Simulation and construction of Single-stage reciprocating pneumatic transmission system Engine

RAHUL KUMAR*, ANAND M G**

*Dept. of Mechanical Engineering, Amrita University, **Dept. of Electronics and Communication Engineering, Amrita University, India

Abstract: Based on the principle of gas expansion, a new structure of reciprocating air-powered engine is proposed. It can convert the reciprocal motion of piston into one-way rotary motion of the output shaft and provide engine power. According to the pneumatic transmission system dynamics, the mathematical model of the air-powered engine is established and simulated. Then analyze the influence of the air state parameters and system structure parameters on performance of the engine, and the principle prototype is processed. The results show that the structure design of the engine is feasible, the average output torque and rotational speed increase with the increase of intake pressure. Under the circumstance with the same intake pressure, the average output torque increases with the increase of cylinder bore, but the rotational speed decreases with the increase of it. The results lay a foundation of further study on optimizing structure design.

Index Terms: Single-stage reciprocating, Air-powered engine, Mathematical model, Simulation research

INTRODUCTION

Air-powered engine utilizes high pressure compressed air to produce dynamic, when the compressed air expands and do work in the cylinder. The compressed air engine does not consume fuel or emits exhaust pollution; it can alleviate-ate the pressure of urban air pollution, so it is the main research direction of the new energy vehicles recently. Currently, related researches of compressed air are carried out all over the world [1]

The French company MDI has developed a partial commercial production of the air powered car. Research in India on air powered cars carries out mainly in IIT and Amrita University, and it is still at exploring stage [2-4]. Domestic study on air-powered engine focus on improving the piston-crank air-powered engine, for the existing air-powered engine only provides one-way power during a single duty cycle, and the gas expansion contributes a lateral force on the crank, which causes the loss of partial expansion work.

Based on the principle of gas expansion, a new structure of reciprocating air-powered engine is proposed. Compressed air does work by expansion to drive the reciprocating motion of rack, through the transmission system, convert to one-way rotary motion of the output shaft.

1.1 The working principle

Fig.1 and Fig.2 is respectively the schematic diagram of control circuit and transmission system.Fig.3 is the principle prototype. High pressure air outflows from tank, achieves the pressure regulation by pressure reducing valve, changes the direction of the chamber or chamber without rod through directional control valve. Compressed air does work by expansion to drive the reciprocating motion of double-sided rack. Then rack drives the upper and lower gear with the first and second gear and the third gear at the same time, in order to produce sustained rotary motion with output shaft. Reciprocating two-way motion uses the whole output force of cylinder to do work, and outputs mechanical energy.

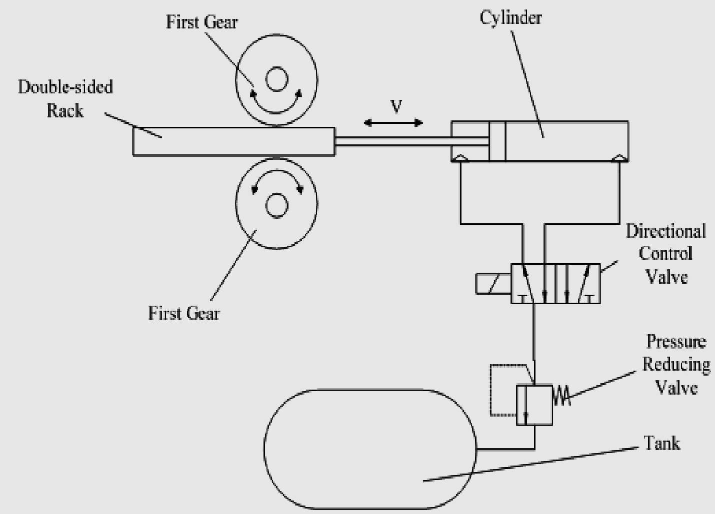

Fig.1 Pneumatic control circuit diagram

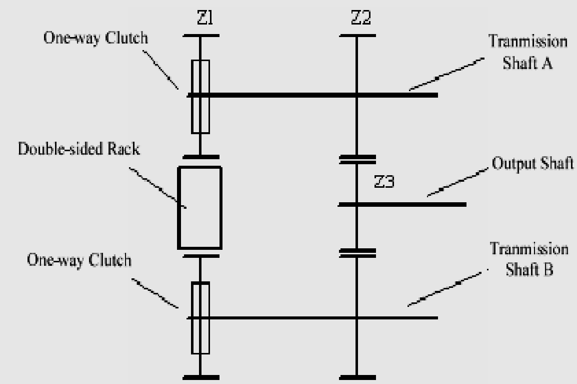

Fig.2 Transmission system schematic

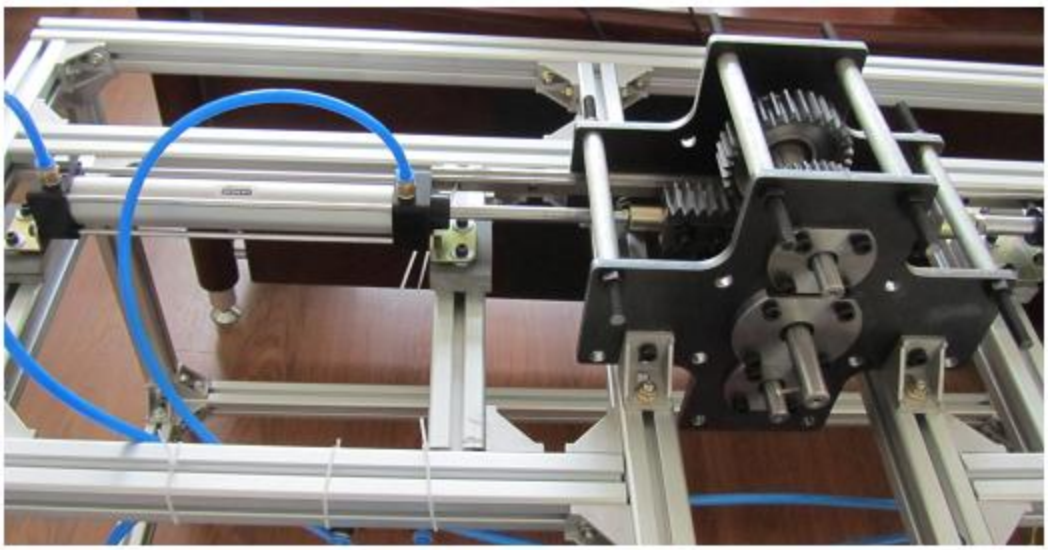

Fig.3 Principle prototype

2. THE MATHEMATICAL MODELING

The power plant of single-stage reciprocating air-powered engine is double acting pneumatic cylinder of single link (Fig.4). Here is a single duty cycle of engine. When compressed air flows into the chamber without rod, it expands and does work to push the rod to move to the right, then drives the double-sided rack to the right, outputs torque through pneumatic transmission system at last, with the chamber exhaust. When the push rod reaches the end of the stroke, the directional control valve changes the direction, compressed air flows into the chamber, it expands and does work to push the rod to move to the left, then drives the double-sided rack to the left, and outputs torque through pneumatic transmission system at last, with the chamber without rod exhaust. The whole system is an open system. Chamber and chamber without rod are changing volume system.

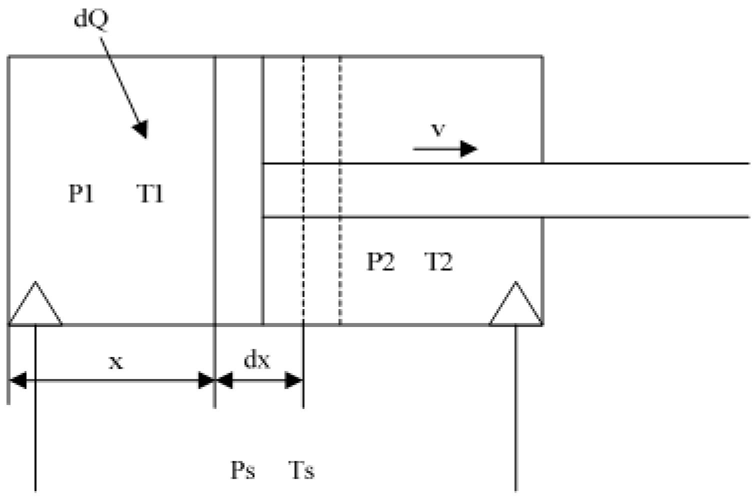

Fig.4 Thermal modeling of single-stage reciprocating air-powered engine

In order to simplify calculation, the compressed air that the engine uses is assumed as [5, 6]

1) The compressed air is ideal air
2) Supply pressure Ps is constant, temperature of supply air Ts is the temperature of the environment, Ts = 293K
3) The air flowing out and into the cylinder is stable
4) The work process of directional control valve is instantaneous
5) The cylinder and valve operation mechanism does not leak during the work process

①Gas energy conservation equation

Under the above assumptions, according to the first law of thermodynamics, the state change of air should satisfy the energy conservation equation during the work process;

Expressed as:

$$\frac{dU_i}{dt} = \frac{dQ_i}{dt} + \sum \frac{dm_i}{dt} h_i - \frac{dW_i}{dt}$$

Eq.1

Where

$$\begin{cases} \dfrac{dU_i}{dt} = \dfrac{dQ_i}{dt} + \sum \dfrac{dm_i}{dt} h_i - \dfrac{dW_i}{dt} \\ \dfrac{dQ_i}{dt} = K \bullet A \bullet (T_e - T_i) \\ \dfrac{dW_i}{dt} = -p_i \dfrac{dV_i}{dt} \end{cases}$$

Eq.2

The specific internal energy and heat ratio of ideal air is

$$U_i = C_v * T_i$$ Eq.3

Substituting Eq.(1) and Eq.(2) into Eq.(3),we get

$$\frac{dT_i}{dt} = \frac{\sum \frac{dm_i}{dt} h_i - C_v T_i \frac{dm_i}{dt} - p_i \frac{dV_i}{dt} + \frac{dQ_i}{dt}}{m_i C_v}$$

Eq.4

②The equation of ideal air

$$PV = mRT$$

Eq.5

Substituting Eqs. (1-4) into Eq.(5),and differential ,we obtain

$$\frac{dP_i}{dt} = \frac{m_i R}{V_i} \frac{dT_i}{dt} + \frac{RT_i}{V_i} \frac{dm_i}{dt} - \frac{m_i RT_i}{V_i^2} \frac{dV_i}{dt}$$

Eq.6

For the chamber

$$V_1 = A_1 (x + s_1)$$

Eq.7

For the chamber without rod

$$V_2 = A_2 (s + s_2 - x)$$

Eq. 8

Under the above equations, subscript i stands for chamber and chamber without rod, i=1, 2, corresponds with Fig.4.

$\sum \frac{dm_i}{dt} h_i$ — the enthalpy flowing out and into each chamber

U_i —air internal energy of each chamber

W_i —the work done by air expansion of each chamber

V_1 —volume of chamber without rod

S_1 —clearance volume equivalent stroke of chamber without rod

A_1 —active area of chamber without rod

V_2 —volume of chamber

S_2 —clearance volume equivalent stroke of chamber

A_2 —active area of chamber

S—piston stroke

A —heat transfer surface area of Chamber

K —heat exchange coefficient

R, C_v —thermodynamic constant

③The kinetic equation of transmission system

Transmission system of rotary motion into an equivalent reciprocating piston, according to the Newton's second law, we obtain the kinetic equation of Piston under the air pressure acting in the cylinder.

Expressed as:

$$P_1A_1 - P_2A_2 - (f + \frac{M_1}{r_1} + \frac{2M_2}{r_1} + \frac{M_3Z_2}{r_1Z_3}) = (m_1 + \frac{2J_1}{r_1^2} + \frac{2J_2}{r_1^2} + \frac{J_3Z_2^2}{r_1^2Z_3^2})\frac{dv}{dt}$$

Eq.9

In Eq.(9):

v —velocity of piston

f—friction of piston

m_1 —weight of piston and push rod

$1_r, 2_r, 3_r$ —radius of first gear, second gear and third gear

Z_1, Z_2, Z_3 —tooth number of first gear, second gear and third gear

J_1 —rotational inertia of first gear

J_2 —rotational inertia of second gear and transmission shaft

J_3 —rotational inertia of third gear and output shaft

M_1 —drag torque of first gear;

M_2—drag torque of second gear and transmission shaft

M_3 —drag torque of third gear and output shaft

Combining Eqs.(1-9), the mathematical model of single-stage reciprocating air-powered engine is established.

1.1. *2.1The Performance Simulation and Analysis*

According to the established mathematical model, simulate the performance of single-stage reciprocating air-powered engine under the circumstance with the different intake pressure and different cylinder bore. Simulation parameters are as follows, piston stroke is 200mm, the first gear module is 3mm, tooth number is 30, the second gear module is 2mm, tooth number is 40, the third gear module is 2mm, and tooth number is 25. Establish the simulation model based on Simulink, get the solution through fixed-step Runge-Kutta method, the fixed-size is 0.01ms.

2.2 The Influence of intake pressure

Fig.5 shows the pressure of chamber without rod at the cylinder bore of 40mm under different intake pressure. As

Shown in Fig.5, the pressure of chamber without rod is alternative variation, has certain periodicity. Intake pressure are 0.4Mpa, 0.6Mpa and 0.8Mpa ,corresponding with cycle time which are 0.437s, 0.403s and 0.389s, the velocity of piston increases with the increase of intake pressure, and the cycle time decreases with the increase of it. Every alternation shows that the directional control valve changes the direction of the chamber or chamber without rod when piston moves to the end of stroke. And then the piston moves to the opposite direction. Compressed air does work by expansion to drive the reciprocating motion of rack, through the transmission system, convert to one-way rotary motion of the output shaft. The peak pressure of chamber in Fig.5 is higher than intake pressure. The result shows that the direction valve starts when the piston is about to reach the end of stroke, at the same time, the piston still has a certain velocity, air in discharge chamber is not completely drained, the residual volume is very small, the source of air fills into the discharge chamber of last cycle, leading to the peak pressure of chamber is higher than intake pressure.

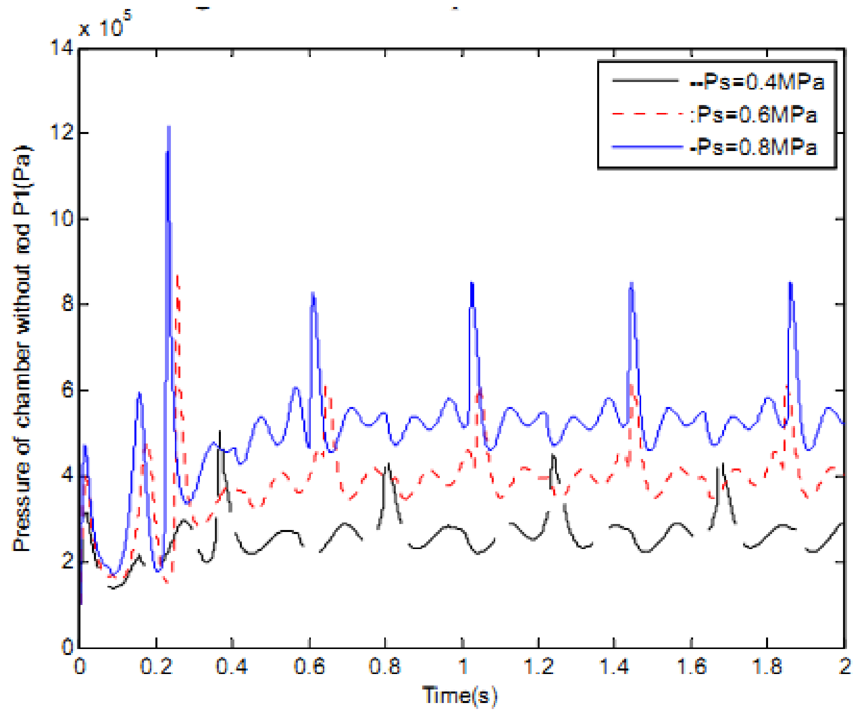

Fig.5 Pressure of chamber without rod under different intake pressure

2.3 *The Influence of cylinder bore*

The directional control valve changes the direction of the cylinder when piston moves to the end of stroke. The velocity of piston will fluctuate within a certain range, so that the output torque and rotational speed also fluctuate within a certain range. Take the average torque and rotational speed of output shaft for analysis, and compare their changes. Under the circumstance with different intake pressure and different cylinder bore, Fig.6 and Fig.7 are the change curves of the average torque and rotational speed. The figures show that the average rotational speed increases linearly and the average of torque also increase with the increment of intake pressure when the cylinder bore are the same. For the same intake pressure, the average output torque increases with the increase of cylinder bore, but the rotational speed decreases with the increase of it. The average output torque is close at different cylinder bore when the intake pressure is between 0.2MPa and 0.5MPa.

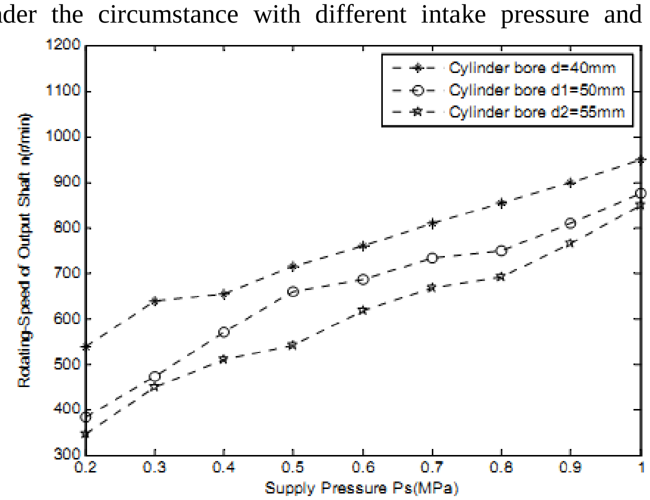

Fig.6 Rotating–Speed of sutput shaft under different intake pressure

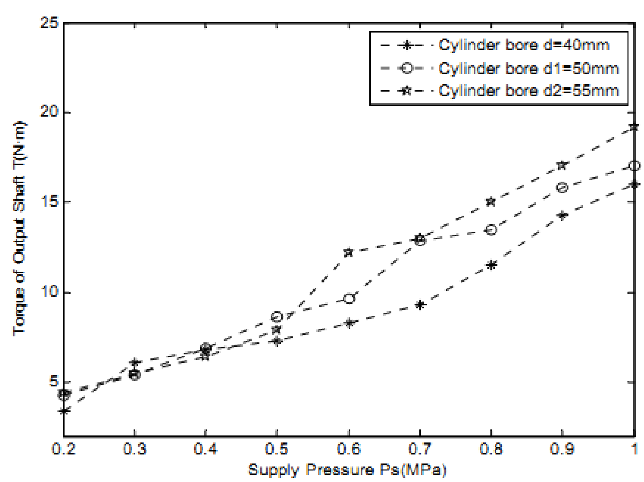

Fig.7 Torque of output shaft under different intake pressure

ISSN 2250-3153

3. Conclusions

According to the principle of gas expansion, the overall structure of single-stage reciprocating air-powered engine is

Designed. The operation of principle prototype confirmed the feasibility of the work principle. The mathematical model of the engine is established and simulated. The results show that the pressure of chamber and chamber without rod is alternative variation, has certain periodicity. The cycle time decreases with the increase of intake pressure. Moreover, the average output torque and rotational speed increases with the increase of intake pressure. Under the same intake pressure, the average output torque increases with the increase of cylinder bore, but the rotational speed decreases with the increase of it. Above research conclusions will provide significant reference for further study on optimizing design.

4. Acknowledgement

Dr Balakrishnan sankar.Professor and Chairman of Department of Mechanical Engineering, and Dean of Amrita University.Amritapuri, Kerala, India.

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First Author – Rahul Kumar, 4th year Mechanical Engineering, Amrita University, rahulkumar_0207@rediffmail.com

Second Author–Anand M G, 4th year Electronics and Communication Engineering, Amrita University, amganand@yahoo.com