Pressure and Temperature Change in Air Cylinders in Charged or Discharged Case

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Abstract

In pneumatic systems the temperature changes during operation owing to air compression or expansion, friction of air movement and friction between solid interface. The temperature change usually has undesirable influence on process. To attain higher quality of pneumatics, studies in thermo-fluid dynamics is needed. This paper presents experimental results and theoretical analysis on the temperature change by air charge and discharge to cylinders, which has no piston yet. The temperature increase by charge shows a strong dependence on axial location along the cylinder, which is proved in theoretical analysis. The temperature decreases by discharge shows rather uniform in the cylinder, which is also proved by theory.

1. Introduction

The change of temperature in pneumatic actuators, when they are operating, is probably due to friction by moving pistons and pressure change by air charge or discharge. It is basically necessary to define their effects, in order to achieve higher qualities of pneumatic systems. This paper presents experimental temperature distributions measured in cylinders in cases of air charges or discharges, and a slightly quantitative theoretical analysis explaining these experimental results. The cylinders used for experiment are not pneumatic cylindrical actuators but simplest ones without piston in them. Our intention was concentrated on the effects of charging and discharging, and not frictions of piston at all.

2. Experiment

2.1 Apparatus

Figure 1 shows a whole system. An oscillator and a solenoid valve gives a regular sequence of charge and discharge of air. Cylinders are of different diameters but the same length of 1m. They are so long as to see the distribution over their length clearly. In order to get experimental informations about lateral heat transfer, four cylinders of different diameter are adopted. Pressure gauges are placed at both ends of the cylinder, denoted by A and A' in the figure. Supply pressures are chosen at every value from 1 to 4 kgf/cm^2 g.

Temperatures are measured by 11 thermocouples of 0.1mm dia. Cu-constantan wire. The thermocouples are placed at 0.1m interval along the length. They are carefully mounted to measure the temperature at the center of the cross section of the cylinder. The measurement is reproduced after replacing the cylinder inversely in the length under the same supply pressure.

2.2 Results

The pressure and the temperature generally change as lines shown in Fig.2, where outputs of pressure sensor A and thermocouples 1,6 and 11 are recorded. The pressure response shows that there are some time lag in charging process and also in discharging process. Every temperature output presents a upward spike during each charging process and a downward spike during each discharging process.

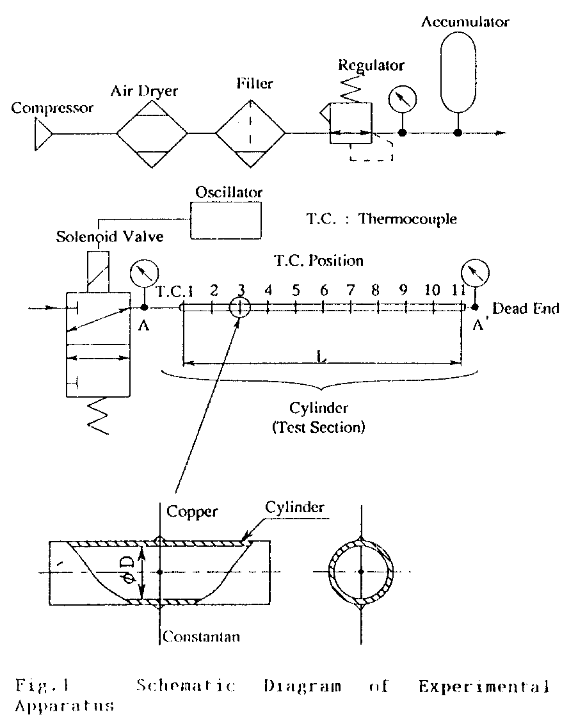

Fig.1 Schematic Diagram of Experimental Apparatus

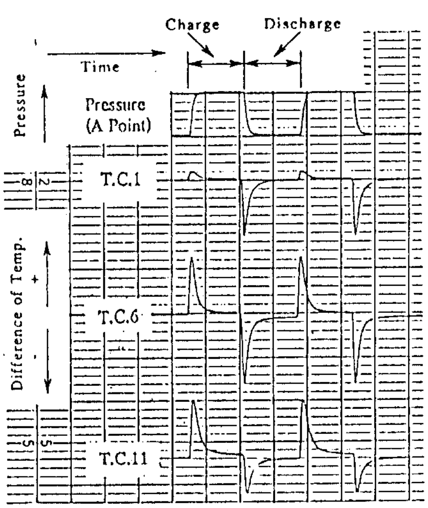

Fig.2 Example of Out Put Signals of Pressure Gauge and Thermo-couples

The upward spike is caused by the temperature rise by compression of air, while the downward one is by air expansion. The falling slope after the peak of upward spike is due to the cooling by heat transfer to the cylinder wall. Likewise, the rising slope after the bottom of downward spike is due to the heat transfer from the cylinder wall.

The height of upward spike depends strongly on its position in the cylinder. The height is low near the inlet, it grows higher approaching the dead end. This phenomenon is explained clear in the following chapter.

The depth of downward spike does not depend on its position so strongly as the upward spike. It is also explained later.

Heights and depths of spikes are shown in Fig.3 to 6 against longitudinal positions of the cylinder. The results of the same cylinder with different supply pressures are illustrated in a figure. Four lines upper are for charge and denote heights of spike. Four lines lower are for discharge and denote depths. Since the basis of spike corresponds to the temperature of environment, these heights and depths denote the magnitude of temperature different from the environment.

Each line shows the temperature is different with the different supply pressure. The

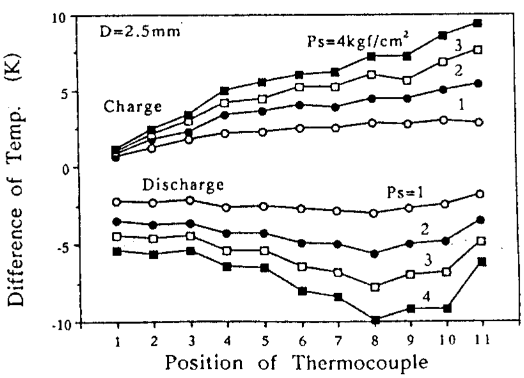

Fig.3 Height and Depth of Spikes of Temperature Change [Cylinder Diameter 2.5mm]

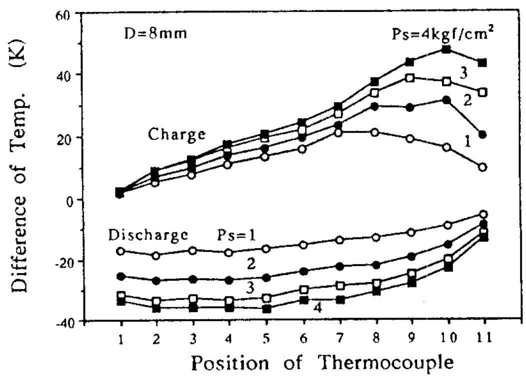

Fig.5 Height and Depth of Spikes of Temperature Change [Cylinder Diameter 8.0mm]

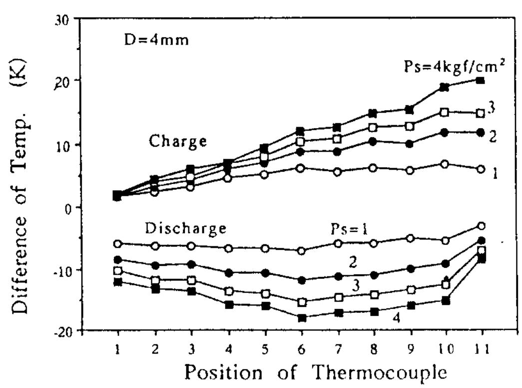

Fig.4 Height and Depth of Spikes of Temperature Change [Cylinder Diameter 4.0mm]

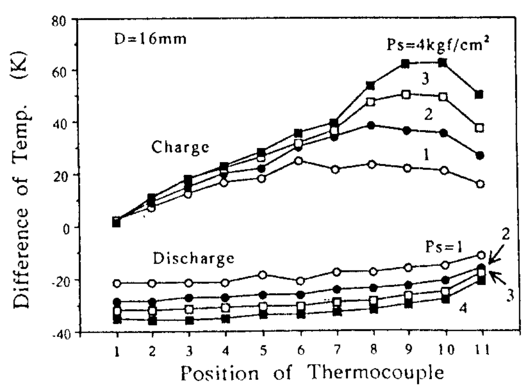

Fig.6 Height and Depth of Spikes of Temperature Change [Cylinder Diameter 16mm]

temperature increase is higher and the decrease is lower, when the air is supplied with a higher pressure.

The temperature change by charge or discharge is large in the sick cylinder. This is because the large distance to the wall depresses the relaxation of temperature by the heat transfer to/from the wall.

Figure 7 shows the magnitude of temperature change against the diameter of cylinder. In this figure the temperature is limited to one measured by T.C.9, partly because to avoid complication. The growth of magnitude with diameter seems saturating for larger diameters, but not saturated yet.

3. Theoretical Analysis

Nomenclature

- c_p: specific heat at constant pressure
- c_v: specific heat at constant volume
- D: diameter of cylinder
- h: specific enthalpy
- L: length of cylinder
- M: molar mass of air
- P: pressure
- P_s: supply pressure
- R: universal gas constant
- T: temperature
- t: time
- u: specific internal energy
- v: velocity
- z: coordinate along cylinder
- κ: ratio of specific heats
- ρ: density

The emphasis is on a qualitative explanation. The model, Fig.8 is as simple as possible. The air works in an adiabatic condition, any heat transfer is neglected. The state and the movement of air are uniform in any cross section in the cylinder. Therefor, the coordinates are time and longitudinal position(t,z).

The model is mathematically composed of three equations; the energy equation, the mass conservation equation and the state equation of ideal gas.

$$\partial(\rho u)/\partial t + \partial(\rho vh)/\partial z = 0 \quad (1)$$

$$\partial\rho/\partial t + \partial(\rho v)/\partial z = 0 \quad (2)$$

$$P/\rho = RT/M \quad (3)$$

where the energy in terms of velocity is neglected. In order to solve these equations, reasonable approximations are introduced as follows.

The pressure propagates with the speed of sound. It is so fast that the pressure is uniform in the cylinder. Therefor it is a function of t only; P(t).

In Eq.(3), the pressure normally changes over hundreds percent, while the temperature changes within ten percent or so. Therefor the density changes mostly by the pressure. Assume that the density of air varies with pressure and does not change with temperature. Then Eq.(3) means

$$\rho(t) = M \cdot P(t)/R/T_0 \quad (4)$$

where T_0 denotes the characteristic temperature, say the initial temperature of the process.

Considering Eq.(4), Eq.(2) becomes

$$d\rho/dt + \rho\partial v/\partial z = 0, \quad (5)$$

which is integrable with z. The integration from L to z gives a relation

$$v(z) - v(L) = -(d\rho/dt)(z-L)/\rho \quad (6)$$

where v(L) is a velocity at the dead end of the cylinder and naturally becomes zero. Here the velocity distribution is written up.

The specific internal energy and the specific enthalpy are related to the temperature as follows

$$u = c_v T, \quad (7)$$

$$h = c_p T. \quad (8)$$

Both heat capacities are assumed constant. Therefor Eq.(1) becomes

$$c_v\partial(\rho T)/\partial t + c_p\partial(\rho vT)/\partial z = 0. \quad (9)$$

After the consideration of Eq.(2) and the differentiation of product, it turns into

$$(c_v/T)\partial T/\partial t + (c_p v/T)\partial T/\partial z = \{(c_p-c_v)/\rho\}\partial\rho/\partial t \quad (10)$$

This equation becomes simpler, with the aide of Mayer's relation and the specific-heat ratio κ, as follows

$$\partial \ln T/\partial t + \kappa v\partial \ln T/\partial z = (\kappa-1)\partial \ln\rho/\partial t. \quad (11)$$

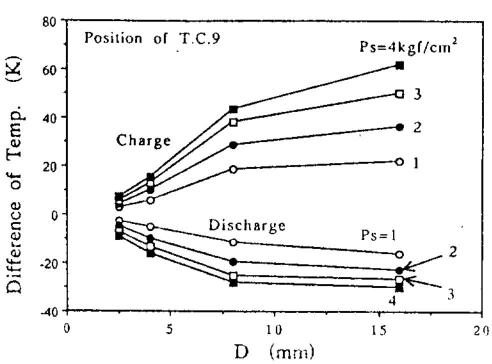

Fig.7 Height and Depth of Temperature Spikes against Diameter of Cylinder

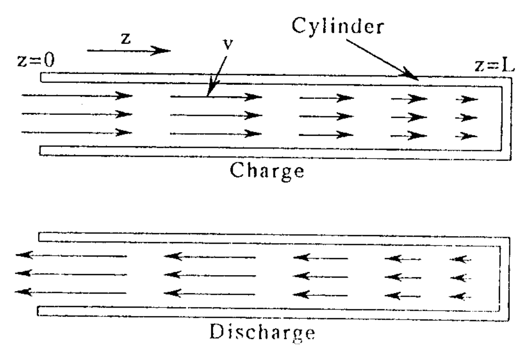

Fig.8 Mathematical Model and Illustration of Velocity Profile

Introducing Eq.(6) into v, and considering that ρ is depend just on t, not on z, this equation is modified as

$$\partial \ln T/\partial \ln\rho - \kappa\partial \ln T/\partial \ln(1-z/L) = \kappa-1 \qquad (12)$$

This is the equation to solve.

The Eq.(12) has a general solution

$$\ln T - (\kappa-1)\ln\rho = f\langle \ln\rho+\ln(1-z/L)/\kappa\rangle, \qquad (13)$$

where a function f is determined from a boundary condition and/or an initial condition. The conditions for charging process and for discharging process are different.

The conditions for charging, where ρ is getting larger than ρ_0, are as follows

$$T = T_0 \quad \text{when } z=0 \text{ and } \rho\geqq\rho_0, \qquad (14)$$

$$T = T_0 \quad \text{when } \rho=\rho_0 \text{ and } 0\leqq z\leqq L. \qquad (15)$$

These conditions determine the solution which has different forms for two different regions of z.

$$\ln T = \ln T_0 - \langle(\kappa-1)/\kappa\rangle\ln(1-z/L) \qquad (16)$$

when $\ln\rho \geqq -(1/\kappa)\ln(1-z/L) + \ln\rho_0$, and

$$\ln T = \ln T_0 + (\kappa-1)\ln(\rho/\rho_0) \qquad (17)$$

when $\ln\rho \leqq -(1/\kappa)\ln(1-z/L) + \ln\rho_0$.

The condition for discharging, where ρ is getting smaller than ρ_0, is as follows

$$T = T_0 \quad \text{when } \rho=\rho_0 \text{ and } 0\leqq z\leqq L. \qquad (18)$$

This is the same form as one of the conditions for charging case. The solution is

$$\ln T = \ln T_0 + (\kappa-1)\ln(\rho/\rho_0) \qquad (19)$$

when $\ln\rho \leqq \ln\rho_0$, necessarily $\ln\rho \leqq -(1/\kappa)\ln(1-z/l)+\ln\rho_0$.

These solutions are illustrated in Fig.9 as the relation between attained temperatures against positions for some supply pressures.

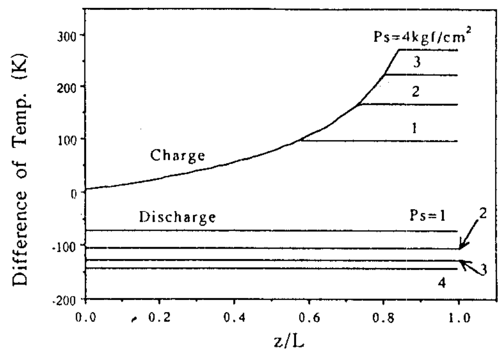

Fig.9 Theoretical Result of Temperature Change

4.Discussions

Fig.9 of the theoretical results qualitatively coincides with experimental results described in Fig.3 to 6. The explanation of temperature rise during charge is that the air existing in the cylinder before charging is compressed like an isentropic compression of the closed gas system which is pressed to the dead end of cylinder as the charge advances. The air enters passing through a valve at constant temperature and compresses the preexistent. In this way, the charge process makes a plateau near the dead end and a slope starting from the inlet at a zero degree of temperature.

In the discharging process, the air in the cylinder undergoes an isentropic expansion and does the work discharging a small part of its own continuously. Therefore the state in the cylinder remains uniform.

The repetition of many number of charge and discharge may cause a temperature distribution in the linear air actuator, which may be low near the opening and high near the piston.

The quantitative difference between Fig.9 and Fig.3 to 6 is chiefly from the lateral heat transfer which is neglected in the theoretical analysis. The thermocouples are assumed to respond perfectly to the air temperature, but they have time constants which are compounded from their heat capacity and heat transfer process to/from the air. The heat conduction occurs through thermocouple wires. These heat transfer processes all make the out put of thermocouples moderate. In the near future theoretical results including these heat transfer processes expect to shift numerically to the experimental results.

5.Conclusion

It is higher temperature attained by charges, when the air is supplied by higher pressures. The distributions along the length of cylinder are particular in comparison to discharges. There appears a maximum peak of temperature near the dead end of the cylinder. The temperature monotonously increases from the lowest degree at the inlet to the maximum.

Lower temperatures are attained by discharge in accordance with the higher initial pressure in the cylinder. The distributions are rather uniform.

The results of theoretical analysis illustrate these distributions made by charges and discharges. The analysis, which is compounded from the energy equation the mass conservation equation and the ideal gas equation, shows the importance of throttling process and expansion or compression process. Theory gives higher values than experiments for charging and lower for discharging, because any heat transfer processes are not considered yet.