SOME COMMON PERFORMANCE CHARACTERISTICS OF GAS-BLAST INTERRUPTERS AND POWER EXPULSION FUSES.

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Abstract: **In this paper are described some common performance similarities of the medium voltage power expulsion fuses and gas-blast circuit breakers. Also is presented a short review of their mechanical operating characteristics paying attention to the movement of contacts and arcing electrodes in both type of devices. And their interaction with the power electric system. Finally is presented a shallow review through the time of the developments made by different researchers, adding a little more emphasis on the so-called conservation equations; the field of their scope and the improvements on the applied mathematics, for instance the change from ordinary to partial differential equations which are more adequated when studying the transient period after current zero on circuit breakers mainly.**

Keywords: **Arc plasma, nozzle, throat, clogging, ablation process, downstream region, upstream region, local thermodynamic equilibrium, self-pressure device, gas-blast device, stagnation pressure.**

1. Introduction.

After melting the fuse wire in an expulsion fuse or after the contacts separation in a gas-blast circuit breaker, an electric arc appears. In power fuses the moving arcing rod or the moving arcing contact in self-pressurizing circuit breakers, both are enclosed within a chamber of insulating material which surface is partially vaporized by the ohmic heat input creating an overpressure inside the chamber that leads to an expansion flow through the open end in fuses or in the downstream region in circuit breakers, this pressure gradient act as momentum source and accelerates the flow of the arc plasma [1] and the surrounding vapor toward the outlet of fuses. Often that flow reach the choking points when it becomes supersonic in the above mentioned outlet in fuses or at the throat of nozzles of gas-blast interrupters.

The pattern of the plasma flow is very similar in gas blast circuit breakers in which the pressure gradient is externally imposed by a nozzle flow in the

gas blast arc, but in both cases the basic physical process is essentially the same.

When high magnitude currents are applied the arc diameter approaches that of the wall confining the arc and burns in a high pressure plasma formed by ablation of wall material [1] building up a strong axial flow of gas and hot plasma. The venting of the ablated vapors through the outlet can be choked as mentioned before, producing very high transient pressure [2] at the closed end of the chamber.

In order to illustrate the basic structure of a gas flow arc in both type of interrupting devices in the figure 1 is presented a single -flow arcing configuration for a circuit breaker: this structure consists of a plasma column consisting of hot gases species or may be contaminated by evaporated electrode material through which almost all current flows. A surrounding mantle of heated gas below that at which significant electrical conduction occurs, and an outer confining flow of gas whose properties are governed by aerodynamics considerations [3].
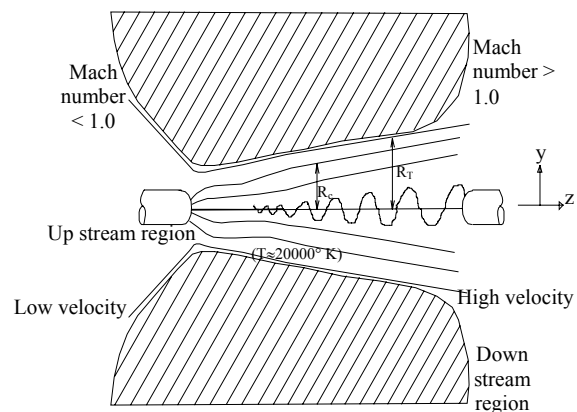

Fig. 1: Basic structure of a gas flow arc in the nozzle of a single-flow circuit breaker.

The interaction of the arc with the electric system when are applied current and voltage waveforms are very important for that devices. In the figure 2 is represented the discharge of a half sinusoid current pulse followed by the rise of recovery voltage across the gap after the current zero value.
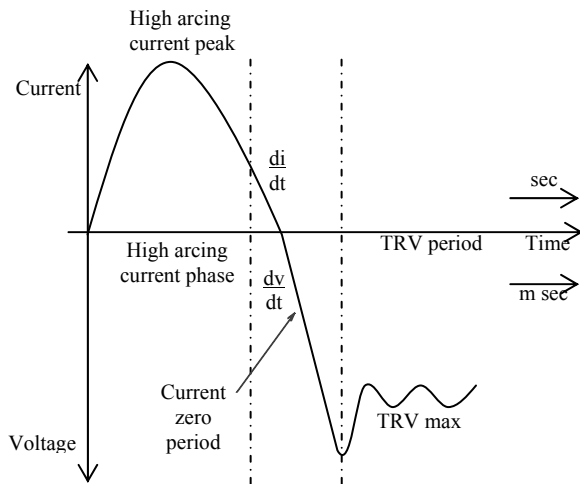
Fig. 2: Conditions of the electrical system.

The electrical energy is transformed in the arc and is dissipated as a stream of hot plasma and gas leaving in the open end of fuses or is the downstream region in circuit breakers. The production of vapor can be adjusted to the requirements choosing suitably: the geometry, dimensions and materials. In the figure 3 is shown a schematic representation of the axial variation of the transient pressure as a result of the ablation of the boric acid chamber of a power expulsion fuse for 25.8 kV of rated voltage after an arcing time of 4.4 ms and before the arcing rod have reached its resting position.
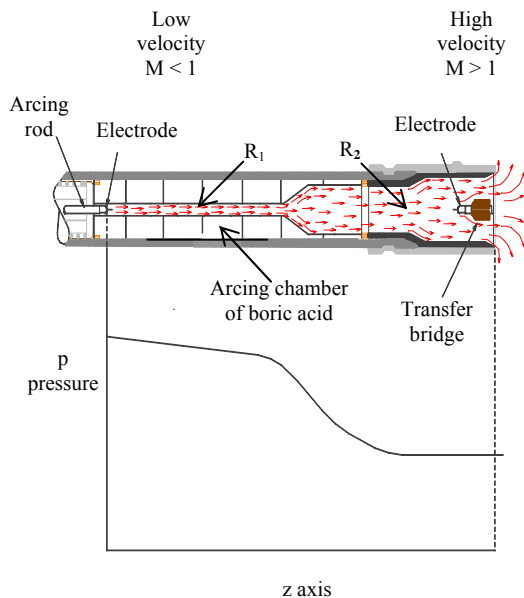

Fig. 3: Schematic representative of the axial variation of pressure for ablation of boric acid and in a power fuse of 25.8kV and rated current of 6A.

$$R_1 << R_2$$

The critical parameter that defines the magnitude of the maximum pressure is the ratio of channel (chamber) inside surface to the cross-sectional area [4].

$$\text{Area ratio} = \frac{2\pi R l}{2l} = \frac{}{\pi R^2} \quad \frac{}{R}$$

Eliminating the constant multiplier, the critical parameter is $\frac{1}{R}$.

In the figure 3 we have $\frac{1}{R_1} >> \frac{1}{R_2}$

2. Action of the system in both type of circuit breaking devices

As it was described before, after melting, during and following the instant of evaporation of the fuse wire or after the separation of the contacts in a gas-blast circuit breaker, the input current is carried by an arc of plasma that is a highly ionized gas from which it derives its conductivity.

- In circuit breakers the high pressure plasma reaches temperatures of the order of 20000 K.

- The conductivity at this temperature and the corresponding pressure inside of the interrupter is a fraction of an ohm-centimeter. Thus the current densities are in the order of several thousands amperes per square centimeter and the voltage gradients in the arc is of several hundred volts per cm [4].

- In such conditions in order to assure a successful interruption at a current zero, the quantity of energy extracted must be greater than the energy that is supplied by the system.

- The plasma must change from a conductor to a good insulator, bearing in mind that the transient recovery voltage (TRV) builds up across the residual plasma when the arcing current comes to zero.

- The dielectric strength between electrodes in fuses and circuit breakers must be regenerated at a rate greater than the TRV imposed by the system.

- In an fuse-unit of dropout type the opening process is the following: during the arcing time a compression or tension spring lengthen the arc path quickly, drawing apart the arcing contacts thereby stretching and finally breaking the arc. Immediately after the upper end of the arcing rod breaks the upper seal and releases the latch located in the upper contact assembly assuring the

dropout action by thrusting the fuse-unit outward to the fully open position. If the rate of rise of recovery voltage (RRRV) is very rapid the cooling time must be only tens of microseconds and the cooling rate of the order of 10^9 K/sec for a successful interruption. The RRRV gives a measure of the circuit severity from a switchgear point of view[5].

- When the decaying plasma has significant conductivity will flow a post-arc current as an indication that the system is applying more energy, but if the rate of energy extracted is bigger, the duration of such a current will be very short. See the figure 4.
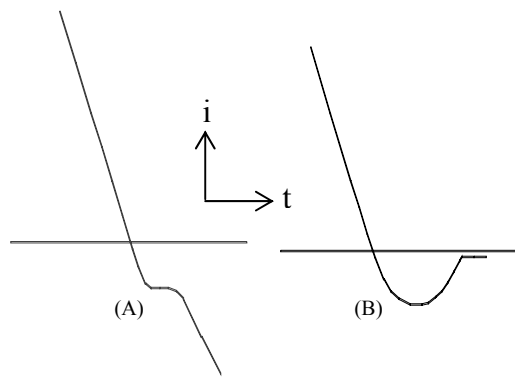

Fig. 4: Post-arc current (A) successful clearing (B) reignition.

In the figure 5 is shown the case of the presence of a small post-arc current when a power fuse unit interrumps satisfactorily a symmetric current of 11.5kA at 23 kV, 60 Hz. Its duration is approximately of 0.34 ms.
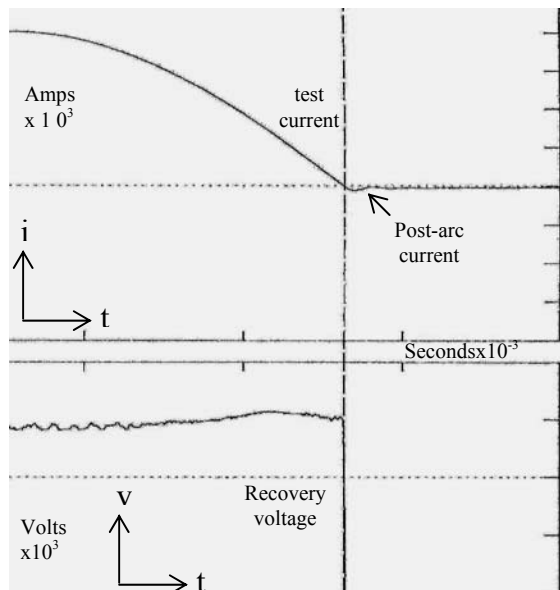

Fig. 5: Post-arc current in a fuse-unit tested with the 90 percent of its interrupting capacity.

- A circuit breaking device can be vulnerable to circuit conditions in which the TRV rises rapidly. When interrupts a secondary fault close to a transformer appears an arcing voltage with a high natural frequency with low damping. In the case of power expulsion fuses this case corresponds to the test series 6 of table 9 of the Std IEEE c37.41-2000. That establishes a TRV critically damped [6].

- In the figure 6 is presented the interruption with a power fuse of a current of 15 A at 23.2 kV in a circuit with a time to peak of 432μ sec and a equivalent frequency of 1.15 kHz.
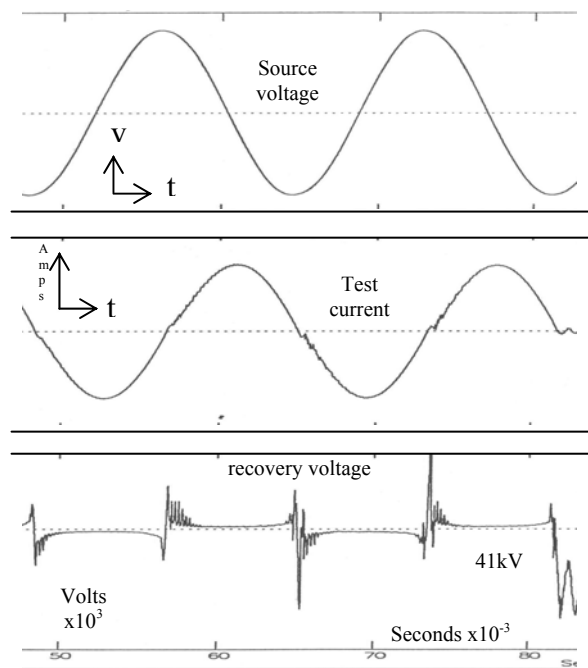

Fig. 6: Interruption of a current of 15 A with a power fuse-unit of 3A of rated current.

In medium voltage circuits a high arcing voltage can be advantageous because it can influence the magnitude of a fault current due its opposition of its flow. See the figure 6.

3. Requirements for circuit breakers and fuses.

The primary function of any of these two circuit breaking devices is the interruption, bearing in mind that they are interacting with the electrical power system.

In the case of circuit breakers, in addition to meeting their interruption functions, are these: to carry load currents, withstand voltage and energize

circuits. In the table 1 are shown the main functions of a circuit breaker [7].

Table 1

3.1 Interrupt faults.
Terminal faults up to the rated interrupting capability: - Isolated three-phase (or two-phase) faults. - Grounded three-phase (or two-phase) faults - Short line faults at any distance from the terminal, out of phase operations (optional).
3.2 Interrupt loads

- Normal loads up to the rated continuous currents
- Capacitive loads.
    • Capacitor banks (optional)
    • Unloads lines
    • Cables
- Small inductive loads
- Magnetizing current of transformers
- Reactors (optional)
- Motors

3.3 Carry current.
- Rated continuous current - Short time fault current
3.4 Dielectric requirements in closed and open positions dry or wet.
- system voltage - Lightning surges - Switching surges
3.5 Energize loads
- Transformers (inrush currents) - Normal loads - Capacitor banks - Lines - Into faults (related to the short line fault current)

The basic functions of a power expulsion fuse are:

- To carry the load currents which magnitudes are as high as its nominal rated current

- To interrupt fault currents until its maximum interrupting capacity. These fuses are tested in accord with the standards, which should reflect as far as possible the operating conditions in the field. Another relationships between circuit breakers and fuses performance parameters are the mechanical and thermal constraints they impose. In circuit breakers with a given rating for which the performance demands are identical, individual mechanical designs will vary widely depending of the particular interrupting medium

employed [8] there is not possibility to define universal principles and consequently certain generally valid concepts are usually applied. In the table 2 are presented only those performance parameters corresponding to circuit breakers and fuses indistinctly.

Table 2

Circuit Breakers [8]
A. Continuous Current
- Contacts cross-section - Contact material - Number of contacts
B. Interrupting current
- Contact stroke - Minimum and maximum velocities limits - Number of series contacts - Opening resistor
Power expulsion fuses
A. Continuous Current.
- Cross section and material of the fuse wire - Time-current characteristic (both melting and total-clearing time
B. Interrupting current
- Isolating distance between electrodes - Minimum velocity of the arcing rod imposed by the auxiliary spring of compression or tension type

In the figure 7 are presented the critical events in the time-story of the opening process in both type of the circuit breaking devices.

4. The theoretical investigation of arc properties in gas-blast circuit breakers and expulsion fuses.

The purpose of this section is to present a brief description of the theoretical modeling of arc discharge in gas-blast circuit breakers and expulsion fuses and as far as possible a comparison of the results obtained by different researchers through the time.

During about thirty years the classical equations of Cassie and Mayr were or still are used in circuit breaking devices design.

In 1939, Cassie developed a differential equation for the arc resistance by assuming an arc column in which the arc temperature is constant and the arc area varies with the current. This model was intended to represent an arc in an air-blast circuit breaker

assuming that the air flow penetrated the whole cross-section of the arc, carrying away heat and making the dissipation per unit volume constant as well [9].

- Circuit breakers.
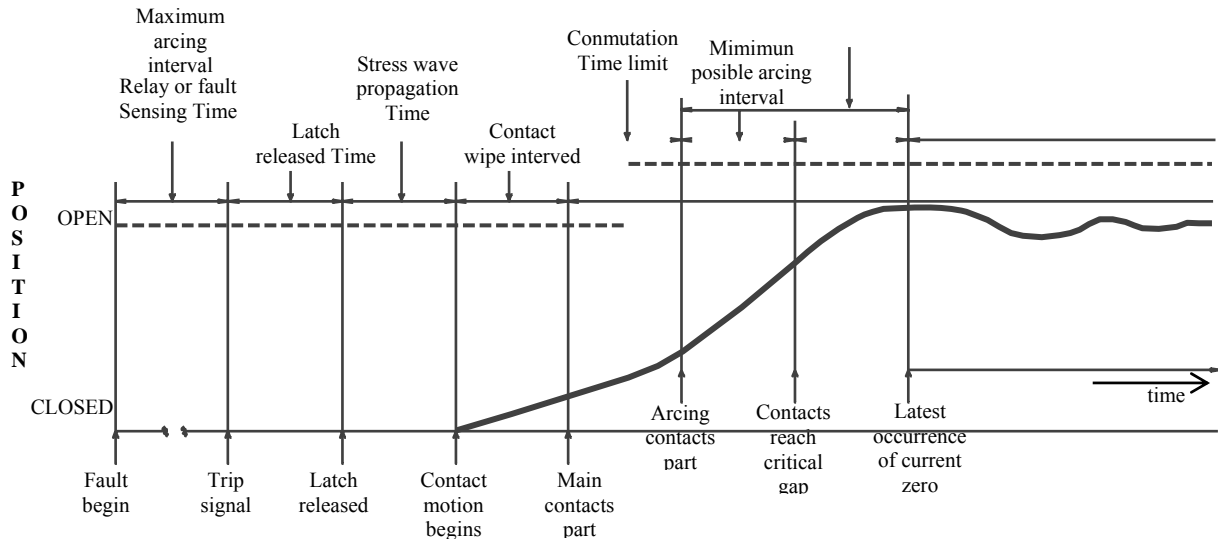
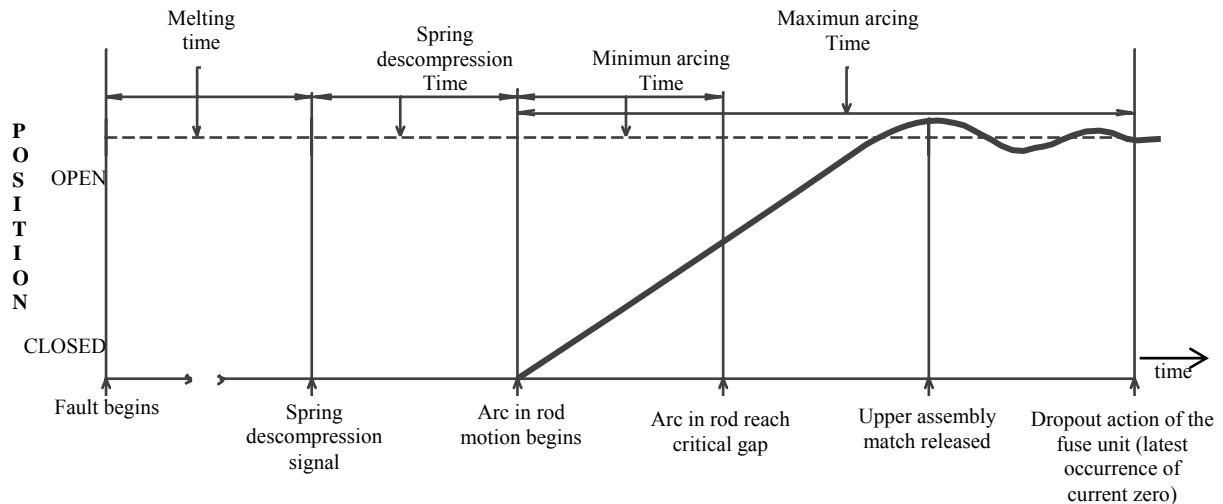- Power expulsion fuses of dropout type.

Fig. 7: Critical events in the time-history of the circuit breakers and fuses opening processes.

Such assumptions led to the following differential equation:

$$R \frac{d\left(\frac{1}{R}\right)}{dt} = \frac{I}{\Theta} \left\{ \left(\frac{v}{v_o}\right)^2 - 1 \right\} \quad \text{where} \quad (1)$$

R= arc resistance
v= arc voltage an any instant
v_o= arc voltage in steady-state
Θ= Time constant =
Energy stored per unit volume
Energy loss rate per unit volume

The resistance increases exponentially as the stored energy is removed at a finite rate by the air flow.

In 1943 Mayr developed a differential equation for arc resistance by assuming an arc column in which the arc radius is constant and arc temperature varies with time. In this arc model energy is transferred only by radial conduction and the conductance of the arc varies exponentially with the energy stored in it. This is the differential equation developed

$$R \frac{d\left(\frac{1}{R}\right)}{dt} = \frac{I}{\Theta} \left\{ \left(\frac{vi}{w_o}\right) - 1 \right\} \quad (2)$$

This equation has certain advantages. In the steady state condition when currents and voltages are changing slowly

$$\frac{d\left(\frac{1}{R}\right)}{dt} = 0 \quad \text{and therefore} \quad vi = w_o \quad (3)$$

And the steady state characteristic arc hyperbolic being a good representation of what happens is an interrupter in the low current region [9].

In 1948 Browne developed a mathematical model of the arc that combined many features of the previous models, but without progress in numerically relating the terms of the equation with the physical properties of the interrupting medium. Due to the Cassie-Mayr arc models are described by ordinary differential equations there is a limit to the amount of information that can be obtained from them.

They cannot shed light on the physics of arc interruption because that is described by partial differential equations of gas dynamics.

Among the reasons for developing advanced models arc these:
- Growth of short circuit current of power systems.
- Consequently the RRRV caused by a line fault that is proportional to the fault current.
- Nozzle clogging that occurs when the arc expands to fill the nozzle throat due to the high

plasma temperature and low density. Clogging the nozzle mass flow and limits the energy carried away by convection.
- The theoretical formulation of all determinant parameters is very useful to provide information of circuit interrupting devices performance, leaving behind the empirical design methods replaced by scientific analytical procedures.

Some decades ago (1950-1970) the difficulties for modeling circuit breakers arise from the complex nature of the equations describing nozzle arcs, the non-linear character of the thermodynamic and transport properties of interrupting gases, the complex flow fields generated with Laval nozzles with supersonic flow and shock waves, stability problems with numerical methods and the uncertainties in modeling arc turbulence and radiation.

Arc turbulence [10]

As has been mentioned before in the past there were little knowledge about turbulence in high pressure arcs but with the development of nozzle arc models it was understood the real need for turbulence information. The primary arc turbulence models were developed in base of aerodynamic turbulence.

In the momentum equation, the transfer of momentum in the y direction:

$$\frac{\partial}{\partial y} \left[(\eta + \eta_t) \frac{\partial v_z}{\partial y} \right] \quad (4)$$

Where η is the molecular viscosity and η_t is the turbulent viscosity defined by the equation

$$\eta_t = \rho \varepsilon_m$$

Where ρ is the gas density and ε_m is the eddy diffusivity of momentum. Similarly, in the energy equation the transfer of heat in the y direction is given by the term.

$$\frac{\partial}{\partial y} \left[(k + k_t) \frac{\partial T}{\partial y} \right] \quad (6)$$

k is the thermal conductivity
k_t is the turbulent thermal conductivity defined be the equation

$$k_t = \rho C_\rho \varepsilon_H \quad (7)$$

Where ε_H is the eddy diffusivity of heat and C_ρ is the specific heat. The eddy diffusitivities of heat and momentum are related by equation

$$\varepsilon_H = \frac{\varepsilon_m}{\rho_{rt}} \quad (8)$$

Where ρ_{rt} is the turbulent Prandtl number assumed equal ½. Therefore to estimate the effects of arc turbulence we must estimate the eddy diffusivity of momentum ε_m

In the inner region of a turbulent boundary layer the eddy difusitivity varies according to the equation

$$(\varepsilon_m)_i = 1\frac{\partial u}{\partial y} \quad \text{for } y_o \leqq y \leqq y_c \quad (9)$$

Where y_o is a small distance from the surface and **l** is the Prandtl mixing length which varies linearly with **y** in this region. In the outer region of the boundary layer, the velocity is fairly uniform and the eddy diffusivity varies according to the equation

$$(\varepsilon_m)_0 = \propto_1 V_e \delta^* \quad \text{for } y_c \leqq y \leqq \delta \quad (10)$$

Where $\propto_1$ is a constant, δ is the boundary layer thickness, V_e is the free stream velocity of the boundary layer and δ^* is the displacement thickness which is proportional to δ and varies in the Z direction. From the equations (9) and (10) are inferred the following: within the core of a radiation dominated arc the flat temperature profile produces a fairly uniform core velocity and core turbulence may resemble turbulence in the outer region of the boundary layer where the velocity is also fairly uniform.

Arc radiation [11]

When the current exceeds 1000A, radiations is the most important loss mechanism at the arc centre Tuma and Lowke shown that nozzle arc models can be developed using two emission coefficients of radiation u an u_t as functions of temperature, pressure and arc radius assuming the arcs are approximately isothermal.

The coefficient u gives the radiation loss at the arc center and is dominated by ultraviolet radiation which is reabsorbed at the arc boundary.
The coefficient u_t gives the radiation which is reabsorbed at the arc boundary and gives the radiation which is completely lost from the arc and which is dominated by the visible region of the spectrum.

The thermal interrupting performance.

- In modeling this type of performance of an arc in a nozzle, the usual assumptions are: axial symmetry, constant gas pressure, local thermodynamic equilibrium (LTE) and no viscous or magnetic effects. Additionally axial variations and convection are assumed negligible in comparison with radial variations.

Arc models in cylindrical tubes and nozzles.

Choosing a cylindrical symmetric arc confinement, E.Z. Ibrahim [12] formulated the equation describing the physical behavior of the arc in the radial an axial directions. The equations for his arc model are:

- The energy conservation

$$J.E. + \frac{\partial}{\partial z}(k.\frac{\partial T}{\partial z}) + \frac{1}{r}\frac{\partial}{\partial r}(k.r\frac{\partial T}{\partial r}) =$$

ohmic power   axial conduction   radial conduction

$$Prad + \rho Cpv_r\frac{\partial_T}{\partial r} + \rho Cv_z\frac{\partial_T}{\partial z} + \rho Cp\frac{\partial_T}{\partial t} \quad (11)$$

radiated power   radial convection   axial convection   thermal inertia

- Conservation of momentum

Radial

$$\frac{\partial p}{\partial r} + \rho v_z\frac{\partial v_r}{\partial z} + \rho v_r\frac{\partial v_r}{\partial r} + \frac{4}{3}\mu\frac{v_r}{r^2} =$$

$$\frac{4}{3}\frac{1}{r}\frac{\partial}{\partial r}(\mu r\frac{\partial v_r}{\partial r}) \quad (12)$$

Axial

$$\frac{\partial p}{\partial z} + \rho v_z\frac{\partial v_z}{\partial z} + \rho v_r\frac{\partial v_z}{\partial r} =$$

$$\frac{1}{r}\frac{\partial}{\partial r}(\mu r\frac{\partial v_z}{\partial r}) \quad (13)$$

Conservation of mass is a balance between the radial influx of ablating wall material and the convective outflow of mass caused by pressure difference between the stagnation zone and tube exit

$$\frac{\partial}{\partial z} + (\rho v_z) + \frac{1}{r}\frac{\partial}{\partial r} = (\rho v_r r) = 0 \quad (14)$$

Axial variation of mass outflow   Radial variation of mass influx

Usual assumptions:
- Axial symmetry
- The arc is isothermal radially, i.e.

$$\frac{\partial T}{\partial r} = \frac{\partial T}{\partial z} = 0, \quad (15)$$

The temperature profile is rectangular / flat.

- The arc is isobaric, i.e. $\partial p / \partial r = 0$
- The arc core is in local thermodynamic equilibrium (LTE).
- The arc is quasi-stationary, i.e. $\frac{\partial}{\partial t} \approx 0$
- The arc core is radiation dominated.

The conclusions he found about analytical modeling of the ablation dominated confined arc in an cylindrical tube developed on the basis of an integral uni-dimensional formulation are:

- The temperature distribution in the ablation dominated, high current arc is almost flat radially and can be approximated by the central temperature.
- The arc's radiative behavior is a function of the formation of the heat.
- For any current density the pressure is a lineal function of tube half-length. He used a tube open in both ends.
- Turbulent plasma flow in the outer axial sections (tube with two open ends) of the confined arcs was established analytically.

The semi-empirically derived scaling laws/formulae, that link the relevant arc parameters are.

$E_2 = 2.65 \times j^{0.4267}$ vcm^{-1} Electric field gradient
$P_c = 6.375 \times 10^{-3} \times j^{0.955}$ bar kinetic stagnation pressure.
$T1 = 1.641 \times 10 \times j^{0.238}$ K arc column temperature.
$T2 = 3.63 \times 10 \times j^{0.308}$ K arc mantle temperature.

Model developed by P. Kovitya and J.J. Lowke [13]

They assumed that if the energy losses from an optically arc are dominated by radiation, the radial temperature profile becomes flat at center and since the axial pressure and velocity gradients are much greater that the radial gradients, it is assumed that the radial variations in plasma temperature, pressure and velocity are negligible.

For instance the energy conservation equation for this arc model is:

$$\rho C_p \frac{\partial T}{\partial t} = \sigma E^2 - U - \rho C p v_z \frac{\partial T}{\partial z} - \rho v_z^2 \frac{\partial v_z}{\partial z} \quad (16)$$

Making a comparison with the equation (11) here in the equation (16) are neglected the partial differential equations for radial convection and conduction.

The axial component of the equation describing the conservation of momentum of the arc is:

$$\frac{\partial(\rho v_z)}{\partial t} + \nabla . \rho (v_z v) = - \frac{\partial p}{\partial z} \quad (17)$$

Where v is the vector velocity and P is the arc pressure

Integrating the equation (17) between cross-section at z and z + Δz and arc boundary, after using the Gauss divergence theorem, and taking m as the rate of vapour entrainment into the arc and v_c is the axial vapour velocity, letting Δz approach to zero was obtained:

$$\frac{\partial}{\partial t}(\rho v_z A) + \frac{\partial}{\partial z}(\rho V_z^2 A) - \dot{m} v c = -A \frac{\partial P}{\partial x} \quad (18)$$

The continuity equation for the arc

$$\frac{\partial(\rho A)}{\partial t} = \dot{m} - \frac{\partial}{\partial z}(\rho v_z A) \quad (19)$$

If equation (19) is substituted into equation (18), is obtained.

$$\rho \frac{\partial v_z}{\partial t} = -\rho v_z \frac{\partial v_z}{\partial z} - \frac{\partial P}{\partial z} - \frac{\dot{m}}{A}(v_z - v_c) \quad (20)$$

The term m $(v_z - v_c)$ / A was not included by Ibrahim, it represent deceleration by the entrained vapour.

Kovitya and Lowke developed a one-dimensional gas-dynamic model of ablation-stabilized arcs in uniform cylinders. They indicated that it was in good agreement with experiments.

In the above equations (11) to (20): ρ is plasma density, Cp is specific heat, T is plasma temperature. t is time σ is electrical conductivity, E is electric field, u is radiation emission coefficient, z is axial position, p is the arc pressure, μ is viscosity, v_z and v_r are the axial and radial velocities respectively, m is the rate of vapor entrainment into the arc.

Theoretical modeling of forced convection-stabilized arcs

In this section is presented a summary of a transients-two dimensional model of forced convection stabilized arc such has those found in gas-blast circuit breakers.

During the 1980-1990 decade Mitchell and Tuma [14] developed a computational model for solving the conservation equations along with

Ohm's Law and an equation of state. For a given current the working gas and information about the nozzle geometry, the model finds temperature and radial and axial mass velocities as functions of cylindrical coordinates r, z and time an also computes electric field as a function of axial position, all in the upstream region of the arc.

The pressure distribution is determined by; the stagnation and exit pressures, the shape of the nozzle and the type of gas. The three conservation equations for mass, axial momentum and energy are respectively:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial z}(\rho v_z) + \frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r) = 0 \qquad (21)$$

$$\frac{\rho \partial v_z}{\partial t} + \rho v_z \frac{\partial v_z}{\partial z} + \rho v_r \frac{\partial v_z}{\partial r} =$$

$$- \frac{dp}{dz} + \frac{1}{r}\frac{\partial}{\partial r}\left(\eta r \frac{\partial v_z}{\partial r}\right) \qquad (22)$$

$$\rho Cp \frac{\partial T}{\partial t} + \rho Cp v_z \frac{\partial T}{\partial z} + \rho Cp v_r \frac{\partial T}{\partial r} =$$

$$\sigma E^2 - U + \frac{1}{r}\frac{\partial}{\partial r}\left(rk \frac{\partial T}{\partial r}\right) \qquad (23)$$

In these equations is assumed that the axial second-order terms of viscosity and thermal conductivity can be neglected.

The model makes two simplifying assumptions which need to be justified.

These assumptions are:

- The axial pressure distribution is taken from the cold-gas potential flow solution, at the axis r=0 and.
- The radial momentum equation is approximated

by $\frac{\partial p}{\partial r} = 0$

When circuit breaker arcs carry very high currents operating with temperatures of the order of 20,000 K the radiation becomes the dominant mechanism of energy transport within the arc [14]. Losses at the arc centre are dominated by the radiation losses and the arc is approximately arc plasma rather than lost as radiation.

- **The steady-state arc at high current.**

Radiation Transport

For sulphur hexafluoride it is found experimentally that the radial temperature profile of the arc is nearly isothermal.

Thus convection and thermal conduction are no significant in this region the local power balance is $\sigma E^2 = u$

The radial temperature becomes flat-topped and 89% of the power input due to joulean heating is transported away from the arc core by radiation.

- **Conduction, convection and the Arc Boundary.**

A simplified analysis of the energy equation in the vicinity of the arc boundary shows a very sharp boundary which is observed experimentally in the double-nozzle flow geometry. In this region the joulean heating and radiation terms are relatively small

For steady-state the time term is zero and in the plane z=0 the axial convection is also zero the simplified energy equation is

$$- \frac{d^2}{dr^2}(kT) + \rho Cp v_r \left(\frac{dT}{dr}\right) = 0 \qquad (24)$$

Neglecting the term $m\frac{dk}{dt}$ a denoting derivatives by primes

$$\mathnormal{\mathcal{C}}T'' + T' \text{ where } \mathnormal{\mathcal{C}} = \frac{k}{\rho Cp v_r} \qquad (25)$$

In the figure (8) are shown the solutions for four values of $\mathnormal{\mathcal{C}}$
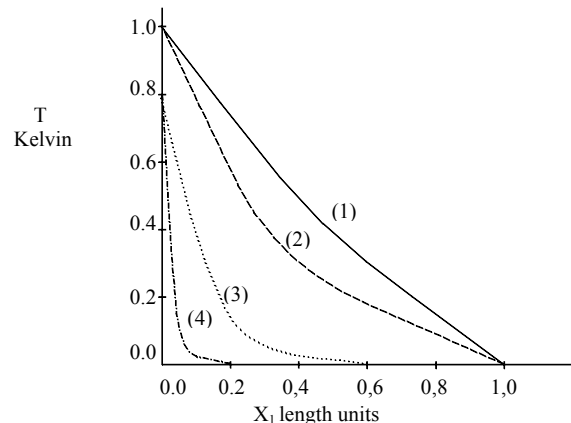
Fig. 8: Solutions to the convection-diffusion equation CT''+T'=0 for four values of $\mathnormal{\mathcal{C}}$ - solid curve (1): $\mathnormal{\mathcal{C}}$=1.0, dashed (2): $\mathnormal{\mathcal{C}}$=0-3, dotted (3): $\mathnormal{\mathcal{C}}$=0.1, chain (4): $\mathnormal{\mathcal{C}}$=0.03 (Fig. 10, Mitchell & Tuma 1985, IEEE)

- **Convection of Enthalpy**

Due to the large axial mass velocities presented in a high-current stabilized arc, much of the arc power deposited by joulean heating is carried away by convection, Using a cylindrical control volume with radius R and a axial length L for representing a part of the arc between the nozzle throats. (model of Mitchell and Tuma):

The power lost by radiation from the arc core is deposited just inside the arc boundary and

consequently the power deposited is lost by convection and thermal conduction

Cold gas flows radially into the control volume with enthalpy ho = h (T = 300K). Hot gases flow axially out of the control volume in the positive z direction. In steady-state all the gas axially exiting enter the control volume radially by conservation of mass.

The mass flow is given by

$$\int_{\partial}^{R} \rho v_z \, 2\pi r dr \qquad (26)$$

And the enthalpy flow exiting the control volume is:

$$F = \int_{\partial}^{R} \rho h v_z \, 2\pi r dr \qquad (27)$$

Where $\rho h v_z$ is the enthalpy flux

This is the net power loss from the volume due to convection and account for about 95 percent of the power loss.

If the control volume radius is chosen at the 15000 K isotherm the plasma entering the volume has almost much enthalpy as the exiting axially.

- **Transient differential Power Balance.**

During the transient arc decay after current zero this balance is quite different from the steady-state when the arc is locally radiation dominated while radiation is absent from the decaying arc a few tens of microseconds after current zero.

- **Upstream turbulence.**

Ragaller et al introduced a large amount of turbulent thermal conductivity into their calculations in order to obtain agreement with the measured dielectric recovery characteristics of Schade and Ragaller [15]; they found that during 100-200 μs after current zero the temperature profile is flattened in the axial and radial direction due to the continue action of turbulence.

The results of Mitchell and Tuma along with the measurements of Graf [14] et al show that the radial temperature profile is constricted with a peak instead at the center
- Mitchell et al have applied a two-dimensional transient model of forced convection stabilized arc. It solves the LTE conservation equations for mass, momentum and energy, using an implicit finite-difference technique for marching in the axial and time dimensions and find the upstream values for temperature T(r, z = 0, t) by using downstream information about the gas flow.

- This model has been used to simulate steady-state arcs in SF_6 and predicts that the arcs are cylindrical in the upstream region of single and double-flow model circuit breakers having parabolic axial distribution.
- The model also simulates the temperature and dielectric recovery of SF_6 arc in laboratory scale devices. It follows the arc from the steady state through the current ramp and during the subsequent free decay.
- Mitchell and Tuma conclude that the mechanism of convection and laminar conduction suffice to cool the upstream region of the decaying arc and that the turbulence has little influence on the upstream temperature recovery and hence on dielectric recovery

5. Conclusions.

It has been attempted to describe in few pages the most relevant performance characteristics of those type of circuit breaking (current zero) devices. Because their primary function of them is to interrupt overcurrents, this paper is focused to the heart of both: the arcing chamber that in fuses is composed by cylindrical chamber with different diameters and geometry and the nozzle of different shapes in circuit breakers without considering the type of arc quenching gas used or if they are self-pressurizing devices where the ablating dominated process is imposed by a given material.

Due to the intrinsecal relationship between the interrupting process inside the arcing chamber, the type and shape of nozzles, if they are of single-flow or double flow and the geometry of the inside wall of outlets of fuses and the velocity of the moving contacts.

Finally are summarized several studies about this subject, beginning with the well known developments of Cassie, Mayr and Browne, to others more sophisticated in these fields: thermodynamic, mathematics and numerical methods mainly in the period 1970-1990, that has been applied to circuit-breakers design as well as for fuses.

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