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Three-dimensional numerical simulation and experimental validation of flows in working chambers and inlet/outlet pockets of Roots pump

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A B S T R A C T

In this study, two cases of three-dimensional computational fluid dynamics (CFD) were established to simulate the flow in Roots pumps, using the dynamic mesh method. The difference between these two cases is in the size of pipes which represents the valves at the inlet/outlet piping. A physical Roots pump was manufactured to allow testing of the pressure distribution and the mass flow rate in order to validate the CFD models. The results showed that both simulated models were fairly acceptable in terms of the mass flow rate, but the results from the case with narrow pipes agreed much better with the experimental results in terms of pressure distribution. The simulated velocity fields during the working cycle showed the presence of vortexes at both the inlet and outlet pockets. The vortexes at the inlet pocket were close to the rotor, but those at the outlet pocket were around the cylinder wall. Furthermore, a two-dimensional model was established to determine whether this simpler model can predict performance accurately. The results showed that the 2-D model gave satisfy accurate results for in terms of mass flow and pressure distribution, but failed to predict the velocity field accurately.

1. Introduction

The Roots pump is a positive displacement machine that is widely used in many fields, including mining, oil refining, the chemical industry or in chemical and environmental protection. Moreover, this tool can be used as either a blower or a vacuum pump. The Roots pump has double rotors, with two or more lobes rotating in opposite directions in the cylinder. These double rotors are driven by a couple of synchronized gears to transport fluid from the inlet to outlet. Due to the existence of clearances between the rotors and the cylinder walls, the Roots pump usually operates in a non-contacting state.

Many researchers have focused their attention on the profile design and meshing analysis of Roots pumps. Mimmi [1]optimized the parameters of the screw rotor based on a mathematical model of the lobe profiles. Wang [2] designed a tooth profile consisting of five arcs, which obtained a better sealing performance due to its longer and narrower clearance. Chiu [3] developed a new profile by using an elliptical roulette, and then compared the performances of the new and the traditional profiles. Hwang [4,5] proposed a new rotor profile with a variable trochoid ratio, and investigated how to achieve higher volumetric efficiency and higher sealing performance. Tong and Yang [6–8] explored a new method of profile design by deriving a function to help choose the most efficient lobe parameters for high-sealing Roots blowers, according to the given flow rate functions. Yao [9] designed a novel three-lobe helical rotor for the Roots pump, with the cross section designed as a combination of concave arcs, convex arcs and cycloidal curves. The simulated cutter trajectory of the new rotor was then analyzed. Yao also devoted much effort to investigating the characteristics of the flows and leakages in the rotor's working cycle. Burmistrov [10] proposed an angular coefficients method to calculate channel conductance in Roots blowers, based on the similarities between the laws of radiation and those of the diffusive reflection of molecules. Valdès [11] used the semi-empirical Knudsen–Dong law to predict the conductance of each clearance within a few percentage points for a wide range of pressures covering the transient flow regime.

With the development of computational fluid dynamics (CFD), growing numbers of researchers have focused on the numerical analysis of positive displacement machines such as the screw compressor and the Roots pump. Concerning the screw compressor, Stosic [12] described generation of twin screw rotors, based on the rack-generation method. Kovacevic [13,14] carried out

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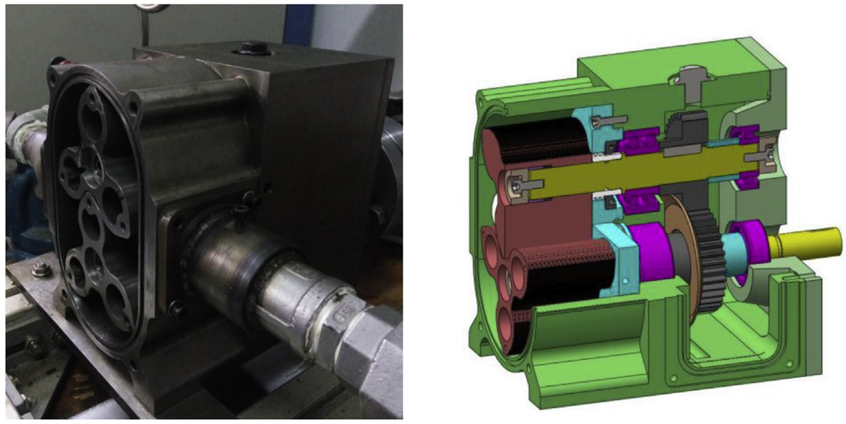
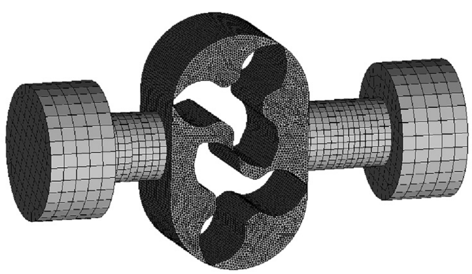
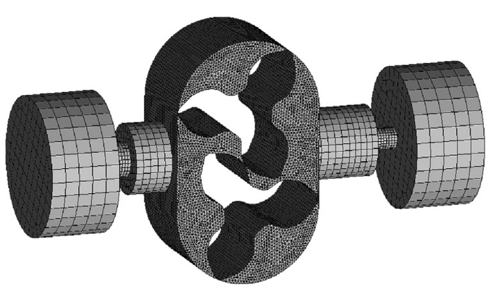


(a) (b)

Fig. 1. The structure of the Roots pump.



(a) The geometry and grid of the case with simple pipes



(b) The geometry and grid of the case with smaller-diameter pipes

Fig. 2. The geometry and grid of the Roots pump.

a full 3-D simulation to determine how pressure and temperature changes could create internal distortion within screw compressors, and thus affect their performance. Kovacevic also presented a numerical simulation for a combined screw compressor-expander machine for use in high-pressure refrigeration systems. Kethidi [15] conducted further studies on the influence of turbulence modelling on the CFD predictions of local velocity fields in twin screw compressors. Arjeneh [16] measured the local pressure losses inside the suction plenum of a screw compressor, and then used the results to evaluate predictions of pressure losses in the suction plenums of compressors derived from 3-D CFD calculations. For the Roots pump, Joshi [17] assumed that clearance between the impellers was almost inevitable during operation, and therefore built a static model to simulate the leakage through the clearance. Li [18] investigated the effects of the rotor's pressure angle on the flow characteristics by using a two-dimensional turbulence model. Hsieh [19,20] compared the differences between cylindrical and screw-type Roots pumps in terms of average outlet flow rates and instant outlet flow rates, based on a CFD case, namely PumpLinx. Hsieh also analyzed the effects of the rotor phase angle in multi-stage Roots pumps with serial or parallel connections in terms of their flow rates and pulsation. Huang [21] used the k-ε model to simulate a three-lobe Roots blower, and compared the results of this simulation with those from semi-empirical formulas in terms of their non-uniformity of outlet flows.

Although much research has been devoted to theoretical analyses and dynamic simulations of Roots pumps, little experimentation has yet been carried out to verify the simulations. In this study, we established two simulated three-dimensional cases to analyze the flow characteristics in Roots pumps by using a dynamic mesh method. These two cases had inlet/outlet pipes with different diameters and different boundary conditions. After these simulation tests, an experimental test rig was built with a novel Roots pump that was identical in size to the simulated models. The pressure distribution in the cylinder and the inlet/outlet pockets was measured with seven pressure sensors, and both the pressure and the flow rate results were used to verify the simulation results. The pressure contours and velocity fields of the simulated models were analyzed to determine the most accurate simulated case. Finally, we established a simplified two-dimensional model to investigate whether such a model was precise enough to calculate the flow characteristics.

2. Numerical simulation

2.1. The structure of the roots pump

A Roots pump has two parallel shafts rotating synchronously in opposite directions. Each shaft is supported by two bearings, and the assembly contains one rotor and one gear. In traditional Roots pumps, the bearings were distributed separately on two ends of the shaft, and the rotors and gears were set in the middle of the shaft. Nevertheless, in the Roots pump we used, the rotor was arranged at one end of the shaft, and was sequentially followed by a bearing, a gear and a bearing, as shown in Fig. 1. All of the bearings were on one side of the rotors, so that the other side of the rotors was free, and only a front plate was needed to cover the cylinder. Once the