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Short communication

# A design method for improving the flow characteristics of a multistage Roots pumps

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ABSTRACT

Based on an analysis of a three-stage design with varying phase angles, this paper proposes a method for improving pump performance in multistage Roots pumps by employing designs that achieve the greatest economy in outlet discharge enhancement. The flow characteristics of multistage Roots pumps with serial and parallel connections are investigated by considering various phase angles in each stage using a two-lobed rotor as an example. The benefits of these varying phase angle designs for both serial and parallel connection pumps are evaluated by comparing their flow characteristic with those of same phase angle designs in 24 different cases. An additional comparative analysis of four-stage serial and parallel connections clearly indicates that multistage Roots pumps with a parallel connection and varied phase angle design is a better choice for vacuum system use.

Although the Roots (or rotary lobe) pump can be used in either blower or vacuum pumps, it is especially useful in dry vacuum pumps for vacuum exhaustion in semiconductor fabrication equipment or high-technology industries. To date, most research on the Roots pump has focused on theoretical mathematical models of its rotor profile [1–3], geometric design and analysis [3,4], new design methods [5–10], leakage and conductance analysis [11,12], cutter design and manufacturing method [13–15], vacuum technology, pump performance and measurement [16–21], vacuum method, pumping of dangerous gases, noise reduction and dynamic unbalance with experimental validation in multistage pumps [22–26], and flow simulation using a two-dimensional numerical approach [27–30]. Other research has addressed the claw vacuum pump, with most studies also focusing on geometric design and analysis [31,32]. Two-dimensional numerical approaches have also been used to develop fluid analysis models [33,34], although more recently, these have been investigated using three-dimensional numerical approaches that assess pump flow performance in a new rotor design [35], a screw rotor design [36], or a multistage rotor design [37]. Research on the effects of two- and four-stage serial and parallel connections on the pump fluid in a Roots pump with a multistage design has identified the three-stage design as the most economical for pumping performance enhancement [37]. All these previous studies, however, are based on rotors designed with the same phase angle in all stages. Hence, the flow characteristics and pump performance of rotors designed with a different phase angle in each stage remains unknown. This paper thus proposes a method for designing varied phase angle rotors and identifying which design type improves pump performance.

In this analysis, rather than assuming an initial right rotor position of 0° in each stage as in earlier research [37], the phase angle is indicated based on an assumption that the right rotor rotates clockwise at angle $\beta$ in each stage (see Fig. 1(a)). It can thus be expressed as $0^\circ{-}0^\circ{-}0^\circ$ for all three stages (see Case 1 in Table 1). Twenty-four different cases of serial and parallel connection designs with identical or varied phase angles are then evaluated and the phase angle data reported in Table 1.

The fluid analysis model is constructed using the new commercial CFD package (PumpLinx), whose efficacy has been demonstrated by comparing simulation and experimental results on various fluid machinery [38]. PumpLinx solves conservation equations of mass and momentum using a finite volume approach. The fluid analysis conducted here makes the following important assumptions:

(1) The fluid is analyzed using a turbulent model ($k{-}\varepsilon$ model) [39].

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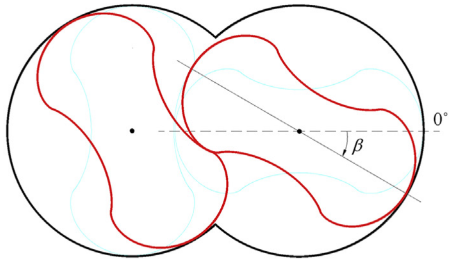
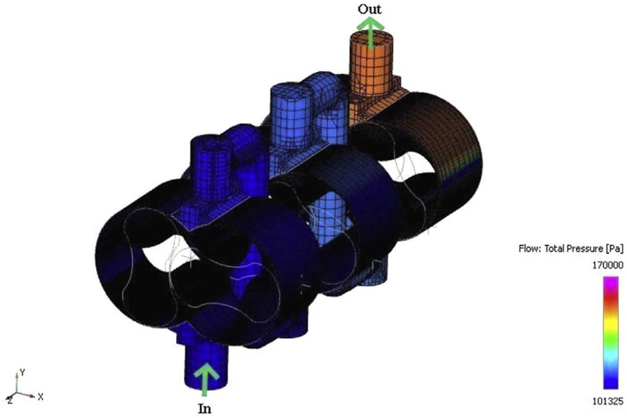
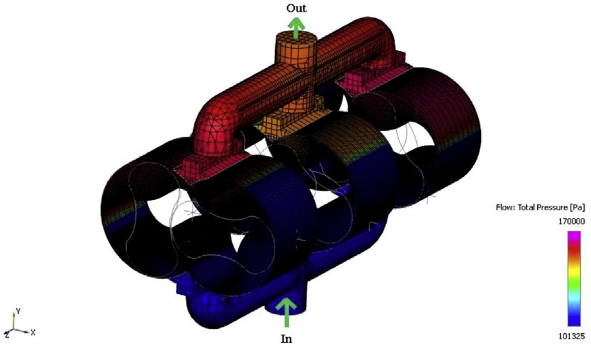


(a) Phase angle design in the initial position of each stage



(b) Grid and pressure calculations for a serial connection



(c) Grid and pressure calculation for a parallel connection

**Fig. 1.** Phase design and fluid calculation method.

(2) The fluid used is air (dynamic viscosity = 1.853e−05 Pa·s, density = 1.766 kg/m$^3$), which is treated as a compressible fluid which density depends on the local pressure and temperature. In this paper, the CFD calculations were done in an isothermal mode, and the temperature is set by 300 K.

(3) Due to the multistage Roots vacuum pumps with a special design having a potential to work directly at the atmospheric pressure [24–26], the inlet pressure is assumed to one atmospheric pressure (101.325 KPa), and the outlet operation pressure is 150 KPa.

(4) The rotor rotation speed is 3000 rpm, with the left rotor rotating clockwise and the right rotor rotating counterclockwise.

In the pump model, in order to understand whether the larger gap can catch the same trend of pumping performance, the clearance value between the rotor and chamber, and between the two rotors both is set to 0.6 mm. The radius of the pipes is 20 mm. In each stage, the chamber volume remains at 1600 cm$^3$ no matter whether the design is serial or parallel.

The 24 cases are evaluated using fluid modeling and a calculation technique [37] that can, taking Case 2 as example, solve the mesh generation and pressure calculation in series and parallel connections, respectively (see Fig. 1(b) and (c)). Based on these calculations, the outlet pressure and flow rate can be solved automatically through iteration.

To enable assessment of outlet flow rate improvement, the increment of the average flow rate is defined as

$$U = \frac{Q_{3-stage}^{(Case\ \ i)} - Q_{3-stage}^{(Case1)}}{Q_{3-stage}^{(Case1)}} \times 100\%, \quad i = 2 \sim 25 \tag{1}$$

where the average flow rate of Case 1 in three-stage serial and parallel design is 0.0249 kg/s and 0.0286 kg/s [37], respectively.

In terms of the increment of the average flow rate (Fig. 2(a)), no matter whether the connection is serial or parallel, cases with a varied phase angle design have a higher rate than those with a same phase angle design (see e.g., Case 1), meaning that the former can reduce the fluid flow resistance and thus produce a higher outlet flow rate. In the cases of serial connections, the increment of the average flow rate is about 6%~8% compared to an increment in parallel connections of about 8%~18%.

The flow rate fluctuation coefficient can also be used to index the fluctuation in fluid flow, defined as

$$Q_I = \frac{q_{\max} - q_{\min}}{q_{ave}} \tag{2}$$

where $q_{\rm ave}$, $q_{\max}$, and $q_{\min}$ are the average flow rate, maximum flow rate, and minimum flow rate at the outlet, respectively.

**Table 1**
Phase angle design for three-stage and four-stage serial and parallel connections.

| | | | | |
|---|---|---|---|---|
| Three-stage serial and parallel cases | | | | |
| Case 1 | Case 2 | Case 3 | Case 4 | Case 5 |
| 0°–0°–0° | 0°–30°–60° | 0°–60°–120° | 0°–90°–180° | 0°–45°–90° |
| Case 6 | Case 7 | Case 8 | Case 9 | Case 10 |
| 30°–60°–90° | 60°–120°–180° | 0°–30°–45° | 0°–30°–90° | 0°–30°–120° |
| Case 11 | Case 12 | Case 13 | Case 14 | Case 15 |
| 0°–30°–150° | 0°–30°–180° | 30°–60°–120° | 30°–60°–150° | 30°–60°–180° |
| Case 16 | Case 17 | Case 18 | Case 19 | Case 20 |
| 60°–90°–120° | 60°–90°–150° | 60°–90°–180° | 90°–120°–150° | 90°–120°–180° |
| Case 21 | Case 22 | Case 23 | Case 24 | Case 25 |
| 120°–150°–180° | 0°–45°–135° | 0°–90°–135° | 45°–90°–135° | 90°–135°–180° |
| Four-stage serial and parallel cases | | | | |
| Case 1 | Case 2 | Case 3 | Case 4 | Case 5 |
| 0°–0°–0°–0° | 0°–30°–60°–90° | 30°–60°–150°–180° | 0°–45°–90°–135° | 45°–90°–135°–180° |