Paper

Examination on Gas Flow in the Tube and Pressure in the Pressure Chamber of the Model Switch

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This paper describes the theoretical calculation and experimental investigation of gas flow in the arc extinguish tube of the model switch. The theoretical calculation discussed here is the second process of the four processes in current interruption. Considering a results of experimental observation on the mass consumption of the tubes to arc energy and the pressure difference of the tube and pressure chambers, the theoretical equations were deduced for the gas flow in the tube during the current interruption process. Using these theoretical equations, the pressure in pressure chamber was calculated, and compared with the experimental results. In spite of adopting many assumptions in the derivation of the theoretical equations, the calculated and experimental values were mostly similar.

Keywords: load break switch, current interruption, ablation gas, pressure chamber

1. Introduction

Recently, the low environmental load and low production cost are priority for switches used in the high voltage distribution lines. Since air switches which interrupt current in atmospheric vessels produce no harmful by-products and are very low manufacturing cost, it is recognized as environmentally friendly one. Therefore it is expected that air switches will be even more widely used in future.

The current interruption capability in air switch is achieved by utilizing the gas produced by the ablation from the arc extinguish material used in arc extinguish tube.

The authors carried out the current interruption experiment in order to observe characteristics of the generation of gas in the current interruption process, and storage of the gas in the pressure chamber using the model switch (1).

Previously the qualitative analysis was carried out by divided the current interruption of the model switch into three processes (2).

This paper describes the theoretically analyzed gas flow in the tube during the second process in which movable contact moves through the arc extinguish tube.

2. Composition of the model switch

2.1 Composition of the air switch The composition of the model switch used in this experiment is shown in Fig. 1. To simplify analysis a more basic level slide structure was used.

As mentioned above, the fixed contact, movable contact, arc extinguish tube and the pressure chamber were horizontally arranged in a straight line. Both ends of the extinguish tube whose inner diameter was 7 mm and length was 34 mm were fixed between the nozzle and the tube stopper made of ceramics.

The diameter of the movable contact was 6.6 mm. It was driven by two tension springs along the stroke, which was approximately 130 mm. The position where the movable contact exit the outlet of the ceramic tube stopper was 68 mm from tip of the fixed contact. The inner diameter of pressure chamber was 60 mm, the length was 100 mm, and the volume was 283 cm^3.

2.2 Experimental circuit The experiment was carried out using an L-C resonance circuit as shown in

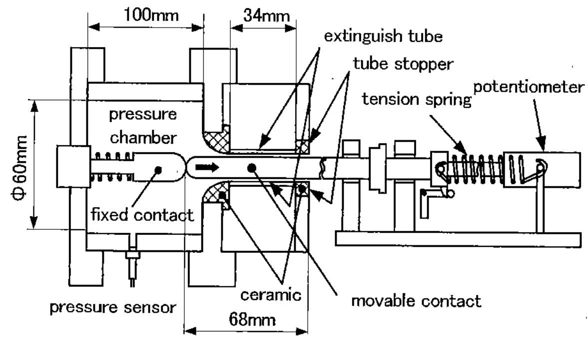

Fig. 1. Experimental apparatus (model switch)

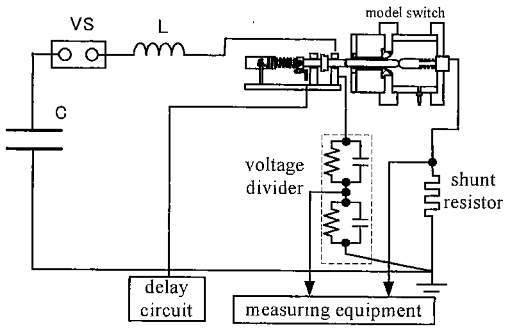

Fig. 2. Experimental circuit

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Fig. 2.

When the vacuum switch closes, the current flows through the model switch. After that, movable contact of the model switch moves so that the contact separation takes place near the current maximum.

3. The Model of the Second Process

3.1 The Current Interruption Process The current interruption from contacts separation to the recovering insulation between contacts is described by four processes as shown in Fig. 3.

The first process designates the process during the period from t_1 to t_2, and on the same way the second process is from t_2 to t_3, designates the second process, third process is from t_3 to t_4, the fourth process is the period after t_4.

(1) The first process The first process is the change of state for a period from the from the contacts separation to the time when movable contact tip reaches the entrance of the arc extinguish tube. In this process, the pressure of the pressure chamber rises according to the thermal expansion of the air in the pressure chamber due to the arc heating.

(2) The second process The second process is the change of state for a period in which the tip of the movable contact moves through the arc extinguish tube.

The arc extinguish tube generates ablation gas by the arc heating, during the tip of the movable contact is in the arc extinguish tube. Most of the ablation gas flows into the pressure chamber, since there is very little clearance between tube inner diameter and diameter of movable contact. The almost energy and almost mass ablated flow into the pressure chamber, and increase the pressure in the pressure chamber.

(3) The third process Owing to the inflow of the gas and energy to the pressure chamber, the pressure in the pressure chamber equals the pressure at the pressure chamber side outlet of the tube. And the pressure rise in pressure chamber becomes gentle since the stagnation point begins to move from the vicinity of the tip of movable contact to the pressure chamber side outlet of the tube.

(4) The fourth process The fourth process is the change of state for a after current zero. Stored gas in the pressure chamber blows out through arc extinguish tube.

3.2 Model and Basic Equations of the Gas Flow in the Tube The second process is the change of state for a period in which the tip of the movable contact moves through the arc extinguish tube and stagnation point is in front of the tip of movable contact. The stagnation point of gas flow moves with the movable contact. It is assumed that the flow velocity of the gas on the pressure chamber side outlet of the tube is the sound velocity, since the pressure at the stagnation point seems to be considerably higher than the pressure of the pressure chamber side outlet of the tube.

In this paper, gas flow in the arc extinguish tube and pressure of the pressure chamber were analyzed theoretically on the second process. The following assumptions

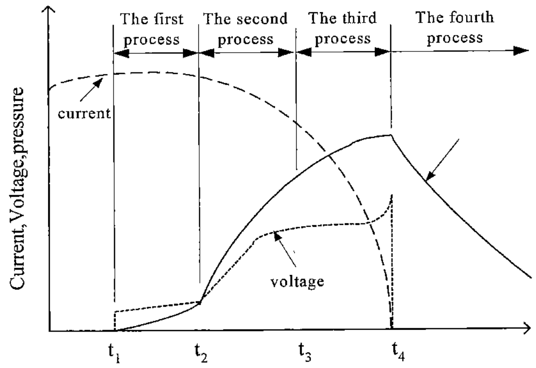

Fig. 3. Four processes in the current interruption

were deduced based on the flow described above.

(1) The flow is an isentropic flow.
(2) The arc positive column fills the tube up.
(3) Temperature T, pressure P, flow velocity v, Mach number M, density ρ and specific enthalpy h of the gas are functions of the axial position only, and the radial direction is uniform.
(4) The compressibility is considered, and viscosity and heat conduction of the gas are disregarded. (ie, the condition of the gas is an "ideal gas")
(5) The gas velocity at pressure chamber side outlet of the tube equals to the sound velocity.
(6) The area of the clearance between tube inner diameter and movable contact is about 10% of the area of the pressure chamber side. The mass flow rate which blasts from both open ends of the tube are assumed to be proportional to those area.

Since the time necessary for state transition of the flow propagating tube overall length at sound velocity seems to be the about 20 μsec, the opening speed of the movable contact of the model switch and the decreasing rate of current are much slower than the state transition rate. In other words, the condition of the flow seems to have always reached the quasi steady state.

The basic equations of the gas flow are conservation of mass, conservation of momentum, conservation of energy and the equation of state.

The coordinate axis was determined, as shown in Fig. 4. x is the coordinate normalized over the overall length of the tube, $x = 1$ is the pressure chamber side outlet of the tube, and $x = 0$ is the open end of the tube. x_s is a coordinate of the stagnation point, and the stagnation point of gas flow moves with a certain separation from the tip of movable contact from the pressure chamber side outlet of the tube to the starting position of the third process.

$T(x, x_s)$, $P(x, x_s)$, $v(x, x_s)$, $h(x, x_s)$ and $\rho(x, x_s)$ describe the distribution of temperature, pressure, flow velocity of the gas, specific enthalpy and density of the gas flow at position x when the stagnation point is located at x_s.

The model of gas flow in the tube assumed the stagnation point existing for the fixed distance from the tip of

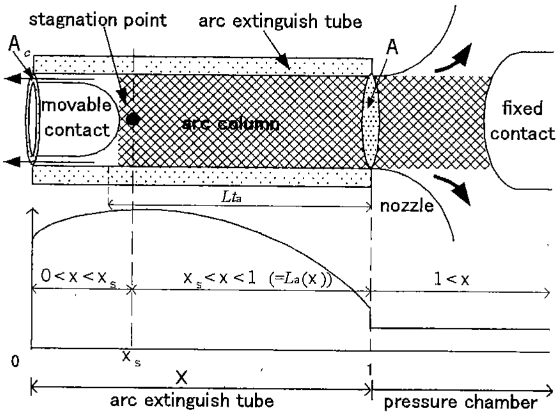

Fig. 4. Stagnation point, distribution of pressure and coordinates in the model switch

movable contact shown in Fig. 4. The left side of movable contact shown in the Fig. 4 is the atmosphere, the pressure of pressure chamber is also atmospheric pressure before the contacts separation. Then, the mass of the gas which blows out from the both outlet of the arc extinguish tube is proportional to the cross section of the flow channel. Therefore, it is assumed that the position of the stagnation point is retained the distance of 10% of arc length in the tube in front of the tip of movable contact. $0 < x \leqq x_s$ is the channel which blows out toward the atmosphere, and this flow does not directly affect the pressure rise of pressure chamber. Then, region of $x_s < x \leqq 1$ is the channel in which the ablated gas flow toward the pressure chamber, the flow in this channel is analyzed in this paper, and the flow in this channel brings the pressure rise of the pressure chamber which is used to inspect the analyzed results of flow in the tube.

The basic equations of the flow are given from equations (1), (2) and (3). Considering the one-dimensional axial flow model and the constant cross section of the tube.

The equation of conservation of mass is

$$\rho(x, x_s)v(x, x_s) = f(x, x_s) \cdots\cdots\cdots\cdots\cdots\cdots \quad (1)$$

The equation of conservation of momentum is

$$P(x, x_s) + \rho(x, x_s)v^2(x, x_s) = P(x_s, x_s) \cdots\cdots \quad (2)$$

The equation of conservation of energy is

$$\left\{h(x, x_s) + \frac{1}{2}v^2(x, x_s)\right\} \rho(x, x_s)v(x, x_s) = g(x, x_s) \cdots\cdots\cdots\cdots\cdots\cdots \quad (3)$$

In addition, $f(x, x_s)$ and $g(x, x_s)$ are given in the following equation

$$f(x, x_s) = \int_{x_s}^{x} \frac{S\omega(x, x_s)L_a(x)}{A} dx \cdots\cdots\cdots\cdots \quad (4)$$

$$g(x, x_s) = \int_{x_s}^{x} \frac{E_a(x, x_s)I_a L_a(x)}{A} dx \cdots\cdots\cdots\cdots \quad (5)$$

where A is the tube cross section, S is the inner circumference of the tube, $\omega(x, x_s)$ is the mass of the gas which flows into the arc per unit time and unit area of the tube internal wall at the position of x, $L_a(x)$ is the arc length from stagnation point deciding by the position of movable contact tip to the pressure chamber side outlet of the tube, $E_a(x, x_s)$ is the axial electric field of arc column, I_a is arc current, $f(x, x_s)$ is the ratio of the ablation mass which generates between x and x_s to the tube cross section, $g(x, x_s)$ is the ratio of the arc power which flows into the tube between x and x_s to the tube cross section.

In addition, the following equations are established.

The relationship between flow velocity and Mach number is

$$v^2(x, x_s) = M^2(x, x_s)\kappa RT(x, x_s) \cdots\cdots\cdots\cdots \quad (6)$$

The equation of state for perfect gas is

$$P(x, x_s) = \rho(x, x_s)RT(x, x_s) \cdots\cdots\cdots\cdots\cdots\cdots \quad (7)$$

The relationship between specific enthalpy and temperature is

$$h(x, x_s) = \frac{\kappa R}{\kappa - 1} T(x, x_s) \cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (8)$$

where κ is ratio of specific heat of the gas in the tube; R is the gas constant for ablation gas, and $M(x, x_s)$ is Mach number of the gas flow.

4. Analysis

4.1 The Flow during the Second Process in the Tube

The analysis of gas flow in the tube requires equations from (1) to (3) and (6) to (8), they are solved simultaneously by assuming gas velocity of the pressure chamber side outlet of the tube as sound velocity.

Mach number is given by

$$M(x, x_s) = \sqrt{\frac{1 - \sqrt{1 - \dfrac{f(x, x_s)g(x, x_s)}{f(1, x_s)g(1, x_s)}}}{1 + \kappa\sqrt{1 - \dfrac{f(x, x_s)g(x, x_s)}{f(1, x_s)g(1, x_s)}}}} \cdots \quad (9)$$

Pressure is given by

$$P(x, x_s) = \frac{1}{\kappa} \times \sqrt{2 \cdot f(1, x_s)g(1, x_s)\frac{\kappa - 1}{\kappa + 1}} \times \left(1 + \kappa\sqrt{1 - \frac{f(x, x_s)g(x, x_s)}{f(1, x_s)g(1, x_s)}}\right) \cdots\cdots\cdots\cdots\cdots\cdots \quad (10)$$

Temperature is given by

$$T(x, x_s) = 2 \cdot \frac{g(x, x_s)}{f(x, x_s)} \times \frac{1}{\kappa R} \times \frac{\kappa - 1}{\kappa + 1} \times \left(\sqrt{\frac{f(1, x_s)g(1, x_s)}{f(x, x_s)g(x, x_s)}} - \sqrt{\frac{f(1, x_s)g(1, x_s)}{f(x, x_s)g(x, x_s)} - 1}\right) \times \left(\sqrt{\frac{f(1, x_s)g(1, x_s)}{f(x, x_s)g(x, x_s)}} + \kappa\sqrt{\frac{f(1, x_s)g(1, x_s)}{f(x, x_s)g(x, x_s)} - 1}\right) \cdots\cdots\cdots\cdots\cdots\cdots \quad (11)$$

Density is given by

$$\rho(x,x_s)=\frac{f(x,x_s)}{g(x,x_s)}\times\sqrt{f(1,x_s)g(1,x_s)\frac{\kappa+1}{2(\kappa-1)}}\times\left(1+\sqrt{1-\frac{f(x,x_s)g(x,x_s)}{f(1,x_s)g(1,x_s)}}\right)\quad\cdots(12)$$

Velocity is given by

$$v(x,x_s)=2\times\frac{g(x,x_s)}{f(x,x_s)}\times\cdot\frac{\kappa-1}{\kappa+1}\times\left(\sqrt{\frac{f(1,x_s)g(1,x_s)}{f(x,x_s)g(x,x_s)}}-\sqrt{\frac{f(1,x_s)g(1,x_s)}{f(x,x_s)g(x,x_s)}-1}\right)^2\quad\cdots(13)$$

Specific enthalpy is given by

$$h(x,x_s)=\frac{2}{1+\kappa}\times\frac{g(x,x_s)}{f(x,x_s)}\times\left(\sqrt{\frac{f(1,x_s)g(1,x_s)}{f(x,x_s)g(x,x_s)}}-\sqrt{\frac{f(1,x_s)g(1,x_s)}{f(x,x_s)g(x,x_s)}-1}\right)\times\left(\sqrt{\frac{f(1,x_s)g(1,x_s)}{f(x,x_s)g(x,x_s)}}+\kappa\sqrt{\frac{f(1,x_s)g(1,x_s)}{f(x,x_s)g(x,x_s)}-1}\right)\quad\cdots(14)$$

By assuming $\kappa=1.2$, the distribution of specific enthalpy, sound velocity, density, flow velocity, pressure, temperature of the gas flow in the tube at stagnation point $x_s=0.1$ was calculated using the equations from (9) to (14). The result is shown in Fig. 5. Each physical quantity is normalized according to the corresponding value at the pressure chamber side outlet of the tube.

As seen in Fig. 5, flow velocity and Mach number of the stagnation point are zero. And flow velocity and Mach number become sound velocity and 1 at the pressure chamber side outlet of the tube ($x=1$). The pressure of the stagnation point is $(1+\kappa)$ times the pressure of pressure chamber side outlet of the tube. The density at stagnation point is the twice of the density at the pressure chamber side outlet of the tube. Temperature and specific enthalpy at the stagnation point is $(1+\kappa)/2$ times of the value at the pressure chamber side outlet of the tube.

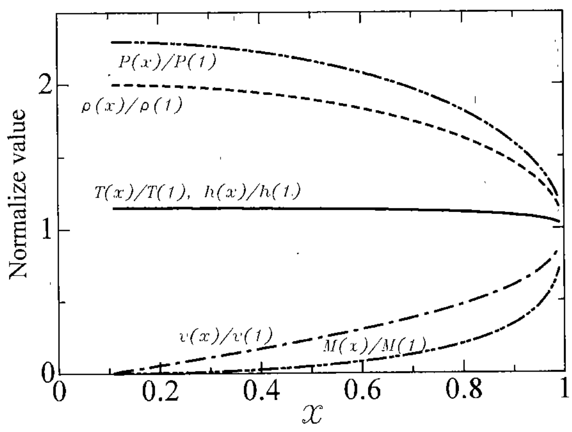

Fig. 5. Distribution of gas flow, temperature, pressure, velocity, density and Mach number along the tube axis

4.2 Pressure in the Pressure Chamber Due to the inflow of the gas from the tube to the pressure chamber, pressure, gas density and temperature increase in the pressure chamber. Mass and energy in the pressure chamber caused by the inflow of mass are given by equations (15) and (16).

$$\frac{V}{A}\cdot\frac{d\rho v(t)}{dt}=f(1,x_s)\cdots\cdots(15)$$

where $\rho_v(t)$ is the gas density of pressure chamber, V is the pressure chamber volume.

$$\frac{V}{A(\kappa_V-1)}\cdot\frac{dP_V(t)}{dt}=g(1,x_s)\cdots\cdots(16)$$

where $P_V(t)$ is the pressure of pressure chamber, κ_V is ratio of specific heat of the gas in the pressure chamber.

Thus pressure, density and temperature in the pressure chamber can be calculated using equations (15) and (16) and perfect gas equation as follows.

Pressure is given by

$$P_V(t)=\frac{A(\kappa_V-1)}{V}\int_{t_1}^{t_2}g(1,x_s)dt+P_1\cdots\cdots(17)$$

density

$$\rho v(t)=\frac{A}{V}\int_{t_1}^{t_2}f(1,x_s)dt+\rho_1\cdots\cdots(18)$$

temperature

$$T_V(t)=\frac{A(\kappa_V-1)\int_{t_1}^{2}g(1,x_s)dt+VP_1}{R_V\left(A\int_{t_1}^{t_2}f(1,x_s)dt+V\rho_1\right)}\cdots\cdots(19)$$

where P_1 and ρ_1 are the pressure and the density of the pressure chamber, T_V is the temperature in the pressure chamber; R_V is the gas constant in pressure chamber. P_1 and ρ_1 arise only by the arc heating in the pressure chamber.

5. The Comparison of Calculation and Experimental Results

It was difficult to measure the physical quantity of gas flow in the tube directly. However, the pressure in the pressure chamber was measured easily, and compared with the calculation result.

In the above numerical calculation, it is necessary to decide the value of ω, κ, κ_V. Though these values are shown by a function of the temperature of the gas and a function of the composition, calculation was carried out using the measured value and the assumed value.

$\omega(x,x_s)$ shows the mass of the gas which flows in unit area of internal wall of the tube and unit time at x. From previous research, the ablated depletion mass by the arc is proportional to the heat input (arc energy) per unit area and per unit time [3]. Therefore, $\omega(x,x_s)$ is shown as follows.

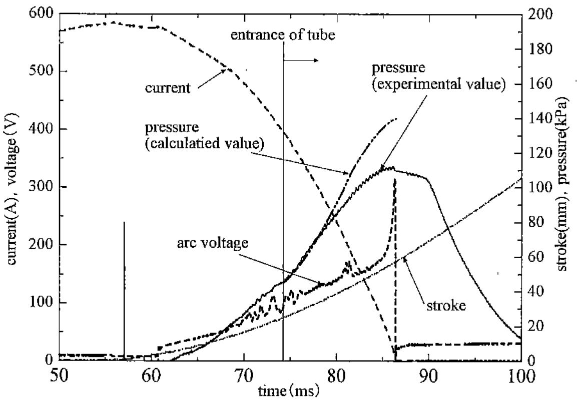

Fig. 6. Comparison of calculated pressure-rise with measured pressure-rise

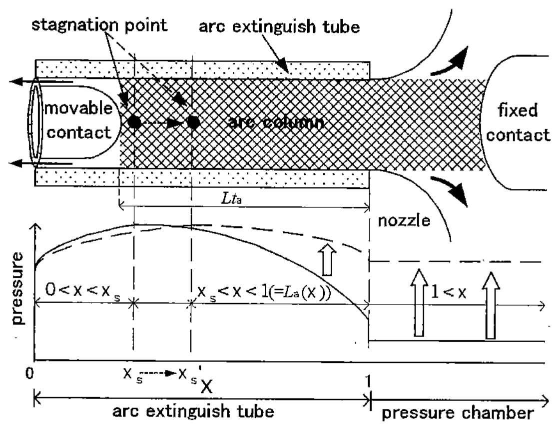

Fig. 7. Stagnation point, distribution of pressure and coordinates in the model switch

$$\omega(x, x_s) = \frac{AE(x)}{E_t} \cdot L_W \cdots\cdots\cdots\cdots\cdots\cdots (20)$$

where E_t is accumulation value of heat input (arc energy) per unit time and per unit area of the tube during the whole arc period, $AE(x)$ is the arc energy of per unit time and per unit area at x. L_w is the depletion mass of the arc extinguish tube.

The experimental values and calculated values agreed well, until the position of the movable contact tip reaches near 1/2 of the tube overall length as seen in Fig. 6. However, in the latter half, the calculated values exceeds the experimental values. The difference between experimental value and calculated value occur that the inflow of the gas for the pressure chamber decreases by pressure of the pressure chamber caught up with pressure of the pressure chamber side outlet of the tube. It seems that the time when the tip of movable contact reached this position is t_3 in Fig. 3. It is considered that the third process shown in Fig. 3 progresses after this period. The image of transfer of the stagnation point and internal pressure distribution in the tube in the third process is shown in Fig. 7.

From this examination, it can be said that calculation result and measured value agree well in the second process.

6. Conclusion

The behavior of ablation gas is investigated using the arc phenomena in the model switch. Theoretical analysis was carried out on the gas flow in the tube using the model switch, following results are obtained.

(1) The theoretical equations on physical quantity of the ablated gas flow in the tube were deduced. The calculated value of specific enthalpy; density; Mach number; velocity; pressure and temperature in the each axial position of the tube was obtained using the theoretical equations.

(2) The theoretical equation for pressure, temperature and density in pressure chamber were deduced.

(3) In spite of adopting many ideal assumptions in the derivation of the theoretical equations, and using the assumed values as the physical constant of the gas, the experimental values and calculated values are similar for the pressure of pressure chamber in second process.

The next stage of this research will focus on the following.

(1) Considering the transfer of stagnation point with pressure rise in the pressure chamber.

(2) Measurement of temperature near the pressure chamber exit.

(3) The comparison between the experimental value and calculated value in the third process.

(Manuscript received Feb. 28, 2003,
revised June 23, 2003)

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