EXPERIMENTAL EVALUATION OF FRACTION K_P OF ELECTRICAL ENERGY CONTRIBUTING TO PRESSURE RISE DUE TO AIR AND SF_6 ARC IN A CLOSED CONTAINER

M. KOTARI[1]*, T. TADOKORO[1], S. TANAKA[1], M. IWATA[1] AND T. AMAKAWA[1]

[1]Central Research Institute of Electrical Power Industry (CRIEPI),
2-6-1 Nagasaka, Yokosuka-shi, Kanagawa-ken, 240-0196, Japan
*k-masa@criepi.denken.or.jp

ABSTRACT

To propose a specific procedure for replacing SF_6 with air and to select appropriate parameters for internal arc tests, it is necessary to clarify the equivalent conditions causing the pressure rise due to air and SF_6 arcing in the tests. In this paper, we describe the characteristics of the pressure rise due to air and SF_6 arcing in a closed container and the ratio of the arc energy to the energy contributing to the internal pressure rise (k_p) from an experimental viewpoint. Additionally, to verify the energy balance resulting from SF_6 arcing in the container, the energy balance is discussed on the basis of the chemical reactions, radiation, and the melting and vaporization of the electrodes.

1.INTRODUCTION

From an environmental point of view, when carrying out internal arc tests on SF_6-insulated power equipment (e.g., MV switchgear), it is necessary to prevent SF_6 from being released into the atmosphere or to replace SF_6 with air in accordance with IEC standards [1]. However, the characteristics of the pressure rise and the thermal characteristics of the hot gas exhausted during arcing when testing in air are still considerably different from those for testing in SF_6 [2]. Thus, it is important to propose a specific procedure for replacing SF_6 with air and to select appropriate parameters for the tests. Therefore, it is desirable to clarify the equivalent conditions causing these characteristics both experimentally and analytically. In simple analytical methods of calculating the pressure rise [3], to reliably determine the pressure rise due to internal arcing in equipment, the ratio of the arc energy to the energy contributing to pressure rise (k_p) must be known. In this paper, we describe the characteristics of the pressure rise due to air and SF_6 arcing and the value of k_p in a closed container. It was found that the energy balance in the container due to air arcing was considerably different from that due to SF_6 arcing. Little detail was has been reported on the energy balance in a closed container resulting from SF_6 arcing. We estimated the energy balance by taking into account the melting and vaporization of the electrodes, the chemical reactions and radiation.

2. EXPERIMENTAL CONDITIONS

As shown in Fig. 1 [4], a damping ac with a frequency of 50 Hz was supplied from a 1,270 μF capacitor bank through a 7.5 mH reactor. The arc duration was controlled by two making switches.

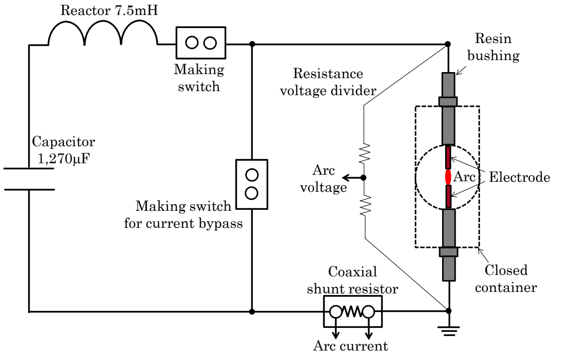

Fig. 1 Experimental circuit [4]

Fig. 2 [4] and Table 1 [4] show the closed container used in the experiments and the experimental conditions, respectively. The container, which was formed from a horizontal and vertical cylinder, had a volume of about 0.063 m^3 and filled with air or SF_6 at an absolute pressure of 0.1 MPa. Electrodes were arranged

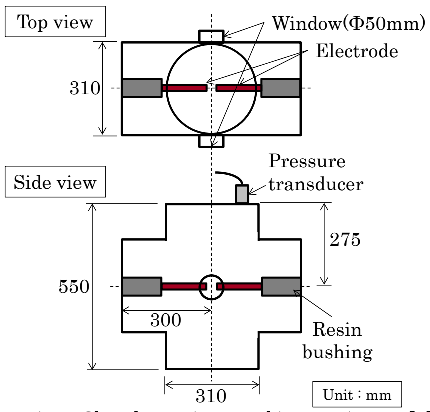

Fig. 2 Closed container used in experiments [4]

Table 1 Experimental conditions [4]

Item		Condition
Closed container	Shape	Crossed cylinders
	Volume	63.3×10^{-3} m^3 (63.3 L)
Electrodes	Material	Copper
	Diameter	5 mm
	Gap length; L_g	20, 40, 80 mm
Frequency		50 Hz
Charged voltage: V_c		10, 20, 25 kV
Peak current in first cycle for each V_c: I_{1st}		4.5, 8.7, 10.7 kA
Duration of arc		40 ms
Ignition method		By fusing copper wire of 0.1 mm diameter
Gas		Air, SF_6
Initial pressure in closed container		0.1 MPa・abs

along the central axis of the horizontal cylinder. The electrodes had a diameter of 5 mm and were made of copper. In the experiments, the charged voltage of the capacitor bank (V_c) was adjusted to 10, 20 or 25 kV (peak current in first cycle for each V_c (I_{1st}): 4.5, 8.7 or 10.7 kA), respectively, and the arc was ignited by fusing a copper wire between the electrodes. The gap length between the electrodes (L_g) was 20, 40 or 80 mm. The arc duration was 40 ms. Also, the pressure rise was measured using a pressure transducer located at the top of the container. After the experiments, we collected the gases resulting from the decomposition of SF_6 in a stainless-steel cylinder and the fine particles scattered in the container. Also, the electrodes were weighted before and after arc ignition to determine the amount of mass loss.

3. EXPERIMENTAL RESULTS

3.1 Examples of experimental waveforms

Examples of the measured waveforms are shown in Fig. 3 for I_{1st} = 8.7 kA (V_c = 20 kV) and L_g = 80 mm. In the diagram, the waveforms represent the arc current I [kA], arc voltage V [kV], arc energy E [kJ] and pressure rise at the top of the

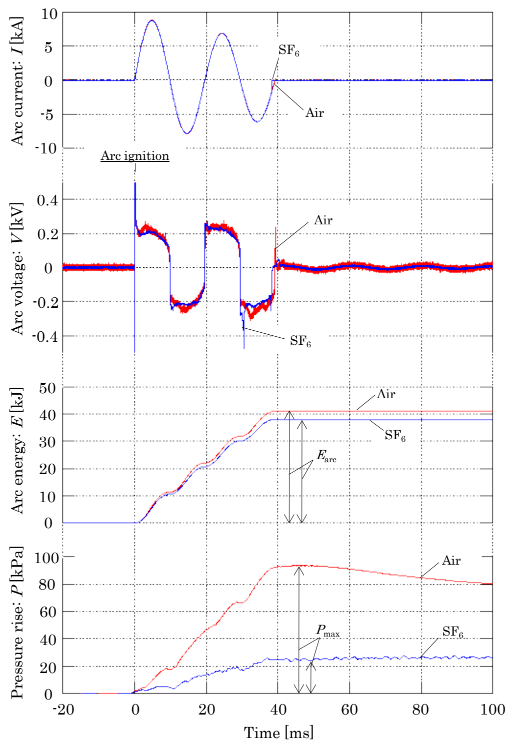

Fig. 3 Examples of measured waveforms
(I_{1st} = 8.7 kA (V_c = 20 kV), L_g = 80 mm)

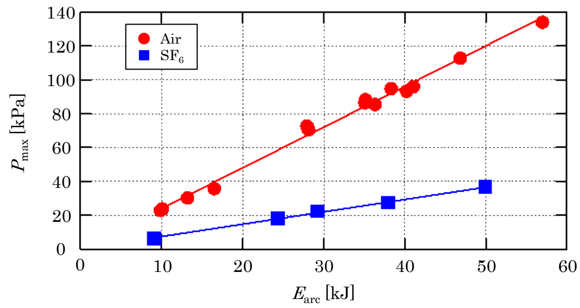

Fig. 4 Dependence of E_{arc} on P_{max} [4]

container P [kPa]. The arc energy was calculated as the time integral of the arc power, which was calculated as the product of I and V. The total arc energy E_{arc} and maximum pressure rise P_{max} were identified from these waveforms for each experiment. As can be seen from the figure, P increases from arc ignition to extinction in both gases in the experiments. The rate of increase of P and the value of P_{max} in air were higher than those in SF_6.

3.2 Characteristics of pressure rise

Fig. 4 shows a comparison of the relationship between P_{max} and E_{arc} in air and in SF_6. As shown in this figure, P_{max} tends to increase with E_{arc} for both gases, and the rate of increase depends on the gas. The value of P_{max}/E_{arc} is about 2.4 kPa/kJ in air and 0.7 kPa/kJ in SF_6. That is, at the same E_{arc}, the values of P_{max} for air and SF_6 were in the ratio of approximately 3:1 because of the specific heat of the gases.

3.3 Ratio of arc energy to energy contributing to internal pressure rise (k_p)

k_p is defined as follows:

$$E_{pre} = k_p \cdot E_{arc} \qquad (1)$$

Here E_{pre} is the energy contributing to the pressure rise in the container.

The relationship between k_p and E_{arc} is shown in Fig. 5. As shown in this figure, k_p lies in the range of 0.38 to 0.46 in air and 0.55 to 0.66 in SF_6. For the case of copper electrodes and the volume of the container used in this study, it was clarified that the value of k_p in air and SF_6 is almost independent of E_{arc}.

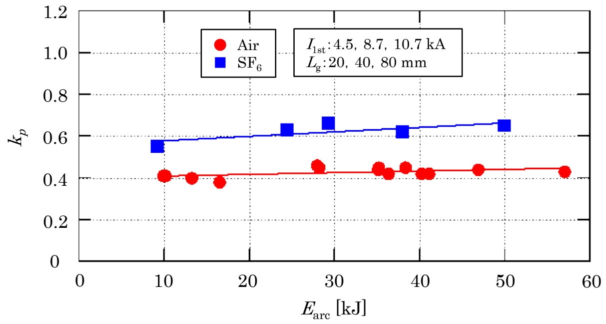

Fig. 5 k_p values for copper electrodes in air and SF_6

4. EVALUATION OF ENERGY BALANCE IN CONTAINER RESULTING FROM SF_6 ARCING

When considering the energy balance in a closed container resulting from SF_6 arcing, we focus on four comportments of the input energy (E_{in}): the arc energy (E_{arc}), the energies produced by fluoridation and oxidation reactions of the metal vapor (E_{flu}, E_{oxi}) and the energy produced by the decomposition reaction of SF_6 (E_{gas}). For the consumption energy (E_{cons}), we also consider four components: the energy contributing to the internal pressure rise (E_{pre}), the energies required for electrode melting and vaporization (E_m, E_v) and the radiation energy loss (E_{rad}). Assuming that the effect of other energy components, for example, the energy of heat conduction into the electrodes (E_{cond}), is negligible, the following equation can be written by virtue of the energy balance between the input energy and consumption energy.

$$E_{arc} + E_{flu} + E_{oxi} + E_{gas} = E_{pre} + E_m + E_v + E_{rad} \qquad (2)$$

Here we used the experimental results shown in Fig. 3.

4.1 Calculation of input energy

E_{arc} is defined as the time integral of the arc power, which was calculated as the product of I and V.

Assuming that entire vaporized part of the electrodes reacted and employing the energy produced by lowering temperature of the fluoridation and oxidation compounds from the boiling temperature of copper (2,843K) to 300 K, we calculated E_{flu} and E_{oxi} using the following equations.

$$E_{flu} = \frac{m_{flu} \cdot dH_{flu}}{M_i} + \frac{m_{flu} \cdot dH_{flu\_300K}}{M_{flu}} \qquad (3)$$

$$E_{oxi} = \frac{m_{oxi} \cdot dH_{oxi}}{M_i} + \frac{m_{oxi} \cdot dH_{oxi\_300K}}{M_{oxi}} \qquad (4)$$

Here, M_i is the atomic weight of copper, M_{flu} and M_{oxi} are the molecular weights of the fluoridation and oxidation compounds, m_{flu} and m_{oxi} are the weights of the fluoridation and oxidation compounds, which were determined by quantitative analysis of the scattered fine particles, dH_{flu} and dH_{oxi} are the energies produced by each chemical reaction at the boiling temperature of copper (2,843 K), and dH_{flu_300K} and dH_{oxi_300K} are the energies produced by lowering the temperature of these compounds, obtained using *HSC Chemistry* (*Ver.4.0*) commercial chemical reaction and equilibrium software, respectively.

Also, assuming that the main chemical energy is the energy produced by the decomposition reaction of SF_6 by the quantitative analysis of the decomposition gas, E_{gas} was calculated using the following equation.

$$E_{gas} = \frac{m_{gas} \cdot dH_{gas}}{M_{gas}} \qquad (5)$$

Here m_{gas}, determined by analysis of the gas composition after the experiments, and M_{gas} are the mass and molar weight of the decomposition gas of SF_6, respectively, and dH_{gas} is the energy produced by the decomposition of SF_6 at the boiling temperature of copper (2,843 K).

4.2 Calculation of consumption energy

E_{pre} was calculated using the following equations.

$$\frac{P_{in}}{T_{ini}} = \frac{P_{ini} + P_{max}}{T_{ave}} \qquad (6)$$

$$E_{pre} = m_{gas} \cdot \int_{T_{ini}}^{T_{ave}} C_{gas} \cdot dT \qquad (7)$$

Here P_{ini} is the initial pressure of the charged gas, T_{ini} is the initial temperature (assumed to be fixed at 300 K), T_{ave} is the average temperature in the container at the time when the pressure rise was P_{max}, m_{gas} is the mass of gas inside the container and C_{gas} is the specific heat at a constant volume of gas.

We calculated E_m and E_v as follows:

$$E_m = \frac{Q_m \cdot (m_r + m_{Cu})}{M_i} \qquad (8)$$

$$E_v = \frac{Q_v \cdot (m_t - m_{Cu})}{M_i} \qquad (9)$$

Here Q_m and Q_v are the energies used in increasing the temperature to melt the electrodes and for vaporization, respectively, m_r is the weight of the molten electrodes remaining at the tips of the electrodes. m_t is the total weight loss of two electrodes after the experiment and m_{Cu} is the weight of copper in the scattered fine particles.

E_{rad} was calculated using experimental results in the literature [5]. Firstly, we calculated the arc power per unit length [W/mm] and obtained the dependence of the radiation power (P_{rad}) on the arc current with considering the variability of measured value from the literature. Secondly, by using the arc current dependence of P_{rad} and the current obtained in our experiments, the time dependence of P_{rad} was obtained, taking differences in L_g into account. Finally, E_{rad} was calculated as the time integral of P_{rad} as follows:

$$E_{rad} = \int P_{rad} \cdot dt \qquad (10)$$

4.3 Results

Fig. 6 shows the energy balance in the container. E_{flu} and E_{gas} are shown with error bars because a chemical reaction (endothermic and exothermic reactions) is not a quantitative value so cannot be used in a ratio. As shown in this figure, good agreement with the energy balance was obtained. Also, E_{in} comprised the majority of E_{arc}. E_{gas} is negligibly small.

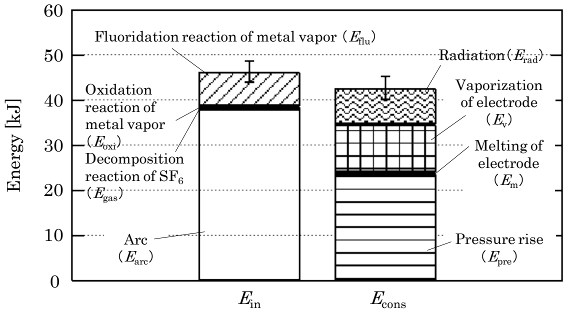

Fig. 6 Energy balance in the container

5. CONCLUSIONS

In this paper, we experimentally clarified the characteristics of the internal pressure rise due to air and SF_6 arcing and the value of k_p in a closed container. Furthermore, the energy balance in the container resulting from SF_6 arcing was estimated in detail taking into account the melting and vaporization of the electrodes, the chemical reactions and radiation. At the same arc energy, the maximum pressure rises for air and SF_6 were in the ratio of approximately 3:1. The k_p values in the experiments were in the range of 0.38 to 0.46 in air and 0.55 to 0.66 in SF_6. Subsequently, it was shown that good agreement with the energy balance was obtained under reasonable assumptions by taking account of the energy components related to the chemical reactions, radiation, and the melting and vaporization of the electrodes.

REFERENCES

[1] IEC Int. Standard 62271-200 Edition 2.0, (2011)

[2] R. P. P. Smeets et al., 20th International Conference on Electricity Distribution (CIRED), Paper 0392, 8-11 June (2009)

[3] J. Douchinet et al., 22nd International Conference on Electricity Distribution (CIRED), Paper 1301, 10-13 June (2013)

[4] M. Kotari et al.,The paper of Joint Technical Meeting on Electrical Discharge, Switching and Protecting and High Voltage Engineering, IEE Japan., ED-13-132, SP-13-055, HV-13-095, pp.151-155 (2013) (in Japanese)

[5] Y. Yokomizu et al., J. Phys. D: Appl. Phys. 41 125203 (2008)