MEASUREMENT OF 3D TURBULENT MIXING IN A SMALL-SCALE CIRCUIT BREAKER MODEL

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ABSTRACT

In this paper we demonstrate that it is feasible to measure turbulent mixing in a 3D small scale circuit breaker model using a bright field schlieren setup with Fresnel lenses.

An example shot in air at atmospheric pressure is studied. The peak pressure was above two bar, i.e. sonic conditions were reached. The resulting radially expanding shock wave was detected and velocimetry applied to obtain quantitative information on the flow speed in the heating volume once the shock wave had subsided.

1. INTRODUCTION

Turbulent mixing of hot and cold gas in the various volumes of high voltage gas circuit breakers is important for the short-circuit current interruption performance. Understanding of this topic remains rudimentary. Mixing in a quasi-2D simplified breaker geometry has previously been measured and quantified [1]. However, the mixing process in 3D was not tackled in this earlier work. Thus, as the next step it is important to address possible 3D mixing effects, which can be due to, e.g., (i) arc instabilities, (ii) flow past obstacles and (iii) deviations from cylindrical symmetry introduced during manufacturing and assembly of the breaker. In this paper, we present first results from a 3D small-scale circuit breaker test device.

2. OPTICAL SETUP AND DISCHARGE

The test device is shown in Fig. 1; the transparent heating volume surrounds the grey polytetrafluoroethylene (PTFE) nozzles. The inset provides an overview of the dimensions of the test device. The heating volume is 0.5 liter and the hollow arcing contacts act as exhaust tubes.

Turbulent mixing is measured using the schlieren technique [2], see Fig. 2. A 20 mW HeNe laser is expanded using a 100× microscope objective and collimated by a Fresnel lens having a focal length of 330 mm. After passing the test device, the laser beam is focused with a 550 mm focal length Fresnel lens. Several means are applied to prevent arc light from reaching the high speed camera serving as our detector:

1. The exhaust jets from the hollow arcing contacts are directed downwards.
2. A polarizing filter only allows linearly polarized light to pass: The HeNe light is linearly polarized whereas the arc light is not polarized.
3. A narrowband HeNe filter only allows light around 632.8 nm to pass.
4. A 2 mm diameter pinhole which (i) increases sensitivity to turbulence (schlieren) and (ii) reduces the overall intensity of light is used.

Light from this bright field schlieren setup is detected using an 18 mm objective mounted on a complementary metal oxide semiconductor (CMOS) camera. The camera sampling rate is 63492 frames per second (15.75 μs between frames) with an exposure time of 1 μs. The area used on the chip is 256 (width) × 128 (height); one pixel corresponds to 0.705 mm.

The typical current of a shot (discharge) is displayed in Fig. 3. The arc was burning in air at atmospheric pressure. The arcing time is 10 ms (50 Hz) and the current peak is 4.5 kA. The deformation of the current at 2 ms is due to the evaporation of the ignition wire used to initiate the shot.

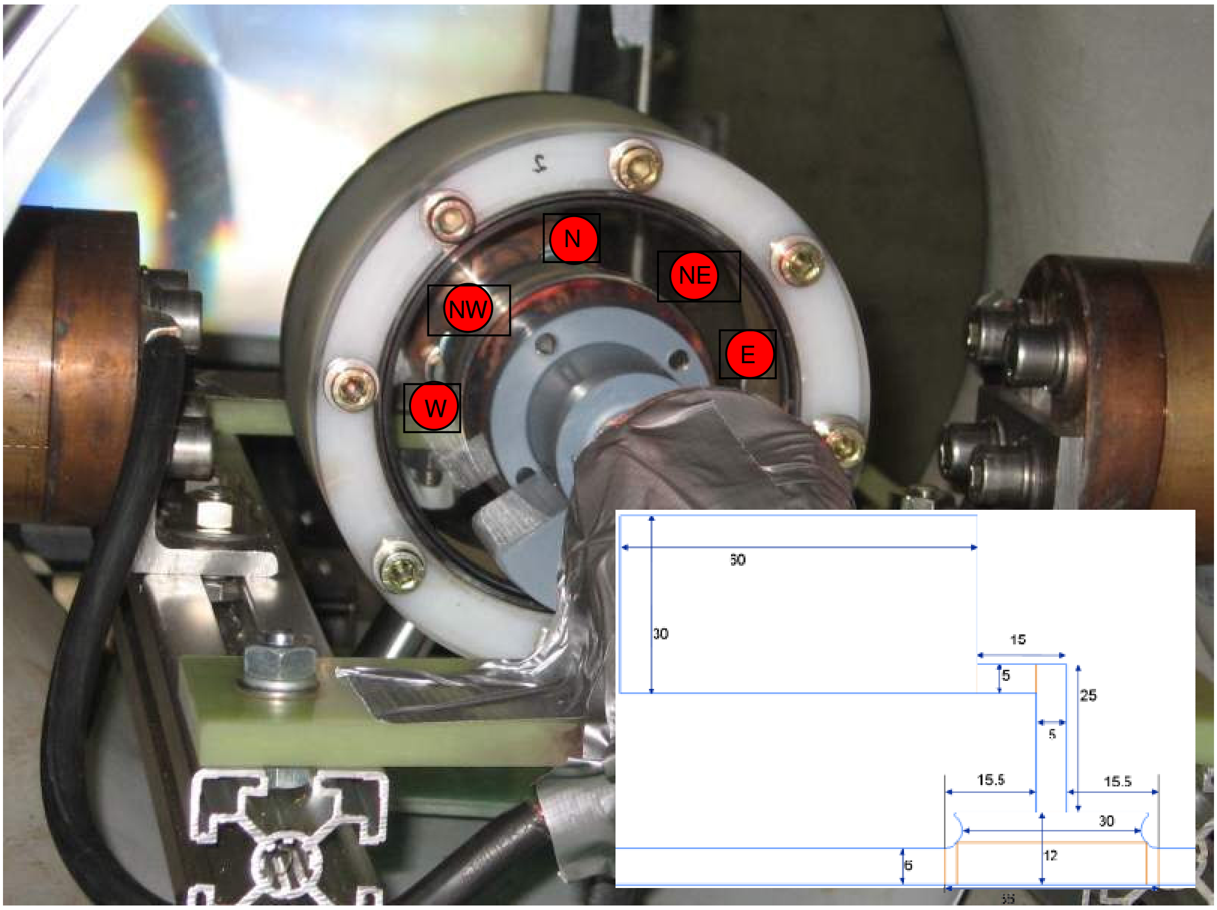

Fig. 1: Picture of the transparent heating volume along with mounting; the letters refer to positions where speed is monitored; see Figs. 6 and 7. The inset shows the dimensions of the heating volume (top left) and the arc zone (bottom right); all distances are given in mm.

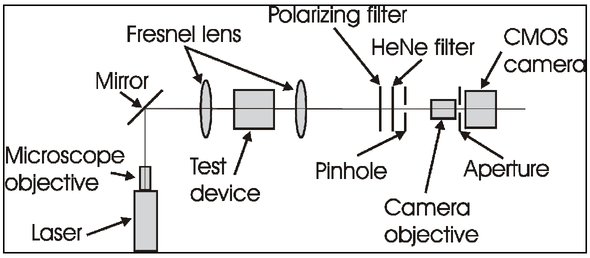

Fig. 2: Sketch of the schlieren setup.

Pressure was measured both in the arc zone and in the heating volume, see Fig. 4. Pressure begins to increase because of backheating after the ignition wire has evaporated. It displays a peak of 2.3 bar after 6 ms. At this time, flow reversal takes place and outflow from the heating volume to the arc zone commences.

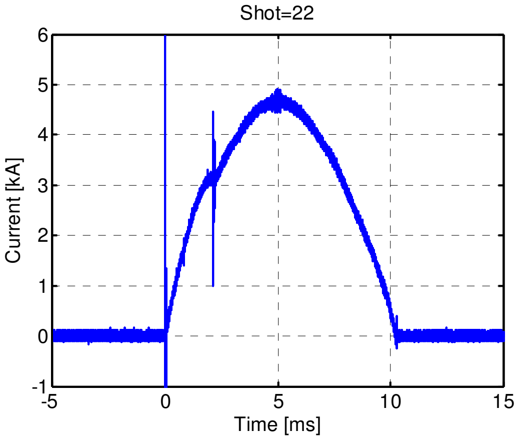

Fig. 3: Current waveform of the shot analysed.

During the outflow phase, the heating volume pressure is higher than the arc zone pressure. The 2 kHz oscillation seen in the arc zone pressure during outflow is most likely a Helmholtz (pipe) resonance excited in the channel connecting the arc zone pressure sensor to the arc zone.

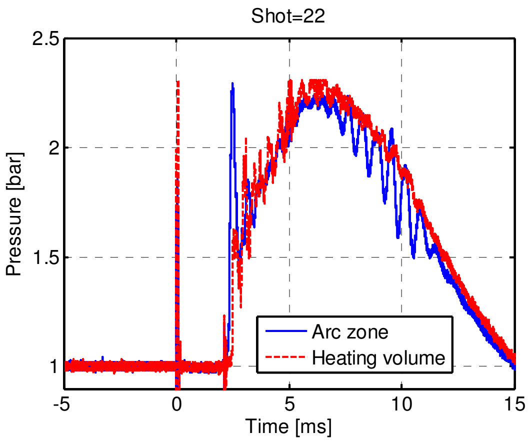

Fig. 4: Arc zone pressure (solid line) and heating volume pressure (dashed line). Note: the peak heating volume pressure is slightly saturated.

3. IMAGES OF THE EXPANDING SHOCK WAVE

An impression of the initial shock wave is given by the sequence of images in Fig. 5. The images are difference images, i.e. the previous image is subtracted from the present image. In this fashion, only changes from one frame to the next are shown. Note: What is observed are line integrated changes in the refractive index, i.e. 3D phenomena represented in 2D. To enable a faster frame rate, only the upper half of the heating volume is imaged. The first image, a, is a reference image to display the image before the shot. The sequence of images b through f shows the radial expansion of the shock wave; the images are two frames, i.e. 31.5 µs, apart. Image b is from before the shock wave enters the heating volume; weak turbulent activity due to the evaporation of the ignition wire is observed, especially in the NW sector (see Fig. 1). The expanding shock wave is first seen at the inner rim of the heating volume in image c and expands in the following images. One can roughly say that the shock wave expands 10 mm radially from image d to image e, yielding a speed of 10 mm/31.5 µs = 317 m/s , close to the sound speed of air at room temperature, 340 m/s. We observe that the shock wave expansion is rather symmetric azimuthally.

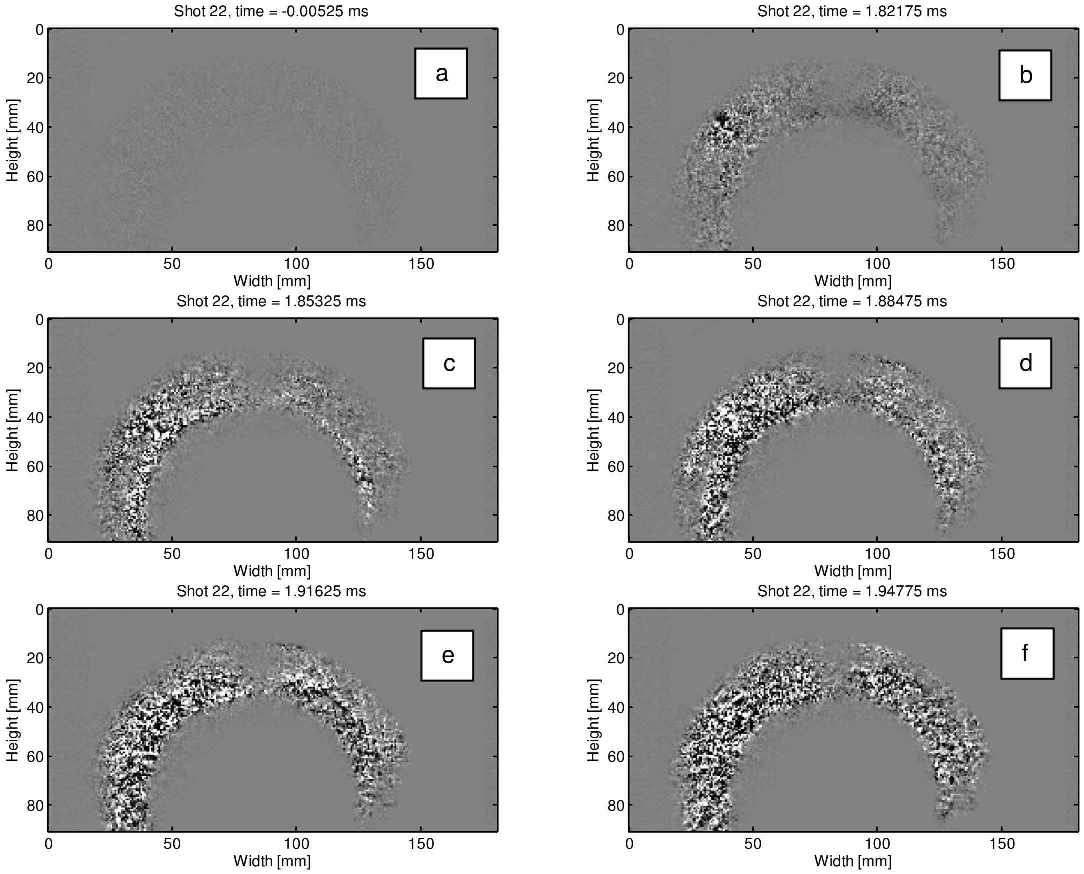

Fig. 5: Sequence of images displaying the expansion of the initial shock wave; image a is a reference image from before the discharge. Images b (first image) through f (last image) show the expansion of the shock wave. The time between the images is 31.5 µs (2 frames).

4. FLOW SPEED

We use schlieren "particle image velocimetry" [3] to track the speed of turbulent structures convected with the flow following the shock wave. To calculate the cross correlation between single (not difference) frames we use 16×16 pixel windows moved in 4 pixel steps; see [1] for further details. The speed is monitored in the five points indicated in Fig. 1 to investigate possible asymmetries or relative time delays at the various positions. Speed at the five points selected is shown in Fig. 6 along with the arc voltage in arbitrary units. Note: Only speed perpendicular to the laser beam is extracted. The peak in the arc voltage at about 2 ms (see trace at the bottom of Fig. 6) marks the evaporation of the ignition wire and the initiation of the actual shot. Subsequently, moving structures are detected, during backheating at the NE and E positions and during outflow first in the W sector, then at the NW and N points. Whether this split between backheating and outflow is significant, i.e. an indication of asymmetric flow, remains to be determined.

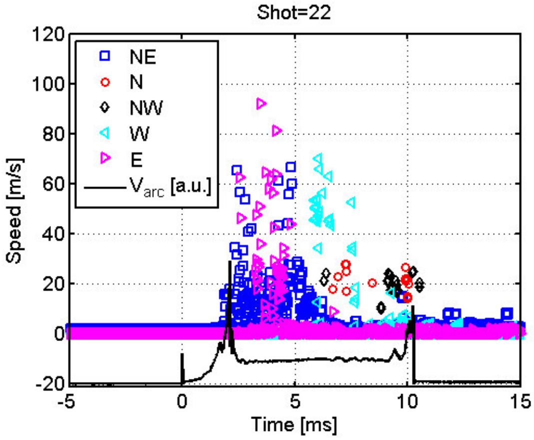

Fig. 6: Speed at the five points indicated by circles in Fig. 1 along with the arc voltage.

The average speed at the various positions is 10 to 20 m/s, similar to previous results [1]; see Fig. 7. The outflow speed is well defined compared to the backheating speed, consistent with the measurements in [1] (Fig. 16). The outflow speed at the W position is much higher than at the NW and N points. Fast flows > 100 m/s, e.g. shock waves, are not tracked, probably because the turbulent structures deform from one frame to the following at those speeds.

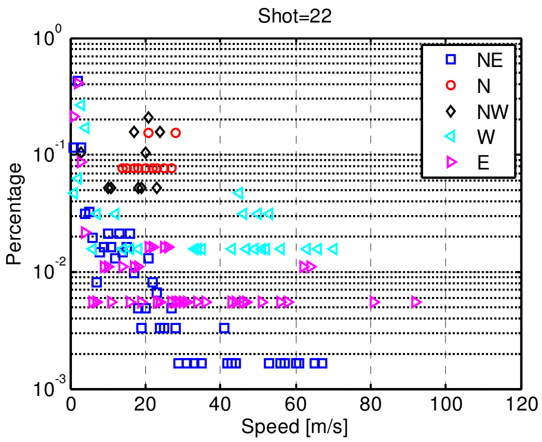

Fig. 7: Histogram of speeds in 1 m/s bins from Fig. 6 using a semi-logarithmic scale.

5. OUTLOOK

Future work includes:

1. Diagnostics:
    a. Improve optics to optimise turbulent structure detection.
    b. Attenuate the arc light more.
2. Analysis:
    a. Improve correlation method to track deforming turbulent structures, i.e. improve velocimetry.
    b. Compare measurements to computational fluid dynamics simulations.
3. Experiments:
    a. Quantify the effect of asymmetries caused by e.g. the current path and the assembly of the test device.
    b. Gauge variations with current amplitude (experiments partially completed) and different gases.

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