FUSE WITH ABLATING WALL

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ABSTRACT

This paper deals with a study related to the process of short-circuit current interruption in low-voltage fuses which have no sand filling. In such fuses, quenching of the arc column within the fuse is aided by the material ablated from the wall of the fuse.

Experiments have been conducted using tubes of 4 and 6 mm internal diameter made of perspex, pvc and Teflon to measure the transient arc voltage and pressure within the tube after the explosion of the fuse wire for approximate step current pulses of upto 100 A. Fuses with ablative walls have also been tested in a short-circuit test circuit rated to provide 1500 A (prospective) from a 250-V, 50-Hz source.

An algorithm has been developed to solve numerically the time-dependent energy balance equation for the arc column taking into account the ablation of wall material and the consequent pressure rise inside an enclosed fuse. Calculated results agree favourably with the measured values.

The study suggests that the process of current interruption is dictated by the temperature distribution in the arc column immediately after the explosion of the fuse wire. It is found that ablative cooling can contribute significantly to the arc interruption process if the initial formation of the arc is in proximity to the ablating wall.

1. INTRODUCTION

This paper addresses a class of cartridge fuses, called "miniature fuses", which are normally used to protect a single apparatus, an instument or a part of an electrical equipment against fault currents. These fuses are used at a nominal voltage of 250 V and have typical outer dimensions of 5 mm in diameter and 20 mm in length. The present limit on the short-circuit current for these fuses is 1.5 kA which is likely to increase in future. Present dimensions, interruption ratings and test recommendations are covered by IEC Publication 127 [1].

These small fuses consist of a thin metallic wire of tinned copper, silver or nickel stretched inside a tube made of glass, ceramic or suitable plastic. End connections to the fuse wire inside the tube are provided by means of two metallic end caps, which make the fuse a totally-enclosed protective device. When the demand on the interrupting capacity of these fuses is as high as 1.5 kA, the tube is also filled with fine-grain sand to absorb the energy liberated and the pressure developed during the arcing process associated with the interruption of fault current. The requirement of sand filling inside the tube introduces problems in their manufacture thus increasing the manufacturing cost.

One way to avoid the necessity of sand filling inside the fuse is to make the tube of the fuse out of a suitable plastic material with somewhat reduced inner diameter [2]. The polymer used to make the tube should then meet the following two important requirements: (i) it should have sufficient mechanical strength to withstand the high pressure generated within the tube; and (ii) the vapour ablated from the inner wall of the tube as a result of arcing inside the tube should have have good "arc quenching" properties, comparable with those of sand filling. As fuses of this type rely upon the process of ablation of wall material for current interruption, such fuses can be called "ablation-dominated" fuses. In order to obtain quantitative guide lines for the design of ablation-dominated fuses over a range of currents, it is essential to understand the mechanism of current interruption in the fuse and to be able to estimate the presure rise inside the fuse. Unfortunately, there appears to be little published literature on the behaviour of ablation-dominated fuses. Although there exist a few publications [3-5] on the behaviour of ablation-dominated arcs, these are not directly relevant in the context of fuse behaviour because these publications refer to arcing at very high current densities in tubes with open ends, which allow the plasma in the tube to escape thus reducing the pressure inside the tube.

This paper investigates the process of arcing in an enclosed tube with ablating wall with a view to obtain quantitative estimates of the pressure and voltage of an ablation dominated fuse. Experimental results of the transient pressure and voltage are presented for tubes made of perspex, pvc and Teflon. An attempt is made to develop a quantitative understanding of the fuse behaviour on the basis of a theoretical model derived from physical principles.

2. EXPERIMENTS

The process of arcing in a totally enclosed tube is inherently non-stationary in character because even for a steady arc current, continued wall ablation results in ever increasing pressure inside the tube until a mechanical failure occurs. During the interruption of a short-circuit current, the arc current changes from a high value to zero which introduces additional non-stationary characteristics to the problem of short-circuit current interruption by a fuse and hence increases the complexity in identifying the influence of ablative cooling. Most of the experiments have therefore been conducted [6] using approximate step current pulses which eliminate the non-stationary nature arising from variations in current. A few experiments have also been conducted on fuses with ablating walls in a short-circuit test scheme based on IEC recommendations.

2.1. TESTS WITH CURRENT STEPS

2.1.1. APPARATUS

Experiments were conducted on simulated fuses (Figure 1) using tubes of internal diameters 4 and 6 mm, and 50 mm long. These tubes were made from perspex, pvc and Teflon and had an outer diameter of 12 mm to provide a thick wall to withstand the pressure generated during arcing. Two brass end caps fitted with O-rings were fitted to the end of the tube and were held tight to prevent the leakage of plasma from the tube. The brass end caps also served as electrodes to sustain the arc within the tube. The arc was initiated by stretching a copper wire of 72.5 microns across the brass end caps. The fuse was loaded inside a polycarbonate holder (Figure 1) which held the fuse in position and also allowed the provision of the required pressure on the brass end caps of the fuse.

The pressure inside the tube was measured by drilling a hole of 1 mm diameter on its side which was aligned with a 3 mm hole on the polycarbonate holder. The 3 mm hole was terminated with a Kistler piezo-electric pressure transducer rated for linear operation upto 100 bars. An O-ring seal was provided at the junction between the holes in the fuse and the fuse holder to prevent plasma leakage. The hole linking the pressure transducer to the fuse was filled with glycerin to improve the frequency response of the pressure measuring system and also to prevent arc products coming into contact with the pressure transducer. The charge developed by the pressure transducer was measured using a charge amplifier calibrated in bars with a bandwidth of 10 kHz.

The arc current for tests using current steps was obtained from a capacitor discharge circuit. The discharge circuit, which had been designed to provide 50 or 70 Hz current circuit, was modified to operate in an overdamped mode by inserting a series resistor. The test circuit provided quasi steady arc current pulses for times upto 10 ms when the fuse was replaced by a short circuit. The presence of the fuse, however, distorted the current waveform, but this distortion was small to affect gross arc properties. In order to prevent a mechanical failure of the arc chamber, the circuit current was diverted away from the arc chamber by triggering a spark gap at the end of nearly 3 ms after the initiation of the arc. The arc current was measured using a 5-milliohm co-axial shunt with a response time of 50 ns. The arc voltage was measured using Tektronix P6015 high-voltage probes.

2.1.2. RESULTS

Typical records of current, voltage and pressure obtained druing tests are shown in Figure 2. It can be seen that immediately after the explosion of the fuse wire, the arc voltage rises sharply to high values and then falls before a further steady and slow increase. The pressure in the simulated fuse increases almost linearly with time while the arc current remains approximately constant. It can also be seen from Figure 2 that the pressure developed in a 4 mm tube is much larger than the pressure in a 6 mm tube.

A comparison of the voltage and pressure obtained with tubes made from perspex, pvc and Teflon having the same internal diameter is made in Figure 3, which shows that for a given arc current, perspex gives the largest voltage and pressure while Teflon gives the lowest values. Results for the rate change of pressure with current for arc currents upto 100 A have also been obtained for the three materials considered.

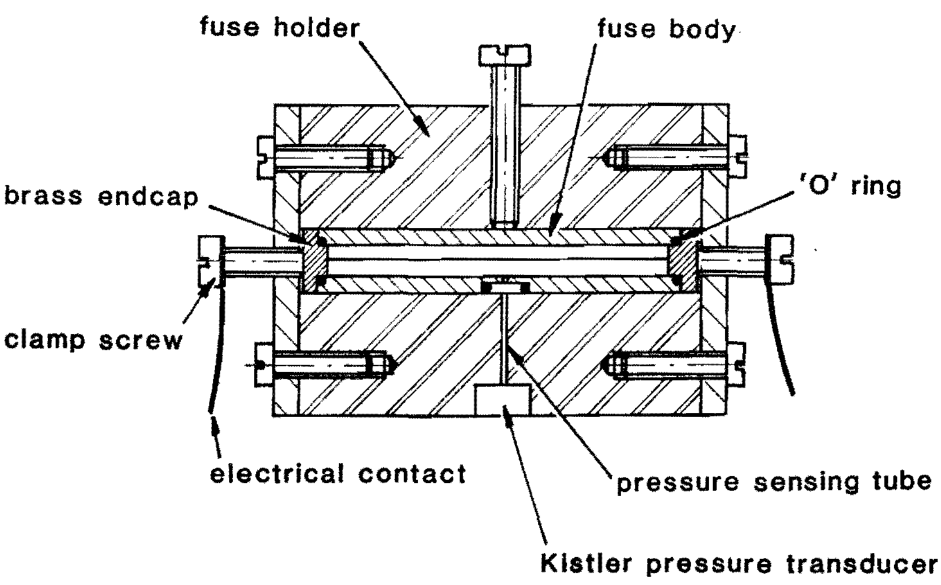

Figure 1 Experimental set-up for fuse studies.

2.2. SHORT-CIRCUIT TESTS

Experiments were also conducted using fuses of standard dimensions in a test circuit built on IEC recommendations [1] to deliver a prospective rms short-circuit current of 1500 A. Although the recommendation of the IEC on the closing angle for initiation of the circuit current relative to the source voltage is in the range of 25 to 35 degrees, the closing angle in the tests was varied from 10 to 45 degrees to investigate the severity of interruption duty.

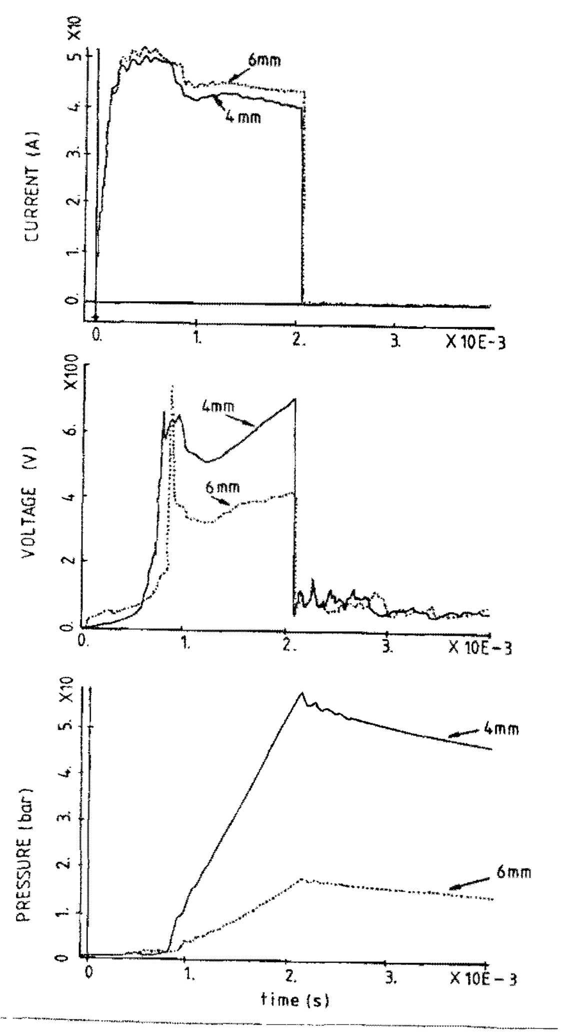

Figure 2 Experimental records showing influence of tube diameter on arc properties. PVC tube and 72.5 microns copper wire.

A typical record of the current and voltage recorded during a test on a fuse of internal diameter of 3 mm with a copper wire of 100 microns is shown in Figure 4. It was found that at a closing angle of 29 degrees, the interruption appeared to be critical. For example, the fuse made out of pvc developed a small hole on one of the end caps although the circuit current was interrupted. Fuses made out of other material showed a small dimple on their end caps which might have resulted in the development of a hole. When the closing angle was increased to 45 degrees, all the fuses failed. In the case of perspex and pvc fuses, the end caps were damaged as a result of arcing and the development of high pressure during arcing. The fuse made out of Teflon was found to explode during the test.

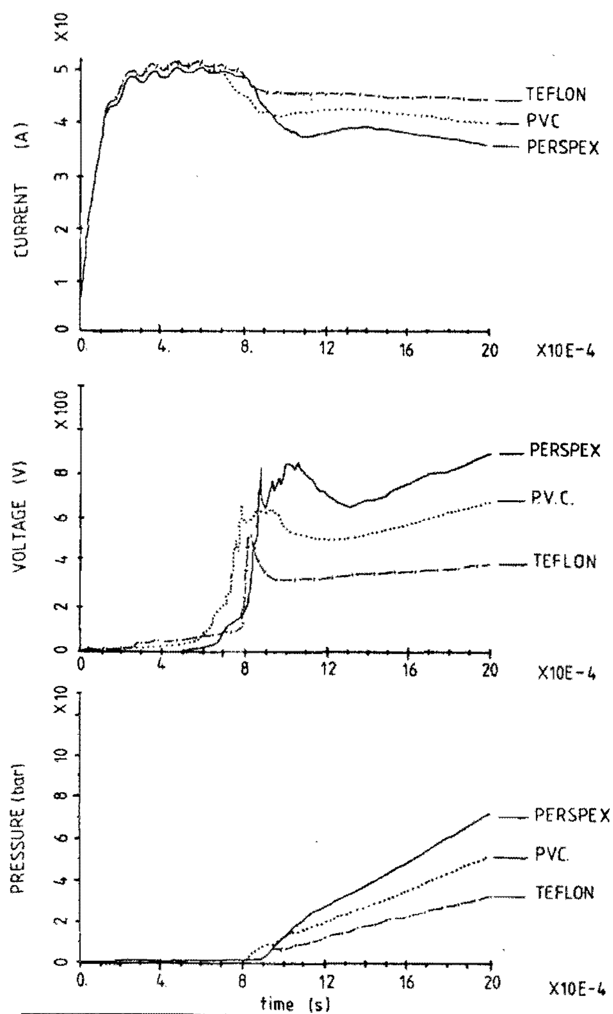

Figure 3 Influence of tube material on arc properties. 4-mm tube and 72.5 microns copper wire.

The tests showed that when the fuses cleared the fault currrent, the current records differed only slightly for the three tube materials. When a failure occurred, it was mainly due to a mechanical failure resulting from arcing at the end caps and high pressure inside the fuse. It was also found from tests with different closing angles that if the cut-off current for a particular closing angle was high due to a high initial rate of rise of current, then the fuse failed to clear the fault. This result shows that the cut-off current or the current at which the fuse wire melts and vapourises has a significant bearing on the arc interruption; the higher the cut-off current the more severe is the short-circuit duty.

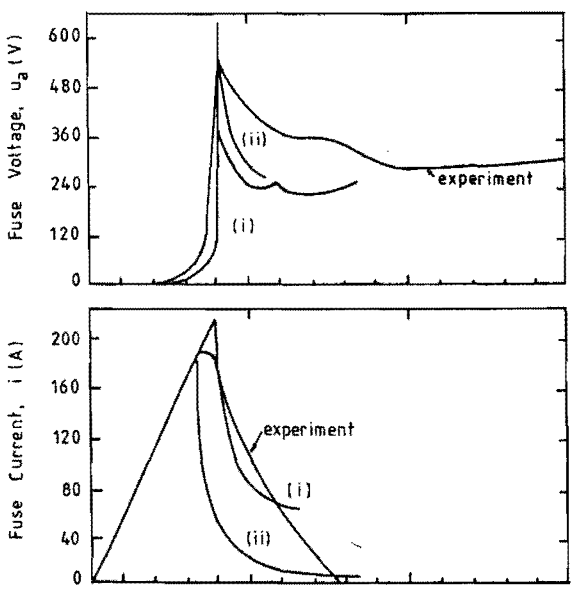

Figure 4 Short-circuit current interruption by a perspex fuse of 3 mm diameter and 20 mm long. Curves (i) and (ii) correspond to theoretical predictions.

3. ARC MODEL

In a fuse of the type shown in Figure 1, when a high current is passed, the fuse wire melts, explodes and an arc column is established within the tube across the end caps. The flow of current through the plasma results in joule heating within the arc plasma which is transported thermal conduction and also by radiation if the temperature of the plasma is sufficiently high. The wall material consequently ablates and gets entrained into the arc column. As the fuse is a totally enclosed tube, the pressure inside the tube increases owing to the addition of wall material as well as the joule heating which raises the plasma temperature. The entrainment of wall material results in a thermal convection directed from the wall to the inner regions of the tube and this thermal convection may be viewed as the energy required to elevate the vapour ablated from the wall to the temperature of the plasma. Thus, ablative cooling of the arc column results.

A detailed modelling of this type of arc should consider all three conservation equations, viz. mass, momentum and energy. As this is extremely difficult, in this study it is assumed that the mass liberated from the wall of tube has negligible inertia and hence distributes itself within the arc column instantaneously. This assumption is equivalent to assuming that the pressure in the radial direction at any instant of time is uniform which allows one to discard the momentum equation.

Further, as the tube is cylindrical in shape, it is assumed that axial variations in plasma properties are negligible. Thus we seek solutions of plasma properties in the radial direction only.

It is to be noted that at the instant the fuse wire explodes, the plasma is made up of the carrier gas, which is a mixture of metal vapour and air. As time progresses, the addition of wall material changes the composition of the plasma in the tube and the ratio of the mass of carrier gas to that of wall gas is a time-dependent function. Calculation of thermodynamic and transport properties of mixtures of gases at different temperatures and pressures is by no means simple. Hence, in this study, only variations in density and heat capacity as a function of gas-mixture ratio are considered at an approximate level. These two material properties contribute considerably towards thermal convective cooling and pressure rise inside the tube.

3.1. ENERGY BALANCE EQUATION

Assuming that the temperature T of the arc column within the tube varies only along the the radial coordinate r because of cylindrical symmetry, the energy balance equation [7] for the arc column can be written as

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p v \frac{\partial T}{\partial r} =$$

$$\sigma E^2 + \frac{1}{r}\frac{\partial}{\partial r}\left[r\kappa \frac{\partial T}{\partial r}\right] - u \qquad (1)$$

where E is the axial electric field in the arc column, v the velocity of the plasma in the radial direction induced by the ablation process and t the time. The material functions of the arc plasma are: ρ the density, c_p the heat capacity, σ the electrical conductivity, κ the thermal conductivity and u the net radiation emission from unit volume. The material functions of the plasma are dependent upon temperature, pressure and plasma composition.

The energy balance equation (1) can be interpreted in simple terms as follows: a fraction of the joule heating resulting from the electical power input into the arc column is transported to wall of the tube by thermal conduction; another fraction is transported as radiation; and yet another fraction is expended in heating the ablated wall material to plasma temperature. The remaining power is used up in raising the plasma temperature, as given by the thermal storage $\rho c_p(\partial T/\partial t)$

In order to solve equation (1) two boundary conditions for temperature are required. One of the two boundary conditions is that the heat flux at the axis of a cylindrical arc column is zero. The second boundary condition is determined by the ablation process at the wall. As the wall is continuously ablating during arcing, the temperature at the wall can be taken to be equal to the vapourising temperature of the ablating material [4].

3.2. RATE OF MASS ABLATION

The rate at which the wall material is ablated and entrained into the arc is determined by the rate at which energy is received by the wall from the arc column and the energy required for the wall material to vapourise. If q is the rate at which unit length of wall receives energy in W/m, h_w the energy required to ablate unit mass of wall material in J/kg and $\dot{m}$ the rate at which mass is liberated from unit length of the wall in kg/m s, then

$$q = \dot{m} h_w \qquad (2)$$

The wall of the tube at a radius of r_w receives energy from the arc by means of thermal conduction and transparent radiation. Hence,

$$q = -2\pi r\kappa \left[\frac{\partial T}{\partial r}\right]_{r=r_w} + \int_0^{r_w} u \; 2\pi r dr \qquad (3)$$

and can be estimated using the temperature profile in the arc column.

The value of h_w, which is the energy required to ablate the wall material, is not known accurately. Niemeyer [3] has shown that for both polymer and ceramic materials, the value of h_w lies in the range of 0.3 10^7 to 10^7 J/kg for vapour temperatures in the range of 1000 to 5000 K. Kovitya and Lowke [4] used a value of 0.65 10^7 for their studies on ablation dominated arcs and this value has been used in this study.

3.3. CALCULATION OF PRESSURE RISE

The procedure to calculate the pressure inside the tube at any instant of time should consider pressure changes due to mass addition as a result of wall ablation as well as those due to changes in plasma temperature. The pressure changes due to both these factors can be estimated from the mass conservation equation, which is given by

$$\frac{\partial \rho}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}\left\{r\rho v\right\} = 0 \qquad (4)$$

In order to use this equation to estimate the pressure rise, we need to know the dependence of density of the plasma on pressure,temperature and plasma composition, which changes with time. For the sake of simplicity, we assume that the density of the plasma in the tube is proportional to pressure. That is, if $\rho_0(T)$ is the functional dependence of plasma density on temperature at a reference pressure of p_0, which is taken as one bar, then the density function at any other pressure p is taken as

$$\rho(p,T) = \left[\frac{p}{p_0}\right]\rho_0(T) \qquad (5)$$

Multiplying the mass conservation equation (4) by $2\pi r dr$ and integrating from $r=0$ to $r=r_w$, we get

$$\int_0^{r_w} \frac{\partial \rho}{\partial t} 2\pi r dr = -2\pi r_w \ (\rho v)_{\ r=r_w} \qquad (6)$$

The right-hand side of the above equation (6) is equal to the rate at which mass is crossing the boundary at $r=r_w$ at any instant of time and hence should be equal to the rate of mass liberation from the wall which is given by equation (2). Thus, we have

$$\dot{m} = \int_0^{r_w} \frac{\partial \rho}{\partial t} 2\pi r dr \qquad (7)$$

If the densities of the carrier and wall gas are equal, then equation (7) can be used together with equation (5) to get an expression [8], which gives the rate of change of pressure with time as a result of mass addition as well as temperature changes. However, it is very unlikely that the mass density of the wall gas will be the same as that of the carrier gas. As it is difficult to estimate the gas density of a complex gas mixture, we use an approximate averaging procedure to calculate the density of the composite plasma consisting of both carrier and wall gases.

We define the density function ρ_0 of the composite plasma at the reference pressure of p_0 of 1 bar as follows:

$$\rho_0(T) = \frac{\rho_c(T) + \ x \ \rho_w(T)}{1 + x} \qquad (8)$$

where $\rho_c(T)$ and $\rho_w(T)$ are the density functions of the carrier and wall gases respectively and x is a ratio which depends upon the relative masses of the gases at any instant of time. The value of the ratio x at any instant of time is evaluated by forcing mass conservation for the two species individually. That is, if m_c and m_w are respectively the masses of carrier and wall gases per unit length of the plasma column at time t, then we require:

$$m_c = \frac{p}{p_0} \int_0^{r_w} \left[\frac{\rho_c(T)}{1 + x}\right] 2\pi r dr \qquad (9)$$

$$m_w = \frac{p}{p_0} \int_0^{r_w} \left[\frac{x \rho_w(T)}{1 + x}\right] 2\pi r dr \qquad (10)$$

$$m = m_c + m_w = \frac{p}{p_0} \int_0^{r_w} \rho_0(T) 2\pi r dr \qquad (11)$$

Knowing the temperature profile in the plasma at time t and also the masses of carrier and wall gases at the same instant, the value of x can be calculated.

The pressure within the tube at any instant of time can be calculated by integrating equation (7) and using the total mass conservation equation (11). The expression given below gives the pressure at time t:

$$p = \frac{m \ p_0}{\int_0^{r_w} \left[\frac{\rho_c(T) + x \rho_w(T)}{1 + x}\right] 2\pi r dr} \qquad (12)$$

3.4. CONVECTIVE COOLING

The entrainment of the ablated wall material into the arc column results in a a radial convection directed from the wall to the axis of the tube. This convection results in a cooling of the outer regions of the arc column and heating the inner regions. Or, it can be viewed as the energy absorbed by the wall gas in being raised from the value of temperature at the wall to the plasma temperature. Assuming that the pressure across the tube to be uniform, the value of ρv at different radial positions can be calculated from the mass conservation equation (4). Integrating equation (4), we get

$$(\rho v)_{r=r'} = -\frac{1}{r'}\frac{\partial}{\partial t}\int_0^{r'} \rho r dr \tag{13}$$

For $r'=r_w$, the above integral reduces to equations (6) and (7).

3.5. JOULE HEATING

The local joule heating of the plasma is given by term σE^2 in the energy balance equation (1) and is determined by the electrical power input into the plasma from the external test circuit. The current, i, through the arc column is related to the electric field through Ohm's law, which is

$$E = \frac{i}{\int_0^{r_w} \sigma 2\pi r dr} \tag{14}$$

As the tube is cylindrical, the electric field can be assumed to be uniform axially and hence the voltage seen by the test circuit for a given current can be obtained by multiplying the electric field by the length of the tube.

3.6. MATERIAL FUNCTIONS

The carrier gas is made up of metal vapour from the fuse wire and air. If the fuse wire made of copper, for a 100 microns diameter wire in a 3.2 mm tube, the mass ratio of copper to air is nearly 8. The values of density, heat capacity, thermal conductivity and electrical conductivity for approximately this mass ratio have been taken from the publication of Shayler and Fang [9].

It is assumed that the transport properties, viz. thermal and electrical conductivities for the composite plasma, are assumed to be the same as those for the carrier gas.

It can be seen from the energy balance equation (1) that the most dominant influence of ablation results from thermal convection which is determined by the density and heat capacity of the composite plasma. The density of the composite plasma is determined by the averaging method given by equation (8). The heat capacity of the of the composite plasma is estimated by summing over the two component gases [9], the product of heat capacity and mass fraction of the two components. That is, the heat capacity c_p of the composite plasma is given by

$$c_p = \left[\frac{\rho_c}{\rho_0(1+x)}\right] c_{pc} + \left[\frac{x\rho_w}{\rho_0(1+x)}\right] c_{pw} \tag{15}$$

where c_{pc} and c_{pw} are the heat capacities of carrier and wall gases respectively.

The values of mass density and heat capacity of wall gases of perspex, pvc and Teflon have been taken from the publication of Kovitya [10].

The values of net emission coefficient u of the composite plasma are taken to be equal to those of nitrogen plasma [11] for temperature above 12000 K. However, calculations showed that if the arc temperature was as high as 12000 K for radiation losses to be dominant then the fuse would not interrupt the current at all.

3.7. NUMERICAL METHOD

An explicit scheme using finite differences was used to solve the energy balance equation (1). The numerical algorithm is basically an integration procedure in time with which we march forward in time to seek solutions of temperature distribution as a function of time, starting from a set of initial conditions. The set of initial conditions correspond to the time when the fuse wire within the tube explodes to establish an arc column. At this instant, we need to specify the pressure p, the mass of carrier gas m_c, the current i and the temperature distribution in the arc column. The mass of carrier gas at the initial instant was taken to be equal to the sum of the masses of the copper wire and the surrounding gas. The value of the initial pressure was determined from the mass of the carrier gas and the initial temperature distribution. The choice of a suitable initial temperature profile is discussed in the next section.

4. RESULTS AND DISCUSSION

Calculations have been made using the arc model to predict properties of arcs corresponding to the experimental conditions for both step-current tests and short-circuit tests. The calculation procedure relies upon specifying the correct initial conditions for the problem. The important initial conditions are the current at which the fuse wire explodes and the temperature distribution within the arc column immediately after the explosion of the fuse wire. The current at which the fuse wire explodes is determined by the I^2t value for melting of the fuse wire and in the case of step current tests, the value of the current and time which the explosion of the fuse wire takes place is not critical. However, in a short-circuit test, the dynamic interaction of the fuse with the test circuit produces certain inaccuracies in the determination of the current and time. Hence, for short-circuit test calculations, the cut-off current obtained in the experiment was used as the initial condition.

4.1. INITIAL TEMPERATURE PROFILE

The temperature profile of the plasma immediately after the explosion of the fuse wire is not known. Preliminary investigations [12] using high-speed framing photography at 35000 frames/second show that the initial location of the arc column within the tube is somewhat random and very often the arc resides in the form of a core near the wall of the tube. A treatment of this type of arc behaviour requires a two-dimensional treatment in both radial and azimuthal co-ordinates and hence is difficult. The arc model considered in this study assumes azimuthal symmetry as a first-order approximation and to be consistent with this assumption, we have chosen two forms of initial temperature profiles: (i) Elevated core : the arc is assumed to have a very thin core near the axis of the tube and (ii) Elevated wall : the arc is assumed to be an annulas near wall of the tube; this elevated temperature near the wall gives a larger value of electrical conductivity near the wall and can also be viewed as an enhancement of electrical conductivity near the wall of the tube owing to the the presence of copper vapour near the wall.

4.2. ARC BEHAVIOUR FOR STEP CURRENTS

Typical results of current, voltage and pressure obtained using the arc model for a 50 A arc burning in a 4-mm Teflon tube with a 72.5-microns copper wire are compared with the experimental results in Figure 5. In the case of the assumption of elevated core temperature as the initial condition, the calculations show that the temperature at the axis increases initially very rapidly to accommodate the imposed steady current, which produces intense joule heating within the core of the arc column. The temperature at the axis then begins to drop as a result of radiation from the core, but the arc column broadens as time progreses. The broadening of the temperature profile within the tube results in an increase of the conductance of the arc column with a consequent drop in the voltage as shown by Figure 5. The rate at which the broadening of the arc column decreases as time progresses because the ablated mass from the wall not only cools the outer regions of the arc column but also increases the mass and hence the thermal inertial of the arc column. The arc voltage drops significantly initially, but this drop tends to flatten after nearly 0.4 ms as shown by the figure. In the case of the assumption of elevated core, most of the heat received by the wall is due to transparent radiation and hence the rate of mass ablation from the wall is small. Consequently, the calculated pressure rise is smaller than the values determined experimentally. Further, calculations using this initial temperature profile for short-circuit current interruption predict unsuccessful interruption for experiments corresponding to successful interruption. It is therefore concluded that this type of temperature profile is a very unlikely consequence of the explosion of the fuse wire.

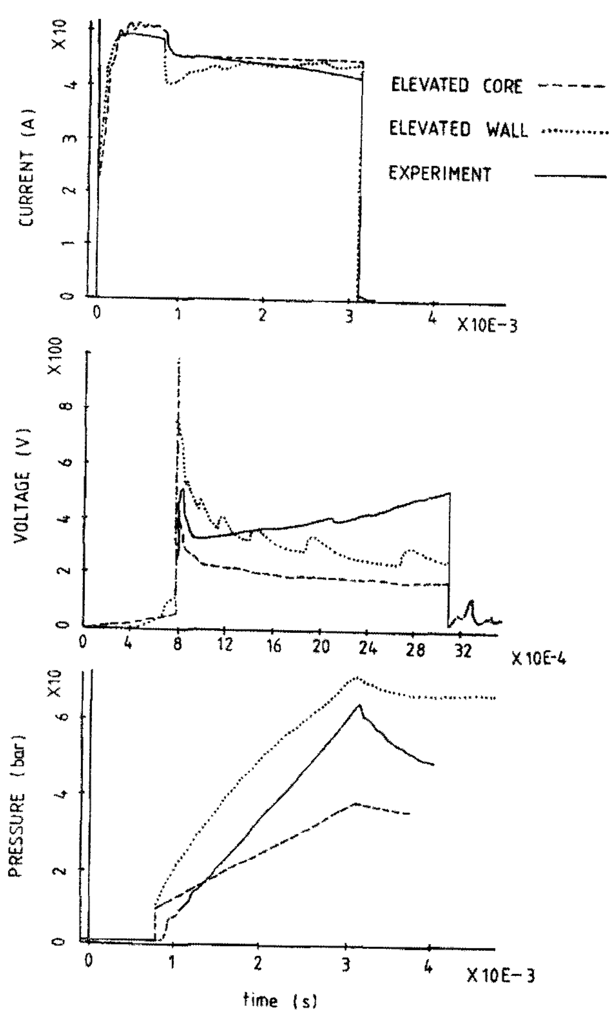

Figure 5 Comparison of experimental and theoretical results obtained for an arc in a 4-mm Teflon tube initiated by a 72.5 microns copper wire.

If joule heating is present near the abalting wall, then very effective cooling of the arc column can take place until heat diffuses to the inner regions of the tube. Calculations based on the initial condition of elevated wall temperature show that entrainment of ablated wall material is larger in this case than in the case of elevated core temperature profile. The results for the elevated wall case compare more favourably with the experimental results as shown in Figure 5. There is however an overestimation of the pressure in the tube because of the assumption that the arc is an annular ring near the wall of the tube which results in an overestimation of the mass ablated from the wall; in practice the heated zone might be more localised than what has been assumed.

The rate of increase of pressure in the tube with time for step currents of different magnitudes is shown in Figure 6. It can be seen that the calculated results agree reasonably with the experimental values for three tube materials considered. Experimental values of (dp/dt) for the 6-mm Teflon tube are much lower than the predicted results. The reason for this discrepancy may be due to the abalting characteristics of Teflon which exhibits highly localised vapourisation resulting in craters instead of uniform ablation over the surface when exposed to electric arcs.

4.3. FUSE BEHAVIOUR UNDER SHORT-CIRCUIT TESTS

In order to predict the behaviour fuses under short-circuit test conditions, the arc model was linked with the equations describing the test circuit bassed on IEC recommendations [8]. Calculated results of current and voltage as a function of time are compared with the experimental results for a fuse made of perspex tube of inner diameter of 3 mm and having a fuse wire of 100 microns in diameter (Figure 4). Case (i) in Figure 4 corresponds to the case where the cut-off current is estimated from the I^2t value for melting for the fuse wire. As the cut-off current in this case is higher than the experimental value, the arc model predicts intense heating of the arc column immediately after the explosion of the fuse wire followed by a failure of the fuse to interrupt the current. In case (ii), we have used the cut-off current obtained in the experiment for calculations, which show that successful interruption is possible. These calculations show that the current at which the fuse wire melts has a significant bearing on the interruption of current by the fuse in the test circuit.

Results were also obtained for current interruption by a pespex fuse with a copper wire of 100 microns in diameter at a closing angle of 10 degees of the test circuit. In this case, as the inital rate of rise of current is lower than the value at a closing angle of 29 degees, the cut-off current is lower and hence a successful interruption is predicted by the arc model. These results confirm our experimental results that while the fuse cleared the fault current at a closing angle of 9.4 degrees, it failed to clear the fault current at 45 degrees.

Calculated results of current, voltage and pressure for fuses made of 3-mm diameter, 20-mm long perspex tubes with fuse wires of different diameter are shown in Figure 8. The values of cut-off current for these calculations have been estimated on the basis of I^2t values. It can be seen that the interruption of current gets more critical as the diameter of the wire is increased.

4.4. DISCUSSION

Results obtained from experiments and theoretical calculations show that for step currents, perspex gives the largest pressure and voltage for a given magnitude of the current while Teflon gives the smallest values. The reason for this can be attributed to the fact that perspex vapour has a lower value of mass density and a higher value of heat capacity. The addition into the tube of a wall gas which has a lower mass density reduces the density of the composite plasma inside the tube and hence results in an increased pressure for a given amount of gas within the tube. If the heat capacity of the wall gas is larger then larger amount of heat is absorbed by the wall gas from the arc column thereby reducing the plasma temperature. A reduction in plasma temperature results in a reduction in the conductance of the arc column and hence an increase in the arc voltage.

This study shows that although ablative cooling of the arc column in fuses can be used to aid current interruption, prolonged arcing in the presence of wall ablation results in an increased mass inside the fuse which can have the two following detrimental effects : (i) the pressure inside the tube increases to very high values and can cause a mechanical failure and (ii) the increased mass inside the fuse increases the thermal inertia of the arc column and hence the plasma cools much more slowly than when no wall ablation is present.

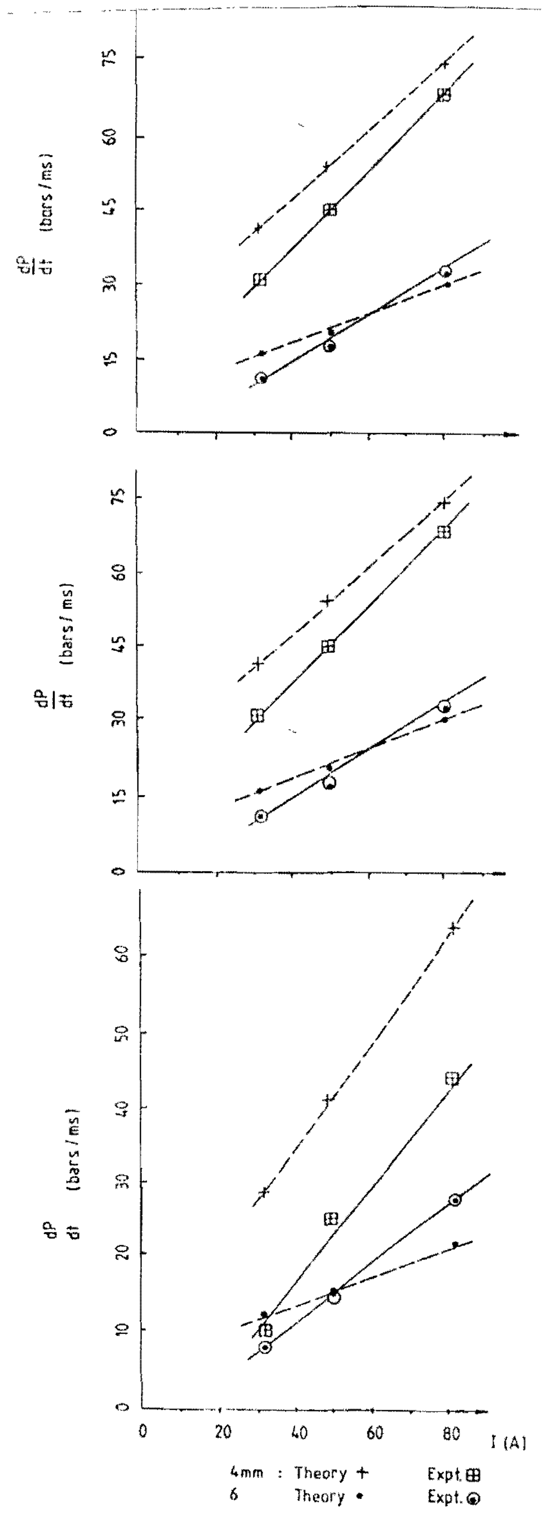

Figure 6 Dependence of rate of increase of pressure with time on arc current. Top: perspex, middle: pvc and bottom: Teflon.

This study also reveals that the current at which the fuse wire explodes has an imporatant bearing on current interruption. Immediately after the explosion of the fuse wire, most of the joule heating is balanced by wall ablation. For a tube of radius r_w, the joule heating is proportional to $(1/r_w^2)$ or is a volume effect whereas ablative cooling is a surface effect which is proportional to r_w. Consequently, a large initial current increases the plasma temperature considerably. Since ablative coling is dominant only near the outer periphery of the arc column, if considerable heating of the inner region the arc column is caused by a large initial current, the interruption of fault current will not result.

We have assumed in this study that the temperature profile inside the arc column immediately after the explosion of the fuse wire is one that offers enhanced conductivity near the ablating wall of the fuse so that most of the joule heating occurs near the wall initially. It is necessary to investigate the initial period of arc development within the fuse to improve our arc model.

5. CONCLUSION

A numerical model has been developed to study the behaviuor of arcs in enclosed tubes and the process of current interruption in small fuses whose wall ablates as a consequence of arcing within the fuse. Results of current, voltage and pressure within the fuse obtained using the model are in approximate agreement with experimental results.

One of the main difficulties of the model stems from the lack of knowledge of the temperature profile inside the arc column immediately after the explosion of the fuse wire. It is found from a comparison of the calculated results with experiments that most of the joule heating should occur near the ablating the wall of the fuse.

In order to produce strong ablative cooling of the arc column during a current interruption process, it is essential that the surface area of the arc column is large and that the arc column lies close to the ablating surface.

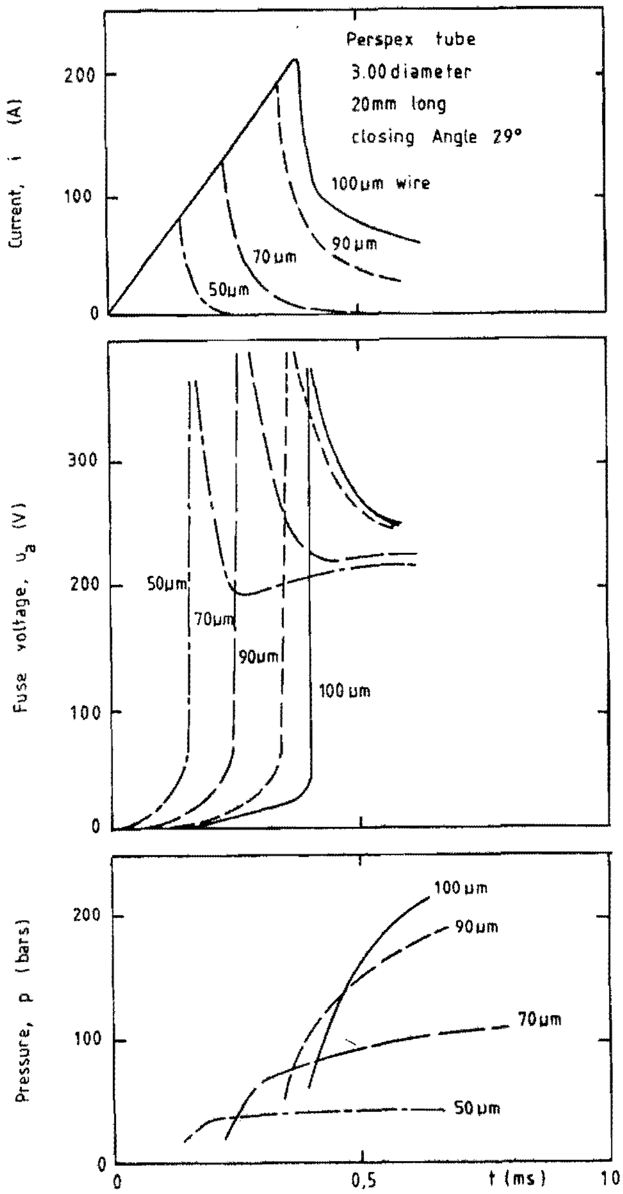

Figure 7 Theoretical predictions of interruption behaviour of a fuse with ablating wall.

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