Performance Research on a Twin Screw Expander Applied to a Power Generation System for Recovering Waste Pressure Energy of Natural Gas

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Abstract. The twin screw expander, applied to a power generation system for recovering waste pressure energy of natural gas (NG), is reliable. It has lower capital costs and maintenance performance compared to the others. In this paper, a computational procedure based on the Benedict-Webb-Rubin (BWR) equation is established. Meanwhile, the experiment is carried out to study the performance of a twin screw expander prototype. The results shows that the twin screw expander has an optimum rotational speed where the specific shaft work, efficiency reach their peaks when delivered a certain gas, and the optimum rotational speed reduces with the decrease of the inlet pressure.

1. Introduction

Natural gas (NG) is mainly transported over long distances through pipeline network systems (corresponding to 67.5% of the global gas trade [1]). It is necessary to transport NG at high pressures (about 10-12MPa [2]) to cut the cost and energy demand. However, the pressure of NG must be significantly reduced to lower levels at pressure reduction stations (PRSs) before it is supplied to utilization sites [3]. Currently, most PRSs employ pressure reducing valves (PRVs) to accomplish pressure reduction and control outlet pressure [4]. It dissipates a considerable amount of available exergy of pressurized gas which can be harnessed to generate work in the expansion process. Many researchers have begun to paid attention to the energy recovery from a NG PRS.

It is possible to convert the available decrease of physical exergy into mechanical work by means of an expander substituting for a PRV [5]. The generated work may be converted to electricity or provided for industrial direct applications. Although numerous theoretical analyses and evaluation methodologies for various NG expansion systems are widely developed, there are little industrial application and experimental research. In this paper, a power generation system for recovering waste pressure energy of NG is presented and a computational procedure based on the Benedict-Webb-Rubin (BWR) equation is established. Meanwhile, the experiment is carried out to study the performance of a twin screw expander prototype.

2. System description
The experiment used compressed air to substitute for NG as working fluid considering that NG has inflammable, explosive, toxic and other dangerous characteristics. The schematic diagram of the twin screw expander performance test is shown in figure 1. It primarily includes three parts: inlet and exhaust system, oil lubrication system, data measurement and acquisition system.

![Figure 1. Schematic diagram of the twin screw expander performance test.](image)

3. Computational procedure
The BWR equation of state, which has high accuracy in the application of hydrocarbons gases, was selected for calculating thermodynamic parameters of NG. The fundamental structure of the BWR equation for real gas is as follows:

\[
p = \frac{RT}{v} + \left( B_0 - A_0 - \frac{C_0}{T^2} \right) \frac{1}{v^2} + \left( B_0 - a \right) \frac{RT}{v^3} + \frac{a \alpha}{v^6} + \frac{c}{v^6} \exp \left( \frac{\gamma}{v^2} \right) \quad (1)
\]

where \( A_0, B_0, C_0, a, b, c, \alpha, \gamma \) are all constants related to the kind of matter [6,7]. For the mixture, the mixing rules of constants in the BWR equation are defined as follows:

\[
A_0 = \left( \sum_i x_i A_{0i}^{1/2} \right)^2 \quad (2)
\]

\[
B_0 = \sum_i x_i B_{0i} \quad (3)
\]

\[
C_0 = \left( \sum_i x_i C_{0i}^{1/2} \right)^2 \quad (4)
\]

\[
a = \left( \sum_i x_i a_{1i}^{1/3} \right)^3 \quad (5)
\]

\[
b = \left( \sum_i x_i b_{1i}^{1/3} \right)^3 \quad (6)
\]

\[
c = \left( \sum_i x_i c_{1i}^{1/3} \right)^3 \quad (7)
\]

\[
\alpha = \left( \sum_i x_i \alpha_{1i}^{1/3} \right)^3 \quad (8)
\]

\[
\gamma = \left( \sum_i x_i \gamma_{1i}^{1/2} \right)^2 \quad (9)
\]

where \( x_i \) is the mole fraction of component I in the mixture.
It was assumed that the whole expansion process was gas single-phase flow. A computational procedure was established to realize the thermodynamic calculation. The flow chart of the computational procedure is illustrated in figure 2.

![Flow chart of the computational procedure.](image)

**Figure 2.** Flow chart of the computational procedure.

### 4. Results and discussions

The twin screw expander prototype, whose male rotor has 5 teeth and female rotor has 6, is based on the “W” rotor profile. The diameter of the male rotor and female rotor were optimized to 106.8 mm and 84.2 mm, respectively. The axial distance between rotors is 75 mm. The length to diameter ratio of the male rotor is 1.6. A series of experiments were carried out to investigate the performance of the twin screw expander prototype. Throughout the trial process, the expander ran smoothly with low noise and little vibration. Some main performances are analyzed as follows.

#### 4.1. Experimental conditions

Taking a set of experimental data as the example, the performance of the twin screw expander at different rotational speeds was analyzed. The air compressor outlet pressure was set between 0.55 MPa and 0.65 MPa, which had contributed to a satisfactory experimental condition that the expander inlet pressure was basically stable at 0.57 MPa and the inlet temperature was approximately 42°C. Meanwhile, the inlet and outlet cut-off valve of the experimental system were fully opened, which implied that the expander back pressure was equivalent to barometric pressure, and the bypass was in a closed state. Moreover, the condition that expander inlet pressure was 0.24 MPa and inlet temperature was 36°C was used for comparison. The specific values of pressure, mentioned in this paper, refer to gauge pressure.

#### 4.2. Shaft power

Figure 3(a) shows the variation of the shaft power and specific shaft work with the rotational speed. It can be seen that the shaft power increases, whose change rate becomes gradually slower, and the specific shaft work changes with approximate parabola law as the rotational speed increases. The specific shaft work reaches the maximum value of 52.38 kJ/kg at about 2500 r/min. However, the shaft power doesn’t reach the maximum value at the rotational speed where has a maximum specific shaft work, and continues to increase. That’s because the value of shaft power depends on two aspects: specific shaft work and mass flow rate of working gas.
Figure 3. Effect of the rotational speed on the performance of the twin screw expander.

4.3. Efficiency
Figure 3(b) shows the variation of the isentropic efficiency and exergy efficiency with the rotational speed. It can be seen that both the isentropic efficiency and exergy efficiency change with approximate parabola law as the rotational speed increases, and respectively reach the maximum values of 57% and 51% at about 2500 r/min.

4.4. Inlet pressure

Figure 4 shows the effect of the inlet pressure on the performance of the twin screw expander. It can be seen that, in contrast with the condition of 0.57 MPa, the shaft power for 0.24 MPa indicates a rough parabolic change with the increase of rotational speed, and reaches the maximum value at about 2000 r/min. The isentropic efficiency for 0.24 MPa also indicates a parabolic changes as the rotational speed increases, and the difference is its optimum rotational speed is 1750 r/min.

4.5. Shaft power for NG
Under the first test condition and with the same isentropic efficiency, the shaft power for NG was calculated by the proposed computational procedure. The components of NG used are shown in Table 1.

| Compositions | CH₄ | C₂H₆ | C₃H₈ | CO₂ | N₂ |
|--------------|-----|------|------|-----|----|
| Mole fraction (%) | 88.48 | 6.68  | 0.35  | 3.52 | 0.97 |

Figure 5 shows the differences between the shaft power for NG and that for air, the specific shaft work for NG and air also are compared in like manner.
It can be seen that the shaft power for NG is slightly bigger than that for air and the difference between them are becoming larger as the rotational speed increases. Therefore compressed air can substitute for NG as working fluid to study the performance of the twin screw expander prototype. The specific shaft work for NG is higher than that for air and the difference between them changes with an approximate downward parabola as the rotational speed increases.

5. Conclusions
The main conclusions drawn from the present research are summarized as follows:

(1) The specific shaft work, efficiency change with approximate parabola law as the rotational speed increases. For a certain twin screw expander, there is an optimum rotational speed where the specific shaft work, efficiency reach their peaks when delivers a certain gas. However, the shaft power doesn’t necessarily reach the maximum value at that optimum rotational speed.

(2) The optimum rotational speed of the twin screw expander, where the shaft power reached its peak, is not less than the rotational speed where the efficiency is at its maximum.

(3) For the twin screw expander with a certain structure volume ratio, the optimum rotational speed where the isentropic efficiency reaches its peak reduces with the decrease of the inlet pressure.

(4) In reality, compressed air can substitute for NG as working fluid to study the performance of the twin screw expander prototype, which can be applied to a power generation system for recovering waste pressure energy of NG.

6. References
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