MEASURED AND SIMULATED SF_6 MIXING BEHAVIOUR

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ABSTRACT

The dielectric performance of SF_6 high voltage gas circuit breakers depends on the temperature distribution of the gas during the post-arc phase. Understanding the details of the mixing process occurring during arcing is therefore fundamental. In this paper we present a shadowgraphy measurement of turbulent mixing induced by an ablation arc inside a transparent device filled with SF_6. The device is designed to resemble circuit breaker geometry and it is equipped with pressure transducers. This approach allowed us to observe qualitatively the mixing behaviour and to obtain information on flow quantities, like pressure, flow structure size and velocity. In the second part of the paper we compare these data with a CFD calculation in order to assess the accuracy of the simulation.

1. INTRODUCTION

Part of the nozzle material ablated during the high current phase in a modern high voltage circuit breaker (HVCB) is forced to flow through a channel into a chamber, where it mixes with cold SF_6. The pressure rises in this chamber due to the energy input of this heated gas. This energy is stored and used to extinguish the arc at the next current zero (CZ) crossing. The dielectric recovery of a HVCB after CZ is influenced by the mixing process inside this chamber. In particular, incomplete mixing can lead to very hot gas (~3000 K) flowing back in between the arcing contacts. Due to its low density and composition, the dielectric withstand of such a hot gas mixture is worse than cold SF_6. Under a recovery voltage this can lead to a re-strike which ends in a dielectric failure of the HVCB. Design studies for the optimization of the geometry are usually performed using a computational fluid dynamics (CFD) approach to calculate the temperature distribution during the high current phase and the resulting temperature of the quenching gas. Validation of such simulations is usually done using pressure measurements [1], which however give no information on the local distribution of flow variables (density, velocity, etc.) inside the circuit breaker. Obtaining such information is especially complicated due to the low diagnostic accessibility of a real gas circuit breaker and the scarceness of measurement techniques suited to provide fast enough information on the spatial distribution of flow variables.

In our previous work [2] we introduced an experimental device especially designed to investigate the turbulent mixing of the hot gas coming from an arc inside a small volume. We successfully applied an optical technique (shadowgraphy) to obtain information on the mixing pattern and extract quantitative information on the velocity field using air as the studied gas. In this paper the same device and technique are used to extend the analysis to SF_6. We will present the experimental results for a single configuration and compare them with dedicated CFD calculations to assess the accuracy of the simulations.

2. EXPERIMENTAL SETUP

The experimental assembly and setup are described in detail in our previous work (please refer to the whole section 2 in [2]). The main chamber, consisting of a 110x60x30 mm parallelepiped volume, is rearranged as depicted in Fig. 1 in order to have an axial inflow from the arcing zone and more realistic ratios between the chamber dimensions and the channel length. The total mixing volume is about 96 cm^3 and the channel length approximately 56 mm. The inserts which shape the mixing volume are made out of PTFE.

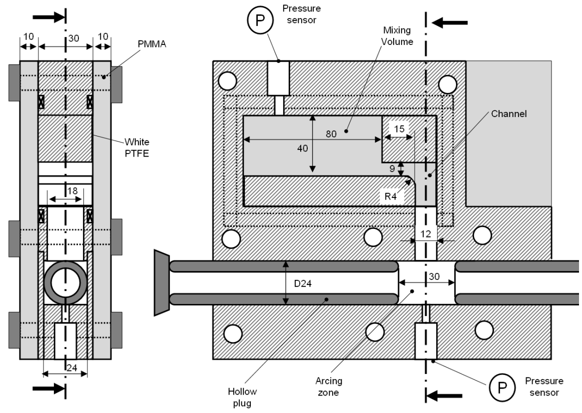

Fig. 1: Test device.

All the other parts of the assembly, as well as the geometry are the same as in [2]. As in our previous experiments in air we measure current and voltage between the arcing contacts, as well as the pressure in the arcing zone and the mixing chamber during the current application. Furthermore, through the optical setup, shadowgraphy images of the mixing volume are recorded by means of a high speed camera [2,3].

3. TEST ANALYSIS

In the experiment we applied a 50Hz halfwave with current peak of approximately 5kA. We performed two subsequent identical current applications to evaluate the repeatability of the experiment, which was very high. Given this, we will present only the results for the first test. The processing of the measured signals is done through a simple Matlab routine to account for the different sensors employed (shunt resistance, voltage divider ratio, pressure calibration). The arc current and voltage for the test is shown in Fig. 2.

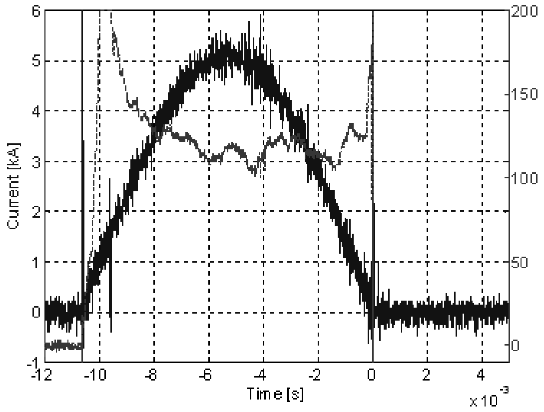

Fig. 2: Measured arc current and voltage.

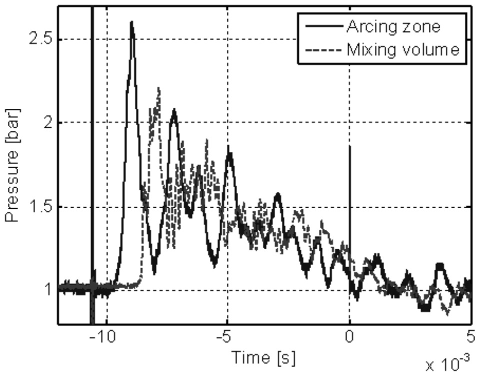

Fig. 3: Measured pressure in the arcing zone and mixing volume.

The average arc voltage is about 115 V, including the arc roots. The arcing time is about 10.6 ms. The ignition wire exploded after about 1 ms from triggering, therefore the arcing time is roughly 9.6 ms. The estimated total arc energy is about 3.6 kJ. Fig. 3 shows the pressure in the arc zone and in the mixing volume. The initial rise in the arcing chamber pressure due to the wire explosion (peak @ 2.5 bar) is clearly observable. This pressure wave travels to the mixing volume sensor, which is reached with a delay of about 1 ms, corresponding to the time needed to travel the distance between the sensors at the speed of sound of cold SF_6 (about 137 m/s). Afterwards a moderate pressure build up (ΔP of about 0.5 bar) is measured during the current phase.

An example of the shadowgraphy images acquired by the high speed camera is shown in Fig. 4. The snapshot refers to 7.4 ms before CZ, therefore the arc has been burning for approximately 3 ms. The lighter blur in the lower left corner of the image is made by the light emission of the arc in the arcing zone. From the snapshot one can see that the channel is completely filled with hot gas, whose density produces a large deflection of the laser beam, resulting in a very dark region. Part of the mixing volume in front of the channel (left part) is filled with hot gas as well. Again, it can be easily distinguished by the cold SF_6 all around, which presents a uniform pattern separated by travelling lines, which are the shock fronts. The cold SF_6 around the hot gas pocket acts as a damper, preventing further penetration inside the mixing chamber. Due to this action, it takes many milliseconds for the hot gas to achieve complete mixing inside the volume. The boundary between the hot and cold gas is clearly defined by a fine, darker turbulent region.

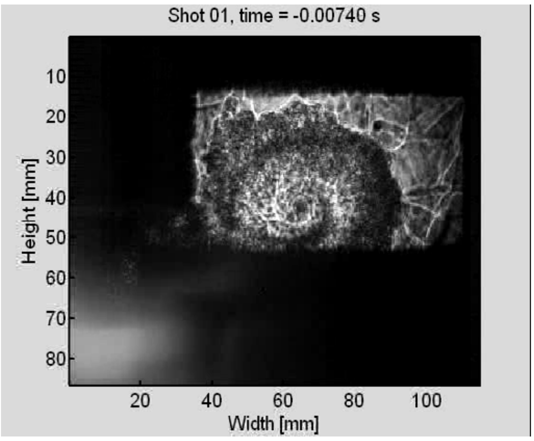

Fig. 4: Snapshot of the optical measurement 7.4 ms before CZ (the image is mirrored with respect to Fig.1 and Fig. 5).

Inside the hot gas cloud a counter clockwise vortex is generated by the pumping action from the arc zone. Here the turbulent structures are elongated. The higher luminosity of this region suggests a further density difference with respect to the fringes. The size of the flow structures differs as well.

4. CFD SIMULATION

The Navier-Stokes equations for the conservation of mass, momentum and energy are solved iteratively by means of a commercial finite volume solver (FLUENT) for a mixture of two species, namely SF_6 and PTFE. Materials properties for pure SF_6 and PTFE, as well as for their mixtures, are calculated with an in-house code. Due to its small depth, the mixing volume can be reasonably approximated by a bidimensional system in Cartesian coordinates, thus transport along the z direction is not included. The turbulent transport is modelled through turbulent transport coefficients obtained by solving two extra equations for the turbulent kinetic energy and dissipation ($\kappa\varepsilon$ model in its realizable formulation [4]). A proper turbulence modelling is essential to capture the features of the mixing process.

The computational domain is depicted in Fig. 5. It is defined from the geometry of the mixing chamber and the channel up to the arcing zone. The arc is not modelled and its presence is simulated through a transient pressure boundary condition, imposing the measured pressure signal in the arcing zone.

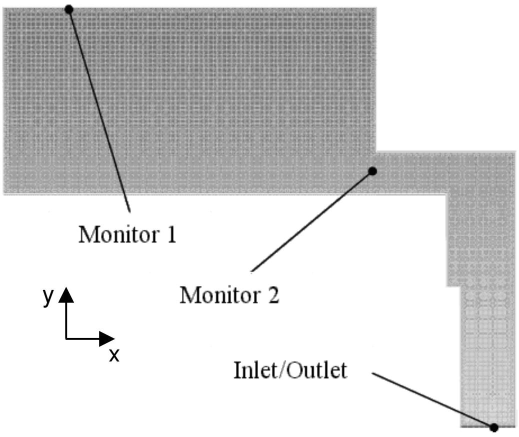

Fig. 5: Computational domain and discretization.

The temperature of the gas entering the domain is imposed to 3500 K and its PTFE content equal to 1, assuming that during the arcing phase only ablated material from the PTFE surfaces feeds the mixing volume. Turbulence coming from the arcing chamber is neglected. Due to the relatively low gas temperatures in the channel and mixing volume radiation transport is not included in the model. Heat transfer in the gas occurs only through (turbulent) conduction and convection. The mesh is structured, with a cell size of 1 mm^2. The mesh is refined close to the boundaries for a proper wall function modelling (standard [4]). The mesh is also refined at the flow inlet for numerical stability. The number of cells is about 8500. The simulation is initialized with properties for pure SF_6 at 1 bar and 300 K. All the boundaries are adiabatic, no-slip walls, except the pressure inlet/outlet, which corresponds to the channel connection in front of the arcing zone. Flow variables are monitored at two locations corresponding to the mixing volume pressure sensor location and the channel end into the mixing volume (monitor 1 and 2 in Fig. 5, respectively).

The comparison between the simulated and measured pressure in the mixing volume is shown in Fig. 6. The simulated pressure build up agrees nicely with the measured one. In particular, the delay and the amplitude of the first pressure wave are exactly reproduced. After this wave, the measured signal shows a high frequency oscillation (about 3 kHz), which is not reproduced in the simulation. From the movie analysis one can observe that these high frequency peaks are related to the bouncing of the pressure waves in the mixing volume. They smear out during the mixing process.

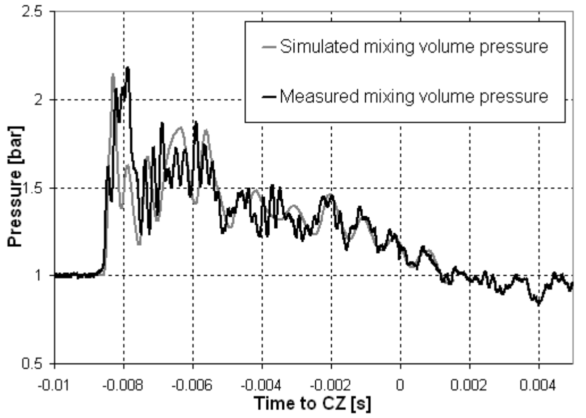

Fig. 6: Measured and simulated pressure in the MV.

The pressure oscillations during the last milliseconds of arcing are again very well reproduced in the simulation. In this region the flow direction is from the mixing volume towards the arcing zone, i.e. the flow has reversed is direction. This result indicates that an arc model which correctly estimates the pressure in the arc region, leads to prediction of the correct pressure build up in the mixing volume.

To address the flow reversal time, we plot in Fig. 7 the horizontal velocity component (x-component) at the monitor 2 location. A positive velocity value means that the gas is flowing from the mixing volume to the arcing zone (flow reversal), vice versa a negative value means that gas is flowing from the arcing zone towards the mixing volume. The full line represents the simulation output, while the squared points are values which are estimated by tracking flow structures in subsequent snapshots. The arrival of hot gas from the arcing zone occurs during the initial phase, up to the current peak.

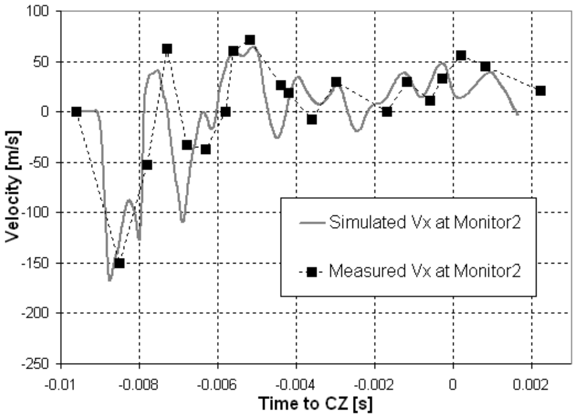

Fig. 7: Measured and simulated x component of velocity at monitor 2.

The quantitative agreement is rather good and the subsequent hot gas "waves" arriving in the mixing volume are well captured. These waves are clearly determined by the pressure oscillations in the arcing zone. At CZ both the simulation and the experiment show a complete mixing of the gas in the compression volume. The flow reversal velocity is then defined by the mixed temperature and the pressure reached in the mixing volume. This indicates that the former is reasonably well estimated in the simulation (~380 K at CZ).

5. CONCLUSION

In this work we studied the mixing process caused by an ablation arc inside a test device filled with SF_6 and made accessible to optical diagnostics. Shadowgraphy was applied to track the differences in the density of the gas. Additionally, pressure both in arc and heating volumes, arc voltage and current were recorded. Observed mixing patterns and velocities were qualitatively and quantitatively compared to CFD simulations. This extended comparison validates the numerical methods presently used for describing such processes inside a gas circuit breaker. The flexible design of the test device makes the extension of this study to different channel and mixing volume geometries straightforward, as well as current amplitudes, arcing times and/or filling gases. Furthermore we are working to extend the investigation to full 3D configurations in order to define the suitability of the 2D assumption.

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