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Dynamic heat transfer model for temperature drop analysis and heat exchange system design of the air-powered engine system

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ABSTRACT

In the operation process of an air-powered engine (APE) system, temperature drops happening in critical locations can influence the engine's performance negatively, and even lead to the ice blocking problem. To predict temperature drops during the operation, firstly, the thermodynamic model of the APE and a calculation method for equivalent air temperatures at intake and exhaust ports are described. The cooling mechanism of the pressure-reducing process is analyzed. Then a simplified calculation model of the throttling effect for dynamic temperature analysis is proposed. Furthermore, a complete dynamic model of the APE system is established, by considering models mentioned above and models of the pressure tank and the supply pipeline as well. The model's feasibility on the temperature drop analysis is verified by comparing with corresponding experiments. Simulation of a practical APE system is carried out. Under specific parameter settings, temperature drops of critical locations in the system are predicted. On this basis, the supply system of compressed air is modified and a principle structure of the heat exchange system for the APE system is proposed. The analysis results in this paper can provide a theoretical support for the design of the heat exchange system.

1. Introduction

Under the background of energy crisis and environmental issue, it has become increasingly important to find environmentally friendly energies to replace fossil fuels [1,2]. The compressed air, as a kind of medium, is considered to have superior energy storage density to other media like batteries. It can be easily obtained from the power generation process of renewable energies, such as solar energy, wind energy and tidal energy [3–6]. The air-powered engine (APE) is driven by compressed air. As a lightweight, non-polluting and safe power device, it can be applied to transportation, general aviation and small-scale power generation in the future. Especially, serving as engines of motor vehicles, the APE discharges breathable air at low temperature and low pressure, so the operation of the APE can achieve zero carbon emissions, which is significant for air pollution abatement in some industrial country, especially in China.

In the past 10 years, MDI, a French company of air-powered vehicles, developed a series of APEs [7,8]. In China, some universities and companies have also been conducting researches and designs on kinds of APEs [9–13]. But generally limited by problems of low working efficiency and low temperature, the APE is still in developing stage. Low temperature due to the air's expansion and the local throttling can lead to poorer power performance of the compressed air, and can even result in ice blockings at critical locations of the APE system which is a problem that cannot be ignored. Liu Hao and Chih Yung Huang both mentioned that there was a certain temperature decrease in the cylinder of the APE and higher inlet pressures resulted in lower temperatures [14,15]. Zhai Xin reported that increasing the inlet temperature is an effective way to enhance the engine's power and efficiency, and Zhai also studied the optimization of the APE's inlet tube for the best heat transfer performance [16]. But few studies established complete heat transfer models of the APE system, as well as methods to calculate the air temperature drops at critical locations, especially the high pressure reducing valve and the exhaust port of the APE.

Several studies provided references for the temperature analysis of the compressed air system. The Joule–Thomson coefficient was

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used to calculate the temperature changes of the throttling [17–20]. The real gas effect on temperature was considered in the discharging process of high pressure vessels [21,22]. But most of these methods need to solve transcendental equations which have large calculation complexity, thus they are not suitable for modeling of dynamic pneumatic systems.

This paper focuses on the temperature drop analysis of the APE system. Dynamic air temperature calculation methods of locations including the APE's ports and the throttling pressure reducer are proposed. Then the complete dynamic heat transfer model of the APE system can be established for temperature analyses and the design of the heat transfer system. Results of this paper are helpful to predict temperature drops in the practical APE system, to prevent the ice blocking problem and to improve the performance of the APE system.

2. Introduction of the APE system

2.1. Working principle of the APE

For a piston-type APE, the compressed air expands in the cylinder, pushing the piston to output shaft power. Its operation is shown in Fig. 1: in the suction power stroke the compressed air enters the cylinder through the intake valve, driving the piston downward. Then the intake valve closes after a specific crank angle while the compressed air expands to push the piston down and output work. When the piston is near the bottom dead center the exhaust valve opens so that the air with residual pressure discharges under the impetus of the piston. After the piston moves back to the top dead center, the APE completes a work cycle.

2.2. Locations of the temperature drop

This paper only concerns the piston-type APE. However, for any kind of APE, the compressed air goes through it will cool due to the expansion power process.

At room temperature, the real gases except hydrogen, helium and neon cool upon expansion by the Joule–Thomson (*J–T*) effect. Therefore when the compressed air discharges from a container or is forced through a pressure-reducing valve it has temperature drops. In the APE system, apart from the cylinder of the APE, the high pressure tank and the pressure reducer are typical locations where the air temperatures are predicted to decrease. Though the compressed air experiences dry processing, it cannot be guaranteed 100% without water. Thus when the temperature of air is lower than the dew point, the locations mentioned above are considerably possible to have ice blockings. In the following sections, thermodynamic models of these locations are established for analysis.

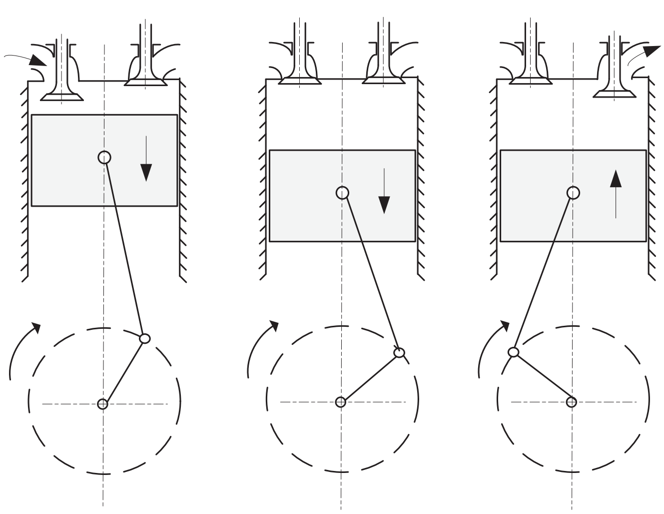

Fig. 1. Working cycle of the APE.

3. Thermodynamic model of the APE and calculation method of the equivalent air temperatures

3.1. Thermodynamic model of the APE

The model based on the crank angle was built at first. In the modeling process, the following assumptions are made.

(1) The compressed air is ideal, which means specific heat u and specific enthalpy h are only related to the temperature.
(2) The air in the cylinder is uniform during the thermodynamic process.
(3) The air flow in and out of the cylinder is considered as quasi-steady, one-dimension and isentropic.
(4) The air's kinetic energy and potential energy are ignored.
(5) There is no leak during the working cycle.

3.1.1. Energy equation

The energy equation can be given in the form of temperature differential equation:

$$\frac{dT}{d\phi} = \frac{1}{mC_v}\left[c_t A_h(\phi)(T_a - T) + h_1 G_1 + h_2 G_2 - p\frac{dV}{d\phi} - uG\right] \quad (1)$$

where $G_1 = dm_1/d\phi$, $G_2 = dm_2/d\phi$, $G = dm/d\phi$, m is the mass of the air in the cylinder, C_v is the constant volume specific heat, c_t is the heat transfer coefficient, $A_h(\phi)$, T_a are the total heat transfer area and the temperature of the internal walls, respectively, here T_a is assumed to be equal to the room temperature, T is the temperature of the air in the cylinder, h_1, h_2 are the specific enthalpies of the air flow in and out of the cylinder, respectively, m_1, m_2 are the mass of the air flow in and out, respectively, V is the instant volume of the cylinder, u is the specific internal energy and ϕ is the crank angle.

The change rate of the volume is described by:

$$\frac{dV}{d\phi} = \frac{\pi}{8}D^2 S\left[\sin\phi + \frac{\lambda\sin\phi\cos\phi}{\sqrt{1-\lambda^2\sin^2\phi}}\right] \quad (2)$$

where D is the diameter of the cylinder, S is the stroke of the piston, λ is the crank ratio.

The total heat transfer area is:

$$A_h = \frac{\pi}{2}D^2 + \frac{\pi}{2}DS\left[1 - \cos\phi + \frac{1}{\lambda}\left(1 - \sqrt{1-\lambda^2\sin^2\phi}\right)\right] \quad (3)$$

3.1.2. Continuity equation

The intake and exhaust airflow rate of the APE can be calculated as follows: