WEB OF SCIENTIST: INTERNATIONAL SCIENTIFIC RESEARCH JOURNAL
ISSN: 2776-0979, Volume 3, Issue 2, Feb., 2022

DEVELOPMENT AND EXPERIMENTAL STUDY OF THE FIRST STAGE IN A TWO-STAGEWATER-FLOODED SINGLE-SCREW COMPRESSOR UNIT FOR POLYETHYLENE TEREPHTHALATE BOTTLE BLOWING SYSTEM

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Abstract

The oil-free compressor is a key component in fabricating polyethylene terephthalate (PET) bottles for beverages and water. At present, the main compressor type used for blowing PET bottles is the reciprocating compressor. However, compared to screw compressors, reciprocating compressors have shortcomings of high energy consumption and too many consumable parts. Many manufacturers of PET bottles in Asia are seeking to replace reciprocating compressors with screw compressors, as we know. Screw compressors can be classified as single-screw compressors (SSC) and twin-screw compressors. Since the load in a twin-screw compressor is far larger than that in an SSC, SSCs are more suitable for being developed for high-pressure applications such as PET bottle blowing. This paper presents a performance study on an oil-free single-screw compressor as the first stage of the PET compressor unit. A 5.6 m3_min1 prototype and its test rig were developed.

The thermophysical process of the moist air is theoretically analyzed. The pressure loss on the flow path and the influence of the important parameters are experimentally investigated. It is found that water vapor cannot be separated during the adiabatic compression process. The results also show that the pressure loss from the discharging duct to the check valve accounts for the largest percentage of the total pressure loss. The experimental results further show that the discharge capacity and shaft power increase almost linearly with the motor speed. The efficiency declines with increasing injected water temperature. The discharge capacity and shaft power all increase with the injected water flow rate, and an optimum flow rate is found to ensure the highest isentropic efficiency. With the increase in discharge pressure, the discharge capacity decreases, and the shaft power increases. The isentropic efficiency is found to have its maximum value at certain discharge pressure.

Keywords: polyethylene terephthalate bottle blowing system, water-flooded single-screw compressor, dehumidification, pressure loss, isentropic efficiency.

1. INTRODUCTION

Polyethylene terephthalate (PET) is widely used in the stretch blow molding process for packaging applications, such as beverage bottles and mineral water bottles. Two-stage stretch-blow molding (SBM) is the most popular process for fabricating PET bottles. In the first step, the preform is heated by infrared heaters and softened. In the second step, the preform is placed in the blow-molding machine, stretched longitudinally by a cylindrical rod, and blown by oil-free compressed air. The air pressure ranges from 2.5 MPa~6 MPa (pressure ratio 25~60) since the bottles have different sizes and thicknesses. Air compressors with comparatively high discharge pressure are the key equipment for the SBM

process. At present, multi-stage reciprocating compressors or screw-reciprocating tandem compressors are the main types of compressor units adopted in SBM. However, compared to the screw compressors, the reciprocating compressors have the downsides of huge space occupation, high energy consumption, low single-stage pressure ratio, more consumable parts, and shorter maintenance cycle. Frequent replacement of the consumable parts leads to big challenges concerning the requirement for continuous air consumption. Therefore, there is an urgent demand to substitute the existing compressor units with two-stage screw compressor units without reciprocating compressors.

Several studies have been published on two-stage dry-screw compressors. Presented a computational fluid dynamics (CFD) model to simulate a two-stage screw compressor provided by Sullair, which has a final discharge pressure of 7.98 bar. The model allows direct coupling of the two
stages without specifying the boundary conditions at the interstage. We investigated the desuperheating process through liquid injection in an ammonia refrigeration system with two-stage screw compressors, which has a total pressure ratio of 22. There is a mathematical model of a two-stage oil-free screw compressor, analyzed how the interstage pressure was built and developed a prototype with a total pressure of 9 bar. Screw compressors mainly include twin-screw compressors and single-screw compressors (SSCs). The screw compressors mentioned in references [3–5] are all twin-screw compressors. However, little research on oil-free twin-screw compressors has been reported in higher pressure ratio applications such as PET. Compared to twin-screw compressors, SSCs have an excellent force characteristic, since the axial force and the radial force applied on the screw rotor are all completely balanced. The force applied on the gate-rotor in the SSC is far smaller than that applied on the twin-screw rotor. The advantage of fine mechanical properties makes the SSC much easier to develop into a comparatively high discharge pressure compressor unit. SSCs have a wide range of applications in the industry. We et al. manufactured a mini SSC with a refrigerating capacity of 2.02 kW to cool CPUs. We et al. simulated a new natural gas liquefaction process, designed and tested an SSC for the process, and conducted performance testing to investigate the optimum oil-gas ratio and motor speed. We et al. investigated the SSC performance in a mechanical vapor recompression system with different amounts of injected water. We presented a mechanistic model for calculating the sealing lines, groove volume curves, and other geometric features for an expander design in the organic Rankine cycle. Wu et al. proposed a model for high-speed SSC working for fuel cells on vehicles and calculated the properties of compressed air, volume efficiency, and energy dissipation at different speeds.
Meshing pair profile (MPP) is one of the key technologies of the SSC. A large volume of research has been published regarding the MPP and the corresponding manufacturing method. We et al. established a mathematical model to describe CC type, PP type, and PC type MMPs, calculated the meshing lines and analyzed the contact stress, and manufactured PP type and PC type meshing pairs by rapid prototyping and five-axis CNC milling.

Based on the original single straight line type (SSLT) MPP, we proposed a new multi straight lines type (MSLT) MPP, enabling the enveloping straight lines to mesh with the screw groove flank alternately, helping to reduce meshing line wear. Furthermore, by combining the advantages of the MSLT and another original single column type (SCT) MMP, invented another multi-column type (MCT) MPP, put forward corresponding machining method of milling process at multi-tool locations, and developed special
machines for processing MCT. To increase the capacity of the SSC without rotor enlargement, et al. developed a fan-shaped tooth profile and achieved a 30% increase in capacity. To disperse the contact area to the maximum on the tooth flank. et al. designed a curved system of differential equations to describe the contour of the meshing surface and modeled a no-gap meshing pair by computer calculations and Boolean operations. To overcome the limitation caused by manufacturability and accuracy, et al. put forward a new design methodology that cancels the upper and lower meshing surfaces to avoid interference with the groove flanks and manufactured a sample meshing pair by 3D printing.
Along with the development of the MPPs, several studies have been conducted on the performance of MPPs, especially concerning their tribological characteristics. We studied the dry friction resistance of different MPPs by calculating friction angle and Hertz contact stress and testing wear loss by an eccentric wheel. The results showed that the MCT had the best wear resistance, and SSLT had a poor performance. However, since the meshing pair are lubricated by an abundant volume of injected liquid, the lubrication performance investigations are more significant. Post and Zwaans researched hydrodynamic lubrication in the meshing pair gaps and calculated the oil film pressure by the finite method et al. optimized the SCT and applied it to an oil-flooded prototype. Li et al. designed a modeling experiment to verify the hydrodynamic phenomenon and compared the lubrication performance between SSLT and MCT, indicating that the MCT could keep the full fluid film on both sides of the tooth.
Several studies have been published on the thermodynamic characteristics of the SSCs. In the refrigeration area, we et al. investigated the heat transfer area influenced by the main geometric characteristics, proposed a model to calculate the heat transfer between the gas and the oil film adhering on the working chamber wall based on an assumption of poor oil atomization, studied the leakage properties and provided optimized design proposals for high volumetric efficiency, presented an injection

model, and analyzed the relationship between the performance parameters of the compressor and the injection hole design parameters. Based on the exergy theory, et al. studied shaft power wastage, classifying it into four components: irreversible heat transfer, adiabatic throttling, mixing of two flows, and heat dissipated to the environment, indicating that the exergy loss decreased with increasing rotating speed. We et al. analyzed the thermal process of an oil-flooded SSC using natural gas liquefaction and tested its main energy efficiency indices. It can be seen that the published studies related to the thermodynamic performance of SSCs are mostly focused on the refrigeration SSC and the oil-flooded SSC.

However, few investigations have been reported on the thermodynamic performance of the water-flooded SSC, especially experimental studies. In this paper, a dehumidifying model is established to analyze the particular problem of the water-flooded air SSC, which is the impact of moist air on compressor performance. A prototype is developed using a water-flooded SSC as the first stage of the PET compressor and its system. The pressure loss information of the whole flow path is tested. The effects of motor speed injected water temperature, injected water flow rate, and the discharge pressure on SSC performance are experimentally investigated. The obtained results may be valuable for developing two-stage SSC units for PET.

2. Theoretical Analysis

Working Principle of the SSC and Its Experimental System The 3D structure of the SSC is. The SSC is mainly composed of a cylindrical screw rotor, a pair of planar gate-rotors, a casing, and two bearing blockings at both ends of the casing. The two gate-rotors are central symmetric about the screw axis. The screw and a gate-rotor on either side constitute a meshing pair. When the SSC operates, the screw is driven by the motor and rotates the two gate-rotors in opposite directions. Air is suctioned into the casing through the filter and unloading valve. As the gate-rotor tooth meshes into the screw groove, the screw groove, the tooth, and the inner surface of the casing enclose a working chamber that is filled with air from the suction chamber of the casing. Water is injected into the chamber from the water injection hole drilled on the casing to cool the gas, seal the gaps of the chamber and lubricate the meshing pair. With further rotation, the chamber decreases, and the gas trapped in it is compressed. The gas pressure rises until the chamber connects the radial exhaust orifice on the casing. The exhaust process expires as the tooth meshes out of the groove completely.

The experimental system is designed and shown. After flowing through the discharge ducts cast on the casing, the mixture of air and water is discharged to the separator through the discharge pipe. By centrifugal separation, the air is separated from the water. Water is stored at the bottom of the separator and pumped to the compressor by the pressure difference between the separator and the suction chamber of the casing. Before being re-injected to the compressor, the water is cooled and filtered in the heat exchanger and water filters. Since the compressed air produced by the water-flooded SSC has a relatively lower temperature than that delivered by the oil-flooded machines, the air separated in the separator can be discharged to the user directly without cooling. ctr. "Nanotechnological research of the mechanical element surface, and internal structure in mechanical engineering".

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