CFD BASED MULTI-PHYSICS SIMULATION OF COMPRESSIBLE FLOW THROUGH NOZZLE OF SF_6 GAS CIRCUIT BREAKER

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ABSTRACT

Physical phenomenon occurring inside a SF_6 gas circuit breaker involves multi-physics such as magneto-hydrodynamics (MHD), nozzle ablation, radiation, compressible flow and turbulent mixing.

The objective of the present numerical study is to understand the physics occurring inside a breaker during small current interruption. The study is done on a simplified geometry - a convergent-divergent nozzle geometry with two electrodes called as Lewis nozzle - which represents most of the physics in a real SF_6 gas circuit breaker.

Numerical simulations are done using general purpose commercial CFD (Computational Fluid Dynamics) software ANSYS FLUENT 13.0. However, in-house C programs – called as user-defined functions (UDF's) – are developed to model physics such as MHD and radiation. The numerical development and its coupling with the software is validated on a transient and 2-D axisymmetric problem - for a low DC current of 300A. Thereafter, the effect of different shapes – semi-hemispherical, flat, elliptical - of the tip of electrodes for the Lewis nozzle is studied; as previous work is on only semi-hemispherical tips. A detailed CFD analysis is presented here to discuss the reasons for the variation of temperature, arc radius and arc voltage along the axis. This study will help in drawing conclusions applicable to the performance of circuit breaker.

1. INTRODUCTION

A circuit breaker should be able to interrupt small (of the order of few hundred amperes) as well as large (i.e. short circuit currents, of the order of 40-50 kA) currents. The physical phenomena occurring inside the breaker during small current and large current interruption - involves strongly coupled gas dynamics and electromagnetic – are quite different and challenging.

The present work explores the physical phenomenon, during interruption of small current, inside the breaker. The numerical investigation is performed using commercial CFD software (ANSYS FLUENT 13.0). These required a numerical development of user-defined functions (UDF) to models physics such as MHD and Radiation; and then couple it with the CFD solver. The development is validated with a test case from literature- Lewis nozzle with semi-hemispherical tipped stationary electrodes [1]. Thereafter, effect of electrode tip shape is investigated using two different electrode shapes- the electrode with flat tip and elliptical tip. The variation of temperature, arc radius and arc voltage along the axis and their probable causes are then discussed.

2. NUMERICAL METHODOLOGY

The governing equations for the present problem are compressible Navier-Stokes equations and simplified form of Maxwell's equations, given as below.

$$\frac{\partial \rho}{\partial t} + \nabla \bullet \left(\rho \vec{V} \right) = 0 \qquad \text{..........(1)}$$

$$\rho \frac{D\vec{V}}{Dt} = -\nabla P + \rho \vec{g} + \nabla \bullet \tau + S_{mom} \qquad \text{...(2)}$$

$$\rho C_p \frac{DT}{Dt} = \nabla \bullet k \nabla T + \beta T \frac{DP}{DT} + Q + S_{energy} \qquad \text{...(3)}$$

$$\nabla \bullet (\sigma \nabla \phi) = 0 \qquad \text{..........(4)}$$

$$\nabla^2 \vec{A} = -\mu_0 \vec{J} \qquad \text{..........(5)}$$

where $\nabla \bullet \tau$ is stress tensor, Q is viscous heat dissipation, S_{mom} is a source term coming from MHD i.e. Lorentz force $\vec{J}\times\vec{B}$, and S_{energy} is source term comprising ohmic loss J^2/σ and radiation heat energy.

In this study, Net Emission Coefficient model (NEC) [3] is used to model radiation, where a source term is added to the energy equation to model emission and absorption of radiations. For arcing arrangements such as in puffer circuit breakers, it was reported [4] that the NEC model as compared to more complex and more computationally expensive P1 model gives almost same accuracy in the results.

This problem is solved as a two-way coupled electromagnetic-thermal model. The additional non-linearity introduced in the CFD equations, by the temperature and pressure dependence on the thermo-physical properties makes this CFD problem very stiff.

UDFs are developed to calculate pressure and temperature dependent thermo-physical properties (density, thermal conductivity, specific heat, viscosity, speed of sound, electrical conductivity), ohmic loss, Lorentz force, and radiation source term.

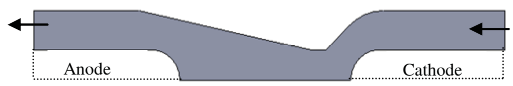

Fig. 1: Lewis nozzle geometry. Note that the flow direction is from right to left.

3. VALIDATION OF NUMERICAL METHODOLOGY

Simulation is performed on a convergent-divergent Lewis nozzle geometry (*Fig. 1*) [1-2]. Steady state simulation is performed with 300A DC current arc struck between the *semi-hemispherical tip electrodes*.

Structured grid with 1,00,701 elements is used in this simulation. Upstream total pressure of 7.48 atm is imposed at the inlet and static pressure of 1 atm is applied at the outlet. Current density corresponding to 300A is applied at the cathode end and zero electric potential is applied at the anode end.

An excellent agreement between the present and published [1] steady state results, for temperature and Mach number distribution, is shown in *Fig. 2*.

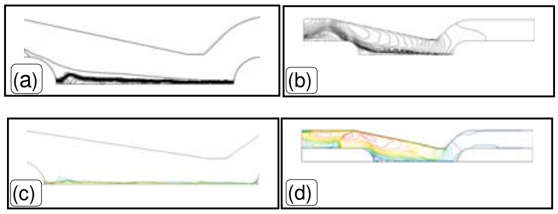

Fig. 2: Validation of numerical methodology for small current interruption, with 300A arc struck between semi-hemispherical tip electrodes: Contours of (a,c) temperature and (b,d) Mach number, with the range of variation for the respective variable as 228K-27130K and 0.00488-2.395 in the (a,b) published[1] and as 247.85K- 28217.4K and 0.0049-2.47 in the (c,d) present results.

4. NUMERICAL INVESTIGATION WITH DIFFERENT ELECTRODE SHAPES

Simulations are performed with two more electrode shapes - the electrode with flat tip and elliptical tip. Mesh and boundary conditions are similar to that in semi-hemispherical tip case. The results of the three cases are discussed in next section.

5. RESULTS AND DISCUSSIONS

a) Heat and Fluid Flow pattern near the Tip of Electrodes

The effect of various shapes of the electrode tip is shown in Fig. 3, as velocity vector and temperature represented by the color of vector. The figure also shows colorbar for temperature.

Near the cathode tip, Fig. 3(a-c) shows the size of the vortex (recirculation region) is much larger for the flat – due to much sharper change in the flow cross-section – as compared to other shapes of the tip. This leads to much heated region near the flat tip.

Near the anode tip, Fig. 3(d-f) shows the size of the vortex as largest for elliptical and smallest for the flat tip. However, the vortex for the elliptical as well as hemi-spherical, as compared to flat, tip is much closer to the tip of the anode. The centre of the vortex for the flat tip is at a larger height as compared to that for the other shapes of the tip. Thus, the relatively colder gas from outside the arc region is able to flow into the anode tip region – lead to lower temperature at the flat tip.

The temperature contours, near the cathode tip, is shown in *Fig. 4(a-c)*. The minimum temperature of the contours is kept as 4000K - to represent the arc boundary. Current density vectors, colored by radial component of Lorentz forces, are also shown in *Fig. 4(d-f)*.

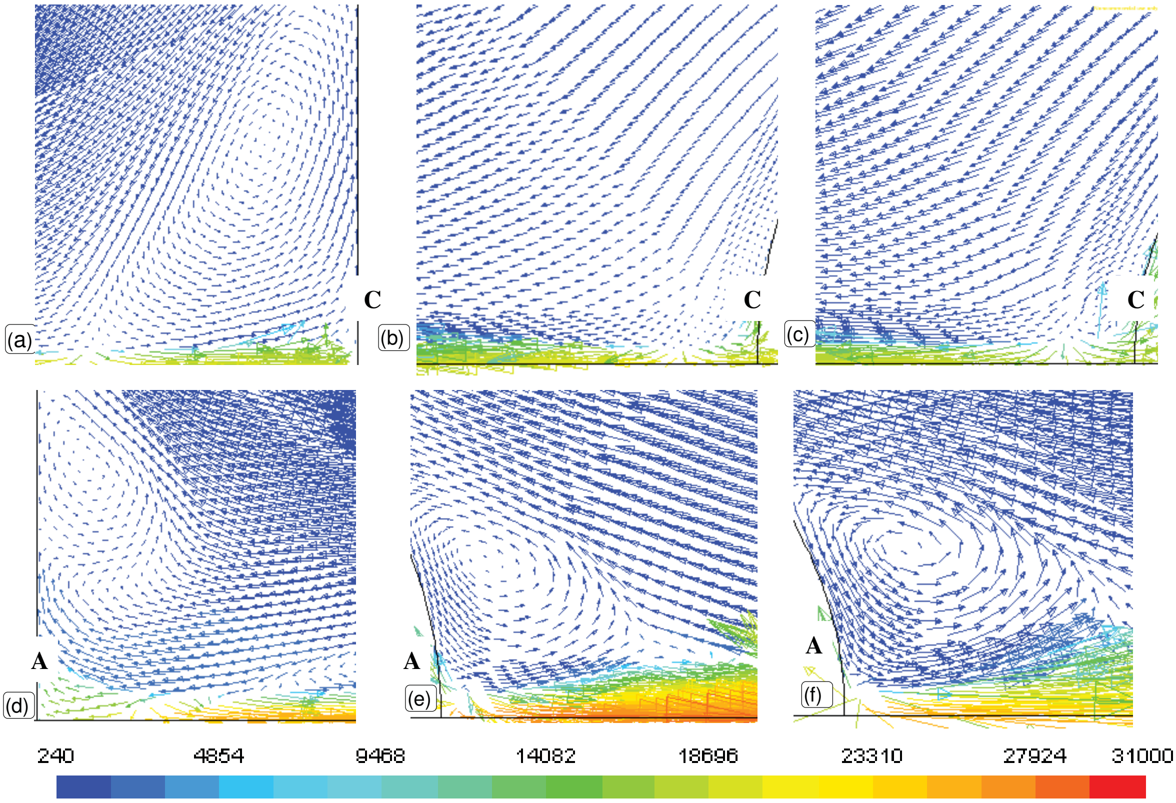

*Fig. 3: Velocity vectors - colored by temperature - near the (a-c) **C**athode and (d-f) **A**node for (a,d) flat, (b,e) hemi-spherical and (c,f) elliptical tip of the electrodes*

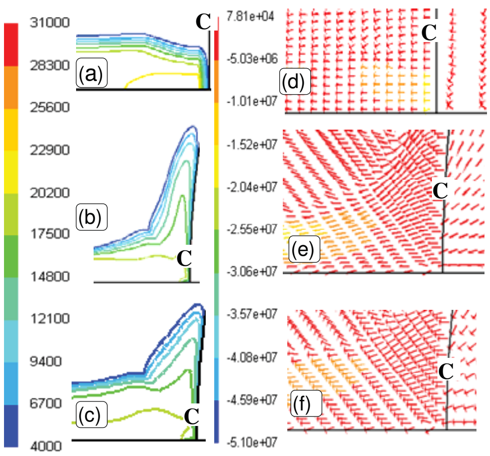

*Fig. 4: (a-c) Temperature contour and Current density vectors (colored by radial Lorentz forces)-near the **C**athode for (a,d) flat, (b,e) hemi-spherical and (c,f) elliptical tip of the electrodes*

b)Temperature at the Tip of Electrodes and average temperature along Axis

Temperature at the tip (at the axis) of anode and cathode is shown in Fig. 5. The figure shows minimum and maximum temperature at the tip of anode and cathode, respectively, for flat tip; vice-versa for elliptical tip. It can also be seen that the average temperature along the axis is maximum for hemi-spherical shape of the electrode tip.

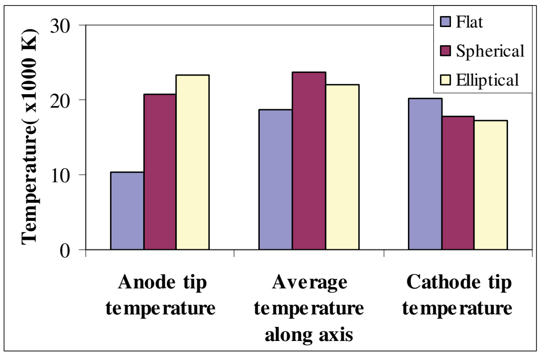

Fig. 5: Comparison of temperature for the various shapes of the tip of the electrodes

c) Arc radius at the Tip of Electrodes

Arc radius at the tip of anode and cathode is shown in Fig. 6. The figure shows maximum and minimum arc radius at the tip of anode and cathode, respectively, for flat tip; vice-versa for elliptical tip. Note the effect of the different shapes of the electrode tip is opposite for temperature and arc radius at the tip (compare Fig. 5 & 6). The variation in arc radius for different shapes of tip of electrode can be attributed to the current density distribution.

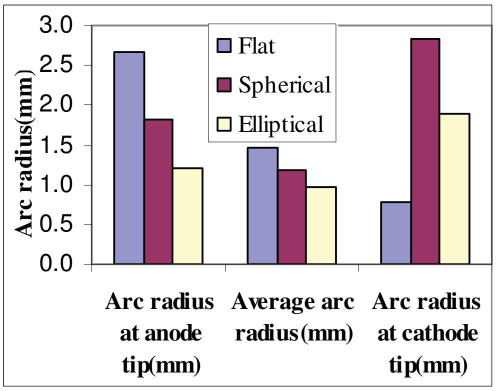

Fig. 6: Comparison of arc-radius for the various shapes of the tip of the electrodes.

At the cathode tip, in case of flat tip electrodes, the current density distribution results in the radial component of Lorentz force (-1.61 x 10^7 N/m^3) which is much more than that in spherical (-0.73 x 10^7 N/m^3) and in the elliptical (-0.98 x 10^7 N/m^3) electrode case (Fig. 4(d-f)). Hence the constriction of arc is the highest in flat tip electrode case. Considering the arc extinguish requirement in a circuit breaker, minimum arc radius at the electrode tip is desirable.

At the anode tip, the magnitude of radial component of Lorentz force is minimum for the flat tip electrode (-0.2 x 10^6 N/m^3), as compared to that for spherical (-1.05 x 10^6 N/m^3) and elliptical (-2.58 x 10^6 N/m^3) electrode case. Hence, the value of arc radius is maximum for the flat tip electrode (2.68mm), as compared to that for spherical (1.83mm) and elliptical (1.21mm) electrodes.

Figure 6 also shows that the average arc radius is maximum for flat and minimum for elliptical shape of the tip of the electrodes.

d) Arc voltage

The variation of arc voltage along the axis is shown in *Fig.7*.

This problem involves two way coupling between CFD and electromagnetic phenomenon. The flow and thermal field - inside the nozzle - modifies the electrical conductivity of the gas, which in turn changes the ohmic loss and Lorentz force values. The modified values of ohmic loss and Lorentz forces further change the flow and thermal field; and the cycle repeats.

Thus, the electric, flow and thermal fields are developed in such a way that the arc voltage is the minimum (1260.4V) for flat as compared to the spherical (1438.3V) and elliptical tip electrodes (1581.1 V).

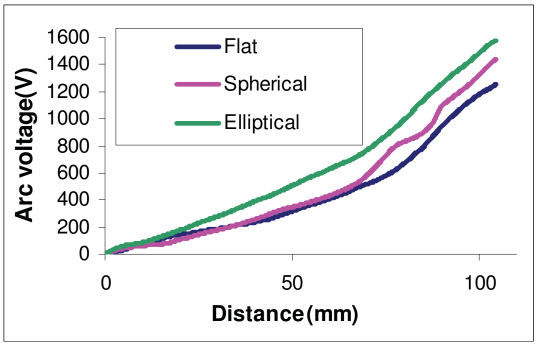

Fig. 7: Comparison of arc voltage for the various shapes of the tip of the electrodes.

4. CONCLUSIONS

- In-house UDF development based numerical methodology has been developed to analyse small current interruption phenomenon in a circuit breaker, using commercial CFD solver ANSYS FLUENT 13.0.
- The effect of three electrode shapes - semi-hemispherical tip, flat tip and elliptical tip - are studied.
- Reasons for a variation of temperature, arc radius and arc voltage along the axis are presented. This study will help in drawing conclusions applicable to the performance of circuit breaker.

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