Analysis of Faults in Distribution Tranformers with MSC/PISCES - 2DELK

by

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Abstract

The problem of explosions in oil-insulated distribution transformers, following an internal electrical fault, has been investigated with MSC/Pisces-2DELK. A user-defined routine was developed to model the mechanical effects of an electric arc in oil. Rupture modes and peak pressures have been evaluated and compared to experimental data from the literature. They show good agreement with the results of MSC/Pisces-2DELK.

1. Problem description

Over the last few years, the problem of explosions in oil–insulated electrical equipment as a result of low–impedance faults has taken on increasing proportions, mainly because of higher fault currents and aging of the equipment. The problem may become critical when the explosion is not confined to the tank and sends oil or shards flying into the environment, jeopardizing the safety of adjacent personnel or equipment. Although all types of oil–filled electrical equipment are affected, this paper presents only the results of an analysis on pole–type distribution transformers as illustrated in Figure 1.1 .

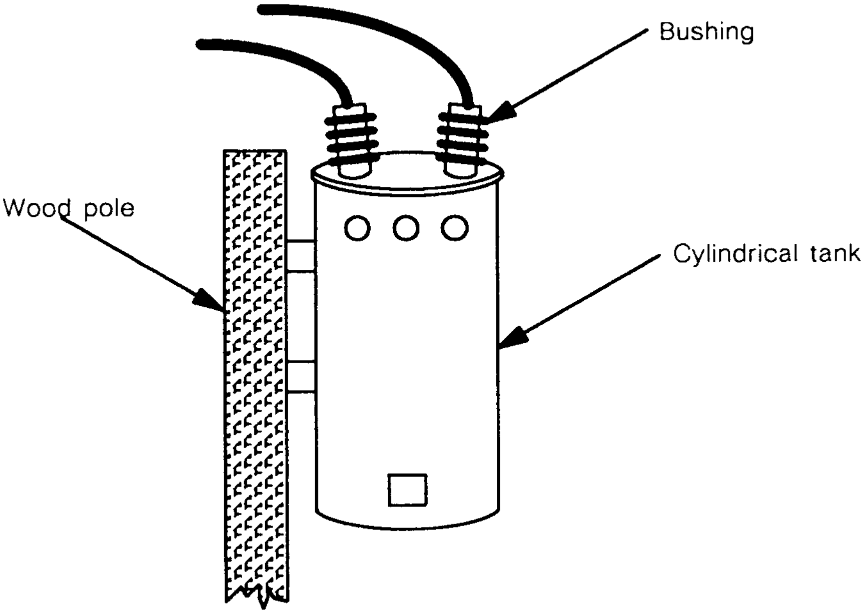


Figure 1.1 A typical distribution transformer tank

Explosions result from breakdown of the electrical insulation, generating a so–called let–through current whose magnitude is limited only by the power system. Typical values are of the order of a few kiloamperes rms, with a maximum of approximately 8 kiloamperes rms for most utilities. The energy released by the arc is given by the integral:

$$\int_{o}^{T} EI \, dt \qquad \text{(a)}$$

with: E = voltage drop across the arc (V)
I = arc current (A)
T = arc duration (s)

The arc duration depends on the operating delay of the protection devices such as fuses, with typical values close to one half cycle, approximately 8–10 ms at 60 Hz. The arc energy liberated must be dissipated or absorbed by the immediate environment in the following forms (1):

- energy losses in the contacts
- radiated energy
- energy to take the surrounding oil to its boiling point
- energy to boil the surrounding oil
- chemical energy for oil decomposition into gas
- energy to heat the gas at constant volume
- energy to expand the gas at constant pressure
- energy for hydrogen dissociation

The mechanical energy injected into the tank takes the form of a high–pressure, high–temperature gas. Therefore, it can be assumed that the mechanical effect of an arc in a distribution transformer is expansion of a gas, which in turn increases the pressure inside the tank up to possible rupture. This mechanical energy is composed of the energy to heat the gas (at constant volume) and the energy to expand the gas (at constant pressure). The total energy liberated by the arc can reach values up to 80 KJ, a fraction of which is converted into a form of mechanical energy that must be contained by the tank. This would be a convenient way to express tank resistance, however it is best characterized by the internal pressure withstand capability. The relationship between arc energy and corresponding pressure must therefore be determined. Previous investigators have made considerable efforts to find this relationship analytically (2–5) but the models developed so far, although very instructive, are not truly representative of all the dynamic aspects of the problem.

MSC/Pisces–2DELK (13) was adapted and applied for the first time to this particular problem by one of the authors in 1986. The methodology was presented to the electrical industry at an IEEE conference and described in a transaction paper (10). It is based on the user–defined routine EXFLOW, which governs the boundary conditions of an external flow, in this case the injection of a gas resulting from oil decomposition in the presence of an arc. The formulation of this routine required prior knowledge of a few gas parameters, namely the quantity generated, composition and temperature. The proper choice of these parameters will be discussed later.

The methodology developed to simulate the effect of an internal arc in a distribution transformer, using **MSC/Pisces–2DELK**, is described next.

2. Model used in MSC/Pisces-2DELK

A standard distribution transformer consists of a cylindrical tank containing a core and coil assembly, which is partially filled with oil, and has a volume of air between the top-oil level and the tank cover. A cross section representing the inside of such a tank is seen in Figure 2.1 .

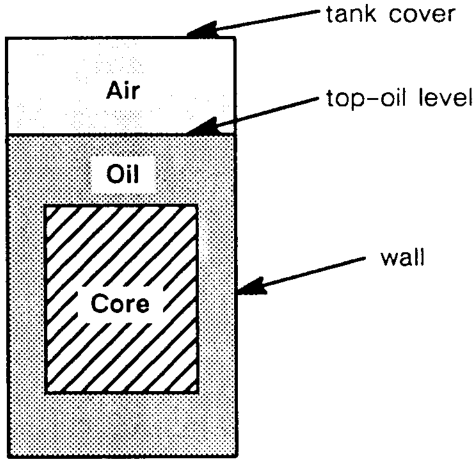


Figure 2.1 Cross section of standard distribution transformer

An arcing fault can occur in many locations in a transformer: between the core and the walls, in the wiring inside the core, between the wiring outside the core and the core or transformer wall, etc. As described in the previous section, the effect of such a fault is to vaporize the oil surrounding the arc, causing the expansion of a gas bubble. This gas bubble, in turn, pushes the oil upward, compressing the air space between the top oil level and the tank cover.

To simplify the problem, the position of the arc is located on the symmetry axis of the tank, in the oil between the core and the top-oil level. This allows the problem to be treated using a 2-D representation with **MSC/Pisces-2DELK**, in cylindrical coordinates, with the properties of the flow varying along the x and r axes and being constant around the x-axis in the θ-direction. The system of coordinates is shown in Figure 2.2 .

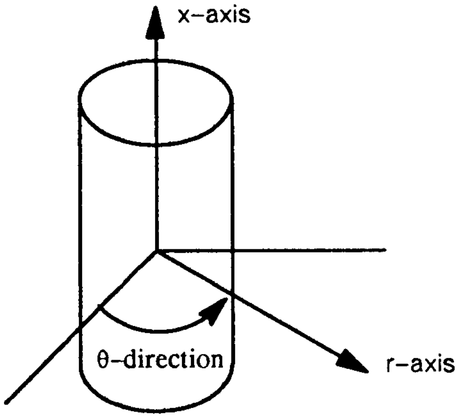


Figure 2.2 System of coordinates used

In this problem, the rigidity of the cylinder forming the tank walls is much more important than that of the air space. Since we are only interested in the pressure rise in the air space, the tank walls can be modeled as rigid and fixed boundaries, admitting no deformation at all. The air, oil and core are modeled with a Euler grid in **MSC/Pisces-2DELK** (see Figure 2.3). Since there is axial symmetry around the x-axis, only half the cross-section of the tank, as shown in Figure 2.1, is needed for modeling.

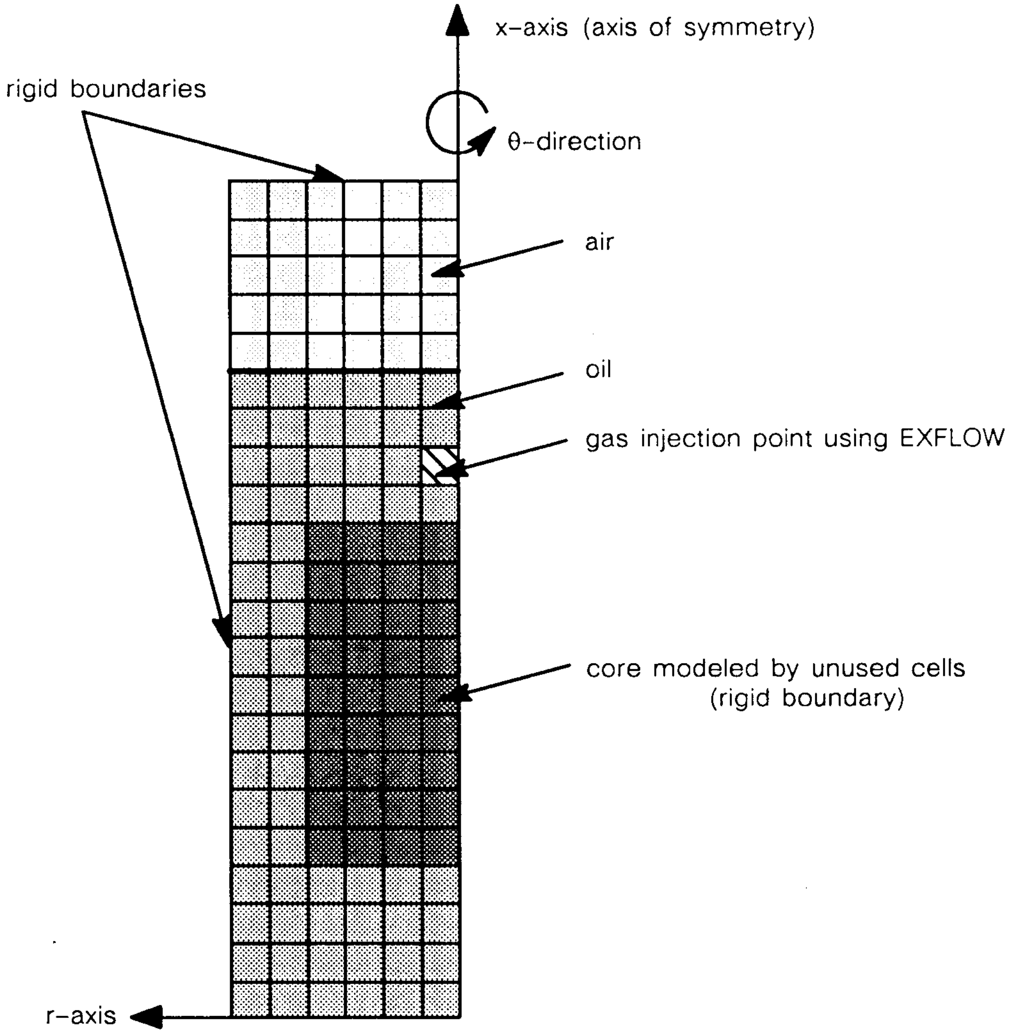


Figure 2.3 Euler grid used to model the distribution transformer in **MSC/Pisces-2DELK**

The main features of the model are:

- tank modeled in 2-D using axial symmetry around the x-axis
- air and gas modeled using the ideal gas law
- tank walls and core modeled by rigid boundaries
- gas inflow modeled by EXFLOW boundary condition
- oil modeled by compressible fluid using polynomial equation of state

3. Arc simulation with MSC/Pisces-2DELK

3.1. Parameters of the arc–generated gas

The formulation of the EXFLOW routine used to simulate the mechanical effects of the arc requires prior knowledge of a few gas parameters: quantity generated, composition and temperature.

3.1.1 Gas quantity

The quantity of gas generated by an arc is expressed throughout the literature in terms of cc per kJ of arc at standard temperature and pressure. This parameter has been observed to vary significantly, mainly with the current level, oil type and test conditions. Some measured and theoretical values are given in Table 1.

Table 1: Quantity of gas generated according to various authors

Reference	Quantity of gas generated
Trencham (1) (measured)	70 cc/kJ at low pressure 100 cc/kJ recommended fo general case
Goodman (2) (measured)	15 to 100 cc/kJ
Castonguay (7) (measured)	100 cc/kJ at -40°C 80 cc/kJ at 20°C
Goto (8) (measured)	50 to 70 cc/kJ
Freidin (9) (theoretical)	85 cc/kJ
Goto (8) (theoretical)	61 cc/kJ

Some of the scatter observed can be attributed to the actual arc temperature, which influences the conversion to standard values and the gas composition. For the present analysis, a value of 100 cc/kJ was initially selected for simulating the phenomena with **MSC/Pisces-2DELK**. After comparing the effect of this value with the results of the CEA test program (11), we lowered it to 85 cc/kJ, which then matched the results of the test program.

3.1.2 Gas Composition

The decomposition of insulating oil following an arc varies slightly according to different studies and, since these variations do not significantly affect the pressure calculations, an average composition was found to be suitable. In terms of volumetric proportions, it consists of:

hydrogen	70%
methane	10%
acetylene	15%
ethylene and others	5%

3.1.3 Temperature

The temperature in the immediate vicinity of the arc can reach extremely high values that are very difficult to measure. Fortunately, we are only interested in the average value of the gas cavity around the arc, which is easy to determine. Experimentally, this value has been established anywhere between 800 K and 2500 K (1,5,8,9). However, according to the analysis of the decomposition gases (9), this value should be at least 1500 K and probably around 2000 K, due to the presence of graphite in the by-products. The latter value was therefore selected for the present analysis, which, according to our review of the literature, represents a good compromise.

When all the parameters above are combined, the enthalpy of gas generated represents approximately 22% of the total arc energy. Other sources have proposed values ranging from 15% to 45%, our choice was governed by the comparison of the calculated and measured pressures resulting from an arc since the volume parameter was fitted.

3.2. Description of the EXFLOW routine

As discussed, the mechanical effect of the arc is modeled in **MSC/Pisces-2DELK** using the user-defined subroutine EXFLOW, which defines the flow of gas into tank. The gas is injected, as shown in Figure 2.3, from the boundary of an unused cell, presented in more detail in Figure 3.1.

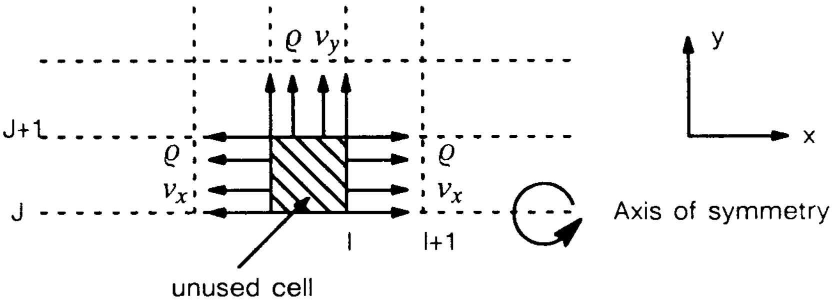


Figure 3.1 : Boundary cell for arc simulation in **MSC/Pisces-2DELK**

The velocity of the flow leaving the cell is set at a constant value with respect to space (i.e. it depends only on time).

The quantites of interest to be computed in EXFLOW are:

- PEX: pressure of gas leaving the injection cell: P
- EINEX: specific internal energy: e
- ROEX: mass density of gas: ρ
- UXEX: x component of fluid velocity: v_x
- UYEX: y component of fluid velocity: v_y

The pressure PEX is determined using the standard gamma law for perfect gas:

$$P\ V^{\gamma} = constant \tag{b}$$

with: P = pressure
V = volume
γ = gamma parameter

The γ parameter is the ratio of the specific heats of the gas. For the gas mixture given in section 3.1.2, this parameter has been found to be 1.352. For the same mixture, the mass flow per unit energy, m_e, was found to be:

$m_e = 3.716 \times 10^{-8}$ kg/J for a generation rate of 100 cc/KJ
$m_e = 3.159 \times 10^{-8}$ kg/J for a generation rate of 85 cc/KJ

and the specific internal energy EINEX:
$e = 5.68 \times 10^{6}$ J/kg

Density and velocity at the boundary are evaluated as a function of pressure variations inside the gas cavity forming around the arc. This is necessary in order to calculate correctly the work required to introduce the volume of gas into the thermodynamic system constituted by the tank.

The density, ROEX, is determined using the following relationship:

Pressure:

$$P = \varrho(\gamma-1)\ e \tag{c}$$

which is an equivalent equation of state (EOS) to (b).

Inverting the previous equation, we get for ROEX:

$$\varrho = \frac{P}{(\gamma-1)e} \tag{d}$$

The velocities of the fluid, UXEX and UYEX (which have the same value), are determined using the mass flow rate equation:

Mass flow rate:

$$\dot{m} = \varrho\ V A \tag{e}$$

where P is the pressure of the cell where the gas is introduced
ρ is the density
V is the velocity at the boundary
A is the area of the boundary

hence, for UXEX=UYEX:

$$V = \frac{\dot{m}}{\varrho A} \tag{f}$$

To compute the velocity, we must therefore evaluate the mass flow rate, $\dot{m}$, which is given by the product of the quantity m_e and the arc power:

$$\dot{m} = m_e EI \tag{g}$$

The voltage drop across the arc, E, is a function of its length and pressure:

$$E = l k \sqrt{P} \tag{h}$$

where : l is the length in cm
k is an empirical constant equal to 60 V/cm
P is expressed in atmosphere absolute.

The arc current, I, is more complex to model, the most general form of the current being given by the relation :

$$I(t) = I_1 e^{-c\omega t} + I_2 \sin(\omega t + \phi) \tag{i}$$

which represents both the transient and stationary terms. I_1, I_2, c and ϕ can be adjusted to fit any current waveform.

For the purpose of this analysis, it is assumed that the EI product is more or less constant giving a linear distribution of energy with respect to time, as shown in Figure 3.2 . This assumption is valid only for symmetrical currents (i.e. when the transient part is negligible) . For asymmetrical currents, the complete set of parameters and their dependencies on time must be considered.

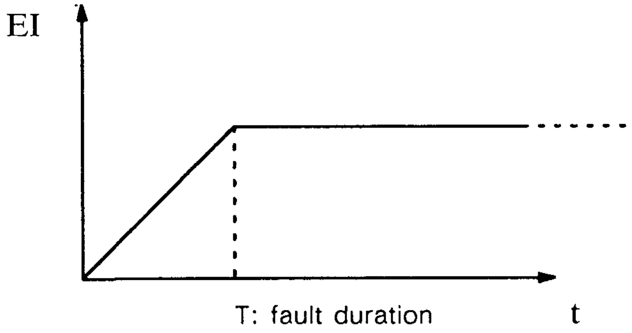


Figure 3.2: Idealized distribution of the EI product with time

Using this distribution of EI with time, we can now compute the arc power for any time and hence, the velocity of the gas leaving the cell.

4. Applications of the model

The simple model created was first used to verify certain assumptions and experiments on the rupture modes of a distribution transformer. The model was then validated by comparing it with the results of a test program performed for the Canadian Electrical Association (CEA) (11).

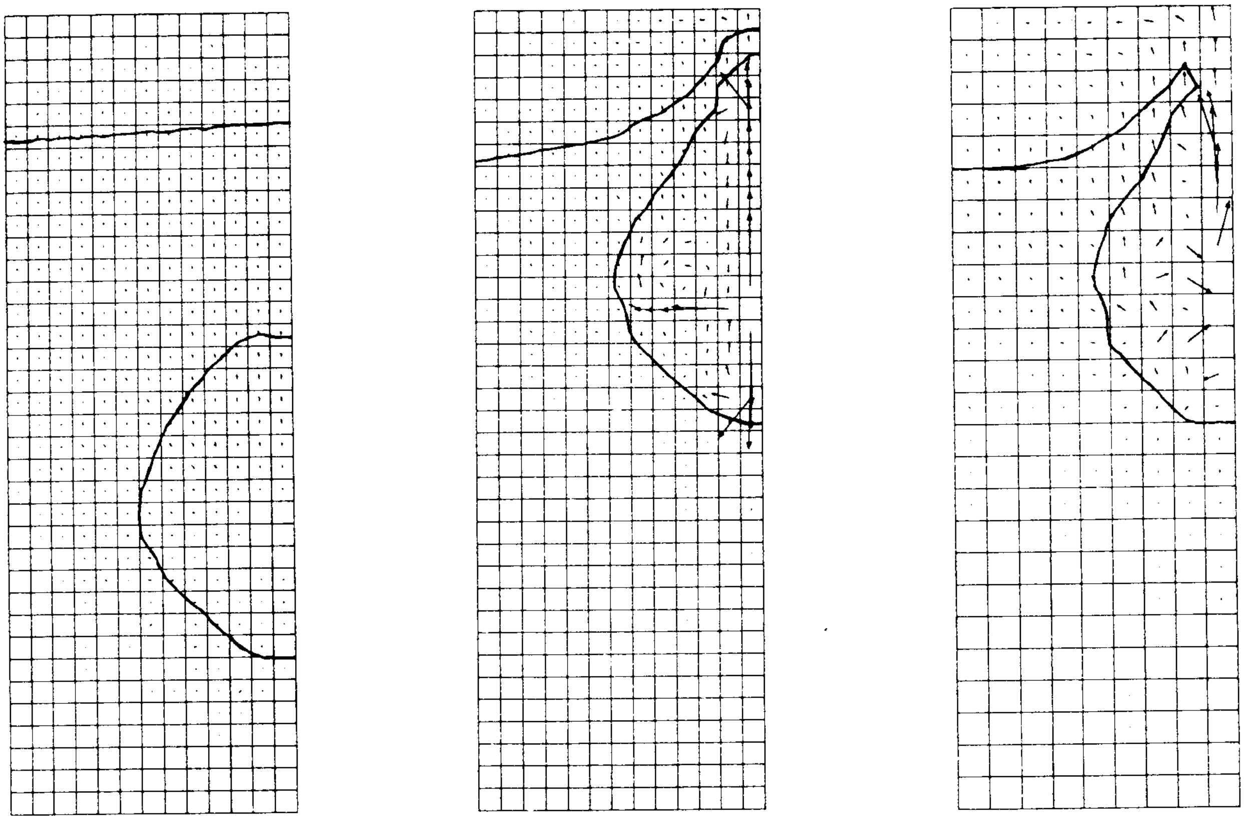
4.1. Rupture modes

Many assumptions have been made in the past to understand the actual causes of tank cover blowing off during internal faults in distribution transformers. In 1976, Barkan et al. performed an experimental test program to verify these assumptions (4). With the help of high–speed photography, they identified three rupture modes which, according to them, were dependent on the depth of the arc under the oil/air interface. The three modes identified were:

- *Oil piston:* the entire surface of the oil moves upward and remains practically plane. This occurs when the depth of the arc under oil is greater than the tank diameter.
- *Domed surface:* the surface of the oil moves upwards and takes on the shape of a dome. This occurs at a closer distance of the arc to the oil surface.
- *Surface breakthrough:* the gas bubble breaks through the surface of the oil. This happens when the arc is relatively close to the surface.

MSC/Pisces–2DELK was used to verify these rupture modes. The model was very similar to that in Figure 2.3, except that no core was used. The energy and fault duration were typical values.

We were able to successfully reproduce these three ruptures modes as shown in Figure 4.1 which represents grid–velocitiy plots produced by **MSC/Pisces–2DELK**. The three plots were taken at approximately the same time and differ only by the depth of the arc.



Oil piston Domed surface Surface breakthrough

Figure 4.1 Rupture modes reproduced with **MSC/Pisces-2DELK**

4.2. Comparison of the model with a test program for the Canadian Electrical Association

A research project was performed recently for the Canadian Electrical Association to investigate other ways of further improving measures intended to prevent eventual failures of transformer tanks (11). For this project, a complete test program was performed to investigate the relationships between different arc parameters and the pressure rise in a transformer tank.

Our model was used to reproduce some of these tests. As mentioned in section 3.1.1, the quantity of gas generated was initially set at 100 cc/kJ. After performing many simulations for different values of arc energy and comparing the results obtained with those of the test program, we concluded that the value of 100 cc/kJ was too high. We later reproduced the same simulations with a value of 85 cc/kJ and concluded that this value was closer to reality. Figure 4.2 presents the results of our simulation for the two gas quantities, along with the results of the test program for a particular set of parameters and variations of the arc energy. The pressures obtained are the peak pressures in the air space as a function of arc energy.

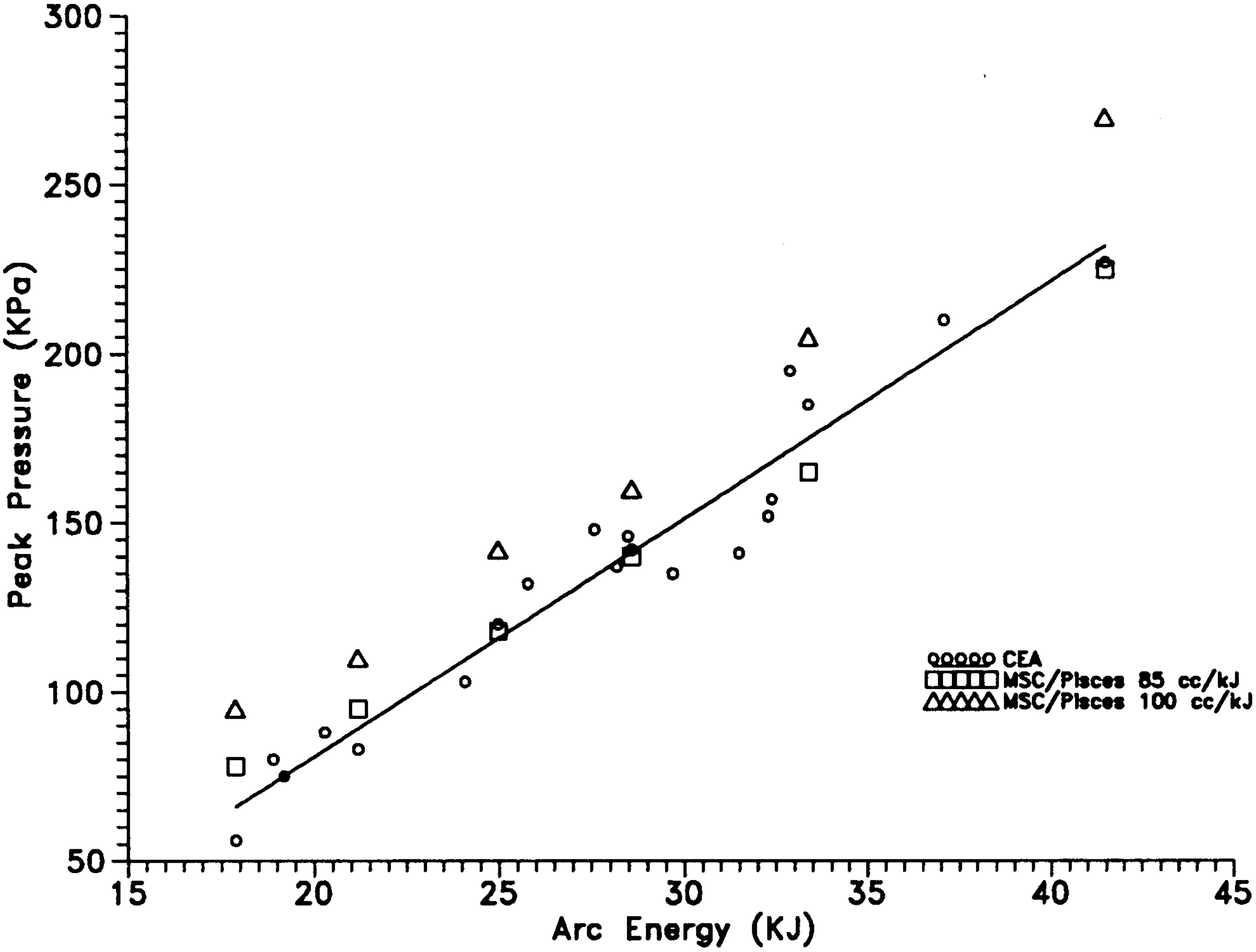


Figure 4.2 Comparison between **MSC/Pisces-2DELK** results and experimental data for the peak pressure as a function of arc energy

5. Conclusion

MSC/Pisces-2DELK was successfully used to analyze the problem of explosions in distribution transformers. The user-defined subroutine EXFLOW served to model the generation of gas caused by an arc in oil. The model allowed the three rupture modes observed in distribution transformers by previous investigators to be reproduced. By comparing the results with experimental data, we were able to deduce the amount of gas generated during an internal fault. Once this was done, the results of our model compared very well to the experimental data, confirming that peak pressures for such faults are linearly related to arc energy.

The main advantage of **MSC/Pisces-2DELK** is that it is a useful tool for successfully treating a problem that may be very tedious to treat analytically, without making major simplifications which would affect the accuracy of the results. Furthermore **MSC/Pisces-2DELK** can be used to investigate the problem of internal faults in electrical equipment insulated with oil, with no need for a costly experimental test program.

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