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3D transient CFD modelling of a scroll-type hydrogen pump used in FCVs

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ABSTRACT

The scroll pump has a great potential to recirculate hydrogen in a fuel-cell vehicle (FCV) because of its high efficiency, low noise and vibration, reliable operation, and a wide range of adjustable flow. This paper presents three-dimensional transient computational fluid dynamics (CFD) modelling of a scroll-type hydrogen pump used in FCVs, including leakage flow through both the radial clearance (RC) and axial clearance (AC). A dynamic mesh was generated for the moving orbiting scroll, and high-quality hexahedral structured grids with sufficient grid-density were applied to the clearances to solve the multi-scale problem. The pressure and velocity fields were obtained at different rotating angles to reveal the dynamic characteristics in the compression chambers. The simulation results showed that the radial leakage through AC has more significant influence on the volumetric efficiency than the tangential leakage through RC, especially on scroll-type hydrogen pumps. The presented modelling and simulation methods were validated experimentally by operating a scroll air compressor at different speeds and pressure ratios. The volumetric efficiency of the scroll pump was 85.39% with 0.02 mm AC and 0.02 mm RC, 81.43% with 0.02 mm AC and 0.04 mm RC, and 70.17% with 0.04 mm AC and 0.02 mm RC. Further, it was found that the performance of scroll-type hydrogen pumps is more sensitive to rotating speed than air scroll pumps under the same conditions. With hydrogen, the volumetric efficiency increased by 30.68% when the rotating speed was increased from 3000 $r \cdot min^{-1}$ to 6000 $r \cdot min^{-1}$; with air, the volumetric efficiency increased by 12.81%. Therefore, it is necessary to consider both AC and RC in the CFD modelling of scroll machines, particularly in the case of hydrogen scroll pumps.

Introduction

The development of new energy vehicles has become a research hotspot because of the continuous increase in transportation requirements, energy usage, and environmental issues [1]. Fuel-cell vehicles (FCVs) have gained increased attention because they are recognised as zero-emission vehicles; they use hydrogen and produce only water and heat [2]. Lipman TE in his study pointed out that 80% of study participant drivers found the FCVs performance “exceeded” or “greatly exceeded” their expectations [3]. The world's leading automobile manufacturers such as Toyota, Honda, Hyundai, Ford, and Shanghai Volkswagen have engaged in the development of their own FCVs. For many automobile manufacturers, the target date for launching their

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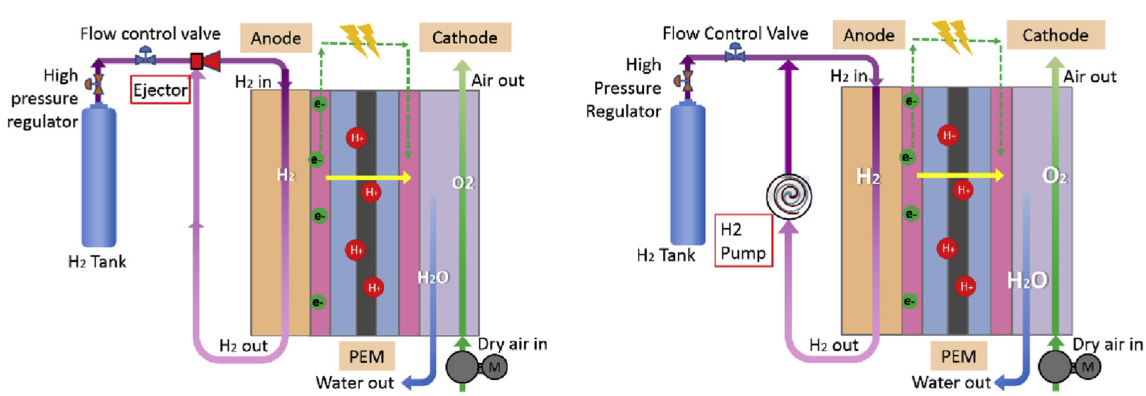
commercial FCVs is before 2025. The FCV is also considered a suitable solution to the problem of environmental pollution in China. The "Made in China 2025 strategy" emphasised the plan of introducing FCVs. Thus, the FCV has become one of the most potential vehicles in the future as a result of the development of related technologies.

The proton exchange membrane (PEM) fuel cell, as an energy power device, is the key component of a FCV, and its performance directly impacts the stability, reliability, and durability of the FCV. In PEM fuel cells, abundant hydrogen supplication is required to improve the performance, particularly when the hydrogen contains impurities. The actual flow of hydrogen should be 1.1–1.5 times the theoretical consumption of hydrogen [4]. Therefore, a hydrogen recirculation system must be applied to recycle the unconsumed hydrogen from the anodic exhaust to the inlet of the fuel cell stack. This system also provides superior water management and improves energy utilisation [5]. At present, there are two main methods of using the unconsumed hydrogen. One method is to apply an ejector to introduce the unconsumed fuel to the fuel supply line [6–8]; this will depend on the high speed of hydrogen supply flow, as shown in Fig. 1(a). This method has significant advantages, because there are no moving parts, and no parasitic power is consumed, as the potential energy of high-pressure flow from the hydrogen tank is used to suck the unreacted hydrogen. However, once the design condition is fixed and an ejector is settled, it is difficult to change the flow rate at different power demands to adapt to the unstable operating conditions of the FCV; this situation is not acceptable in a FCV [5,9]. The other method is to apply a hydrogen compressor/pump as illustrated in Fig. 1(b); this method has the advantage that the flow rate can be adjusted to address different working conditions. In December 2014, Toyota released the first commercialised FCV, named Mirai, using a lobe pump as the hydrogen recirculation system [10]. However, the high level of noise and vibration of the lobe pump is a major disadvantage that limits its application in FCVs [11]. The scroll pump has the advantages of low noise and vibration, high efficiency, reliable operation, and a wide range of adjustable flow [12,13]; these features ensure the performance and comfort of the FCVs. Therefore, a scroll-type hydrogen pump is one of the promising hydrogen recirculation systems for FCVs. Although scroll machines are used in air conditioning, refrigeration systems, and vacuum equipment, hydrogen recirculation is a new application for scroll pump/compressors which requires further research.

Numerical simulation with computational fluid dynamics (CFD) technique is considered an effective method to predict the performance of scroll machines and optimise their design. Some studies [14–17] have focused on overall steady-state scroll models, because there are many challenges in obtaining accurate thermodynamic properties and transient flow characteristics. The first challenge is to generate a high-quality mesh in multi-scale fluid domains. 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. Mirko Morini et al. [18] applied a 2D transient numerical model with triangular elements for a real scroll compressor geometry and obtained its dynamic behaviour, but there were only two triangular mesh elements in the radial clearance (RC) in some cases. Wang et al. [19] proposed a method of generating a structured dynamic mesh for scroll compressors, having an acceptable mesh quality in RC, but axial clearance (AC) was not considered. The results of the study demonstrated that a structured grid is more accurate than an unstructured grid. Shuaihui Sun et al. [20] established a three-dimensional transient flow model of a scroll refrigeration compressor operating with refrigerant R22, and analysed in detail the flow mechanism and characteristics under a certain pressure ratio. Although RC was considered in the model, the AC was neglected, because of which the accuracy was low when hydrogen was used as the fluid. Song Panpan [21] proposed a 3D model that included both RC and AC, and studied the unsteady leakage flow in a scroll expander. The value of AC was set at 0.10 mm for better mesh quality; however, this was much larger than the actual size. The results indicated that radial leakage occurred not only between the asymmetrical working chambers, but also between the symmetrical working chambers. Another challenge in the simulations is the generation of dynamic mesh in changing fluid domains because of the movement of the orbiting scroll. Xiangji Yue et al. [22] established a two-stage scroll vacuum pump model based on the dynamic mesh method using the hexahedral grid. The grid deformed according to the movement of the



(a) FCV with ejector (b) FCV with scroll pump

Fig. 1 – Hydrogen cycle in FCV.