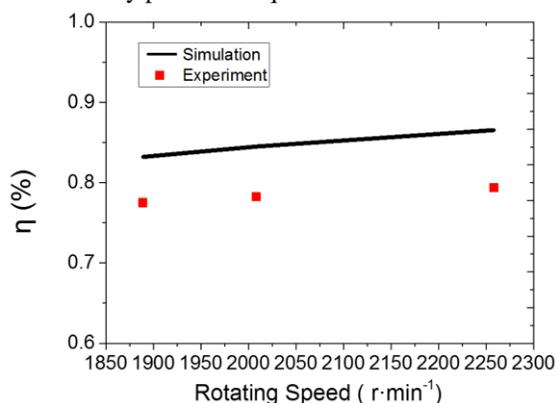


Figure 6: Results of experiment and simulation

4. RESULTS AND DISCUSSION

4.1 Results of the Scroll-type Air Compressor

As the suction and discharge pipes were nearly symmetrical for the chambers, these symmetrical pressure field were obvious in a pair of working chambers. Figure 7 describes pressure distribution in case 17 at different angles of a stable cycle: radial clearance was 0.04 mm without axial clearance, pressure ratio was 4.0, and rotating speed was 2008 r-min⁻¹. There is little difference in the results for different compression chambers; this shows that there is no

time delay in the pressure distribution, and that the pressure changes immediately with change in the angle in each compression chamber.

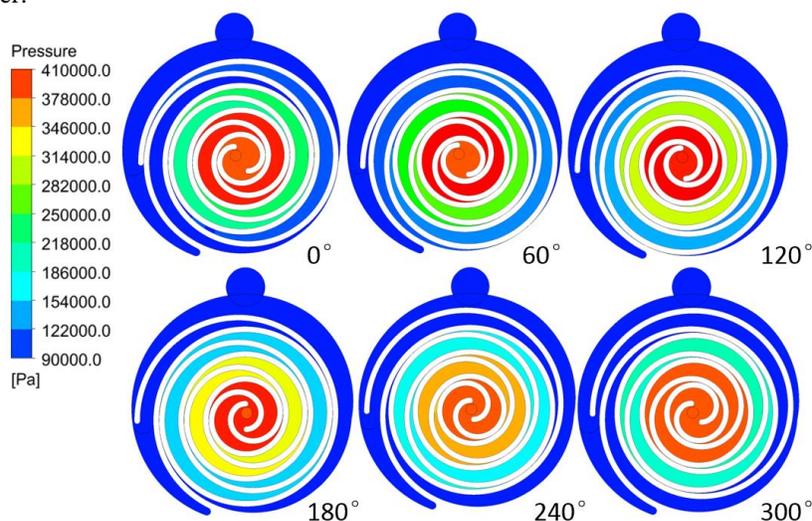


Figure 7: Pressure distribution in the scroll chambers in case 17

The velocity field of case 17 was presented in Fig. 8 with the upper limit of $50 \text{ m}\cdot\text{s}^{-1}$ for the velocity. However, the maximum leakage velocity up to $200 \text{ m}\cdot\text{s}^{-1}$ occurred in radial clearance. It is consistent with the results of Sun^[7]. The higher velocity occurred near left inlet chamber at 180° . This is because, at 180° the inlet chamber required feeding of a larger volume of fluid, and the velocity in the left inlet chamber was in the direction opposite to that of the inlet fluid.

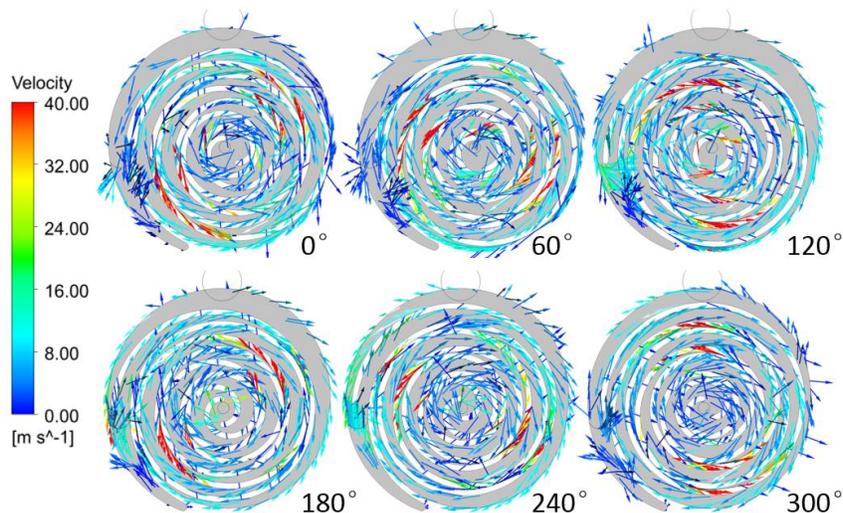


Figure 8: Velocity field in the scroll chambers in case 17

Even though pressure ratio and discharge pressure can satisfy the requirements in this study, mass flow rate is a challenge for scroll-type air compressor to use in FCVs. Theoretical mass flow rate is decided by involute design and rotating speed. The higher mass flow rate will demand larger compressor volume and weight which is sensitive for vehicles design. More importantly, dynamical analysis including the stress and deformation of orbiting scroll need to be verified when the compressor volume is large. This need further study.

4.2 Results of the Scroll-type Hydrogen Compressor

Figure 9 presents the effects of working fluid in a scroll compressor for cases 3-5 and 3.1-5.1 with 0.04 mm axial clearance, 0.04 mm radial clearance and 1.3 pressure ratio. Volumetric efficiency was used to analyze the leakage level. As Fig. 9 presented, the volumetric efficiency with air is approximately 15% higher than that with hydrogen.

This means that the leakage in a scroll compressor is more serious when hydrogen is used as the working fluid, and great care should be taken to avoid this problem.

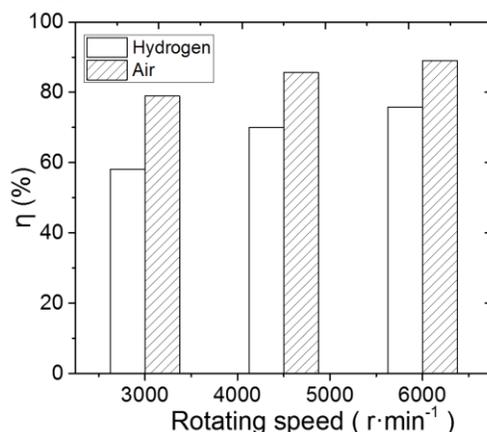


Figure 9: Change in volumetric efficiency with rotating speed

The effects of rotating speed is also presented in Fig. 9. The volumetric efficiency has an increasing trend with the increase in rotating speed, and finally it tends to remain flat. The volumetric efficiency increased by 30.68% in the case of hydrogen when rotating speed rose from 3000 r·min⁻¹ to 6000 r·min⁻¹. In the case of air, the volumetric efficiency increased by 12.81%. The rotating speed has a much larger influence on the scroll-type hydrogen compressors than on the air compressors under the same conditions.

The effect of pressure ratio on volumetric efficiency at different rotating speeds was studied for cases 3-11 with 0.04 mm axial clearance and 0.04 mm radial clearance. As shown in Fig. 10, at the rotating speeds of 4500 r·min⁻¹ and 6000 r·min⁻¹, the volumetric efficiency declines linearly with the rise of pressure ratio. At the rotating speed of 3000 r·min⁻¹, the volumetric efficiency drops significantly at a pressure ratio of 1.4. This is because, the scroll compressor is in an under-compressed working condition at 3000 r·min⁻¹. This simulation results recommend that the volumetric efficiency of the scroll-type hydrogen compressor could increase by rising rotating speed in a proper range of pressure ratio. When pressure ratio reaches a higher level, the backflow of discharge chamber would decrease the performance.

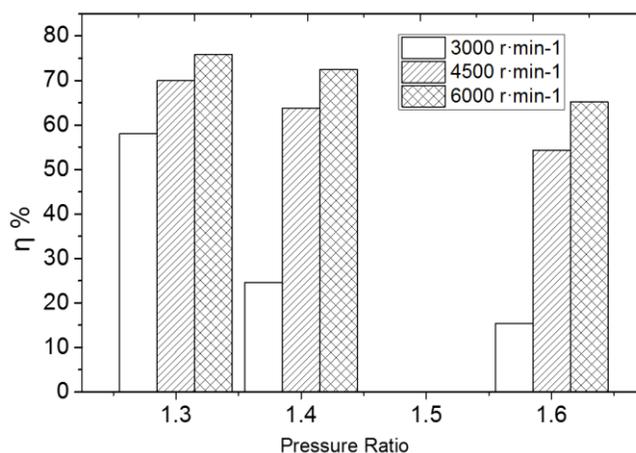


Figure 10: Change in volumetric efficiency with rotating speed

4.3 Effects of Clearances

Figure 11 reveals that axial clearance has a significant influence on the performance of scroll compressors, especially when hydrogen is applied as working fluid. When hydrogen is applied, the volumetric efficiency with 0.04 mm axial clearance decreased by 26.41% from 95.12% without axial clearance, when the radial clearance was 0.04 mm. Therefore, axial clearance must be considered in numerical simulation of scroll compressors to obtain accurate results.

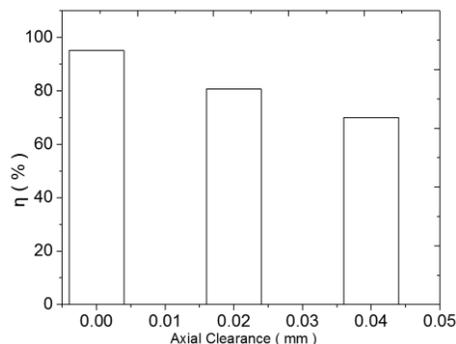


Figure 11: Change in volumetric efficiency with axial clearance at a certain radial clearance

Figure 12 shows the pressure distribution and velocity at the top and bottom axial clearances at an angle of 270° . The top clearance is between orbiting scroll tooth and fixed scroll root. The plain color shows the pressure, and the arrow shows the velocity. The radial leakage is observed mainly in half of the axial clearance domain between the asymmetrical working chambers where there is a high differential pressure, such as in the area M between chambers A and B2, area N between chamber B1 and C2, as shown in Fig. 12(a). However, the other half of the axial clearance domain between the symmetrical working chambers also has a little radial leakage, such as in the area P between chambers C1 and C2, area Q between chamber B1 and B2, as shown in Fig. 12. It is consistent with the results of the analyses conducted by Panpan Song^[8]. This is because of the movement of the orbiting scroll which causes leakage near the orbiting scroll area.

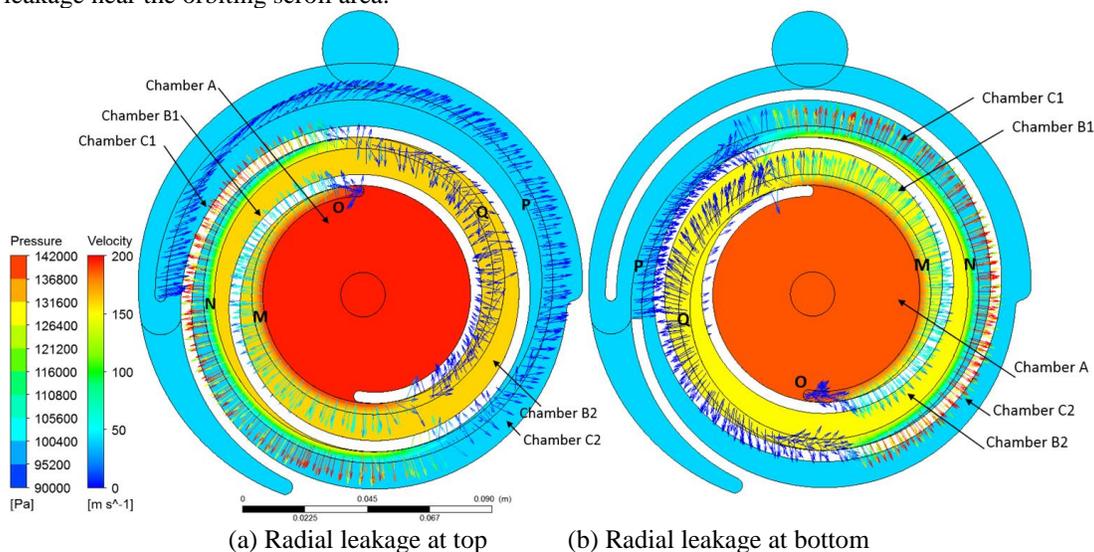


Figure 12: Pressure distribution and velocity on top and bottom axial clearances at angle 270°

5. CONCLUSIONS

In this paper, the performances of the scroll-type hydrogen and air compressors in FCVs were discussed in several cases, focusing on the effects of rotating speed, pressure ratio, leakage clearance, and working fluids. 3D transient CFD numerical simulation with dynamic meshing, considering both the radial clearance and axial clearance, was presented. The main conclusions are given below.

- The axial clearance has more significant influence than the radial clearance on the performance of scroll compressors, especially when hydrogen was applied as working fluid. Axial clearance must be considered in numerical simulation to obtain accurate results. Measurements must be taken such as seal rings to reduce radial leakage.
- Mass flow rate is a challenge for the scroll-type air compressor to apply in FCVs, even though pressure ratio and discharge pressure can satisfy the requirements. Higher mass flow rate will demand larger compressor volume which is sensitive for vehicles design. More importantly, dynamical analysis including

the stress and the deformation of the orbiting scroll need to be verified in further study when the compressor volume is large.

- The rotating speed influences scroll-type hydrogen compressors much more than air compressors under the same conditions. The results show that the volumetric efficiency increased by 30.68% in the case of hydrogen when the rotating speed increased from 3000 r·min⁻¹ to 6000 r·min⁻¹. In the case of air, the volumetric efficiency increased by 12.81%. Further, it is found that the volumetric efficiency increases with decrease in the pressure ratio.
- The scroll-type hydrogen compressor is one of the most promising compressors for FCVs. However, method must be taken to solve the leakage issue through the axial clearance and radial clearance. Numerical simulations technique of CFD is an effective method to predict performance and optimize design.

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