

PIV-MEASUREMENTS OF REACTANT FLOW IN HYDROGEN-AIR EXPLOSIONS

Vaagsaether, K.¹, Gaathaug, A.V.¹ and Bjerketvedt, D.¹

¹ Faculty of Technology, Natural Sciences and Maritime Sciences, University College of Southeast Norway, P.O. Box 235, Kongsberg, 3603, Norway, knutv@usn.no

ABSTRACT

A study with PIV-measurements for gas explosion in hydrogen-air mixtures is presented in this paper. The present work is part of an ongoing research project. The experiments are performed with hydrogen-air mixture at atmospheric pressure and room temperature. The experimental rig is a square channel with 4.5 X 2.0 cm² cross section, 30 cm long with a single cylindrical obstacle of blockage ratio 1/3. The equipment used for the PIV-measurements was a Firefly diode laser from Oxford lasers, Photron SA-Z high speed camera and a particle seeder producing 1 μm droplets of water. The gas concentrations used in the experiments was between 14 and 17% hydrogen in air. The resulting explosion can be characterized as slow. Explosions in the gas mixtures at the highest hydrogen concentration produced measured flow velocities of up to 17 m/s as the flame passed the obstacle. Similar velocities was also measured one channel height behind the obstacle. The flow vortices produced behind the obstacle seemed to give separation between the liquid droplets and gas flow. The experimental results can be used for reference in validation of CFD-codes.

1.0 INTRODUCTION

PIV-measurements is used to measure the flow field in fluids. In gas explosions there is a positive feedback between flow field and total reaction rate. A strained flow field will distort the flame and increase the flame surface. An increased flame surface will increase the total reaction rate in the system leading to stronger explosions. At smaller scales turbulence will influence the flame, mainly by increasing the reaction rate. Several studies has been done in this area [1], [2], [3], however these studies used methane-air as reactants.

The objective of the work is to measure the velocity field of the reactants in front of a propagating flame front in pre-mixed hydrogen air. This study will be on lean hydrogen-air mixture between 14 and 17% hydrogen in air. The laminar burning velocity range in these experiments are from 0.6 m/s to 1 m/s. The flow velocity in front of a planar laminar flame propagating from a wall is between 2.3 and 4.6 m/s for these mixtures. One cylinder is placed in the channel giving a blockage ratio of 1/3.

The results will be used as input to sub-mesh modelling of flame acceleration in CFD-codes for large scale application.

2.0 EXPERIMENTAL SET-UP

A drawing of the experimental set-up is shown in Figure 1. It consists of a 30 cm long channel with 4.5 x 2.0 cm² cross section and a 1.5 cm diameter cylindrical obstacle, giving a blockage ratio of 1/3. The channel was closed at the ignition end and open to the atmosphere at the other end. The hydrogen-air gas mixture containing the seeding particles entered the channel at the ignition end. The side walls of the channel were made of transparent poly-carbonate and the laser sheet could enter a slit on the top of the channel.

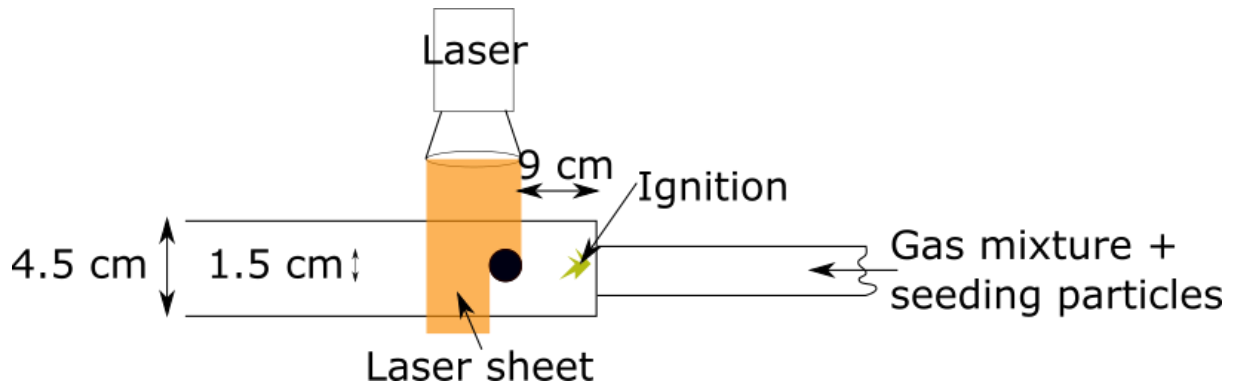


Figure 1: Drawing of the experimental rig for PIV-measurements.

The seeding particles was water droplets of about $1\ \mu\text{m}$. The laser was an Oxford Laser Firefly LED-laser with a wavelength of 808nm and the camera was a Photron SA-Z camera with a 1:1 reproduction ratio lens, figure 2. The laser pulse separation in a pair was $10\ \mu\text{s}$ and the time separation between the pairs was $100\ \mu\text{s}$. By doing calculations like discussed in [4], the apparent droplet diameter, due to light scattering, captured by the camera is about $10\ \mu\text{m}$. Thus, each droplet will be seen as one pixel when the pixel size is larger than the apparent droplet diameter. In these experiments, the actual pixel size in the high-speed images is about $25\ \mu\text{m}$ and the physical window captured is about $2.5\ \text{X}\ 2.5\ \text{cm}^2$.

The gas mixture in the experiments was 14 vol% to 17 vol% hydrogen in air at atmospheric pressure and ambient temperature. The OpenPIV toolbox for Matlab [5] was used to calculate the velocity field from the high speed images. The interrogation window used in the present results are of $32\ \text{X}\ 32$ pixels.

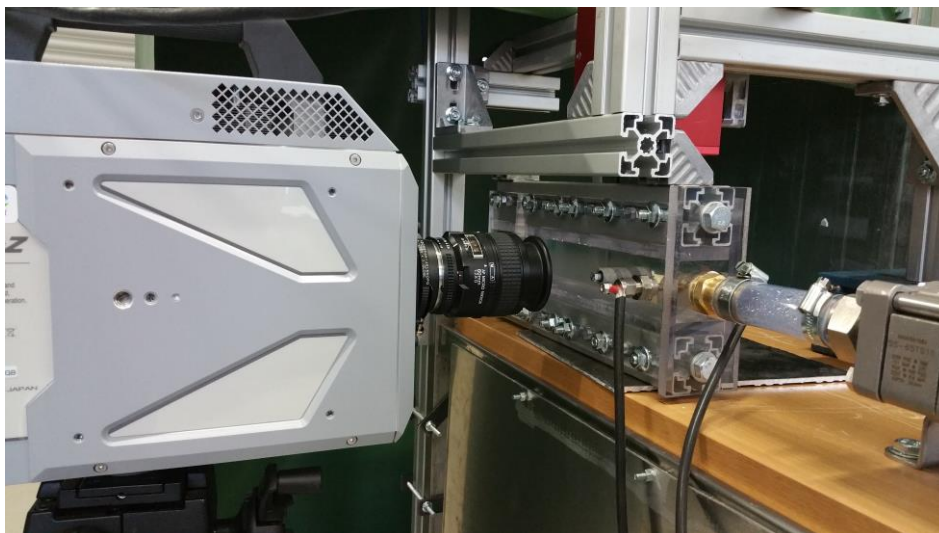


Figure 2: Photo of the experimental rig showing the camera and the filling inlet.

3.0 RESULTS

A typical raw image from the experiments is shown in figure 3 where the droplets and the propagating flame is seen. The passing flame has evaporated the droplets and no flow field is measured in the products. The vectors are calculated by cross correlation with FFT.

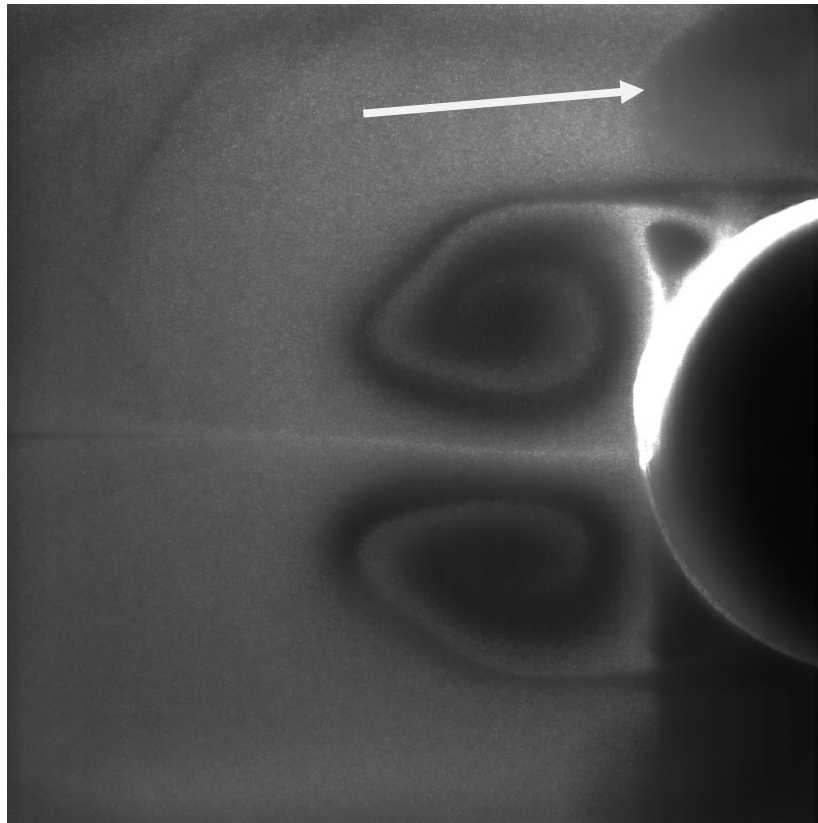


Figure 3: Image from the high-speed film showing the particles and flame front (arrow). The image is from an experiment with 16% hydrogen in air.

Figure 4 shows the calculated vector field superimposed on the image from the high speed film. The field is not “cleaned”, so a number of outlier vectors are seen. The laser sheet does not reach the shade blow the obstacle. The particles has separated from the flow as is seen by the darker areas in the vortex.

For closer investigation of the flow field, the absolute velocity is compared at a few positions shown in figure 5. The position Vel 1 is above the obstacle to show the measured flow velocity as the flow accelerates in the reduced flow area. The position Vel 2 is placed to show the absolute velocities in one of the vortices. Figures 6 and 7 shows the absolute velocity of the flow as a function of time for mixtures of 14 and 17% hydrogen. The velocities at position Vel1 and Vel3 for the same concentration are from different experiments since the imaging window is too small to include both positions.

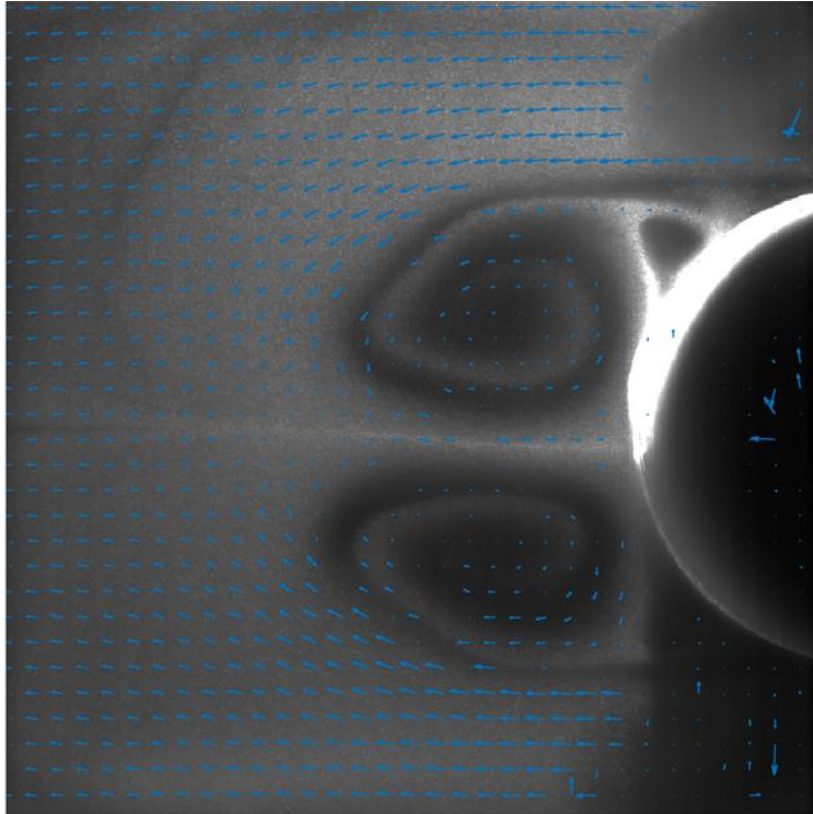


Figure 4: Superimposed vector field on the image from the high speed film. Some outlier vectors is seen “inside” the obstacle and in the shade below the obstacle.

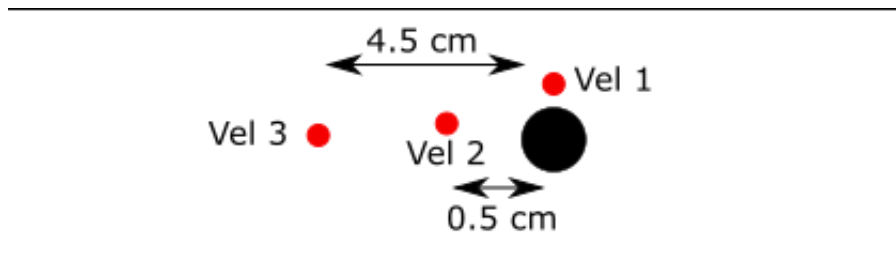


Figure 5: Positions relative to the obstacle for plotting and comparing velocities. Vel 1 is positioned 5 mm above the obstacle. Vel 2 is offset 3 mm above centre line and 3 is placed on the centre line.

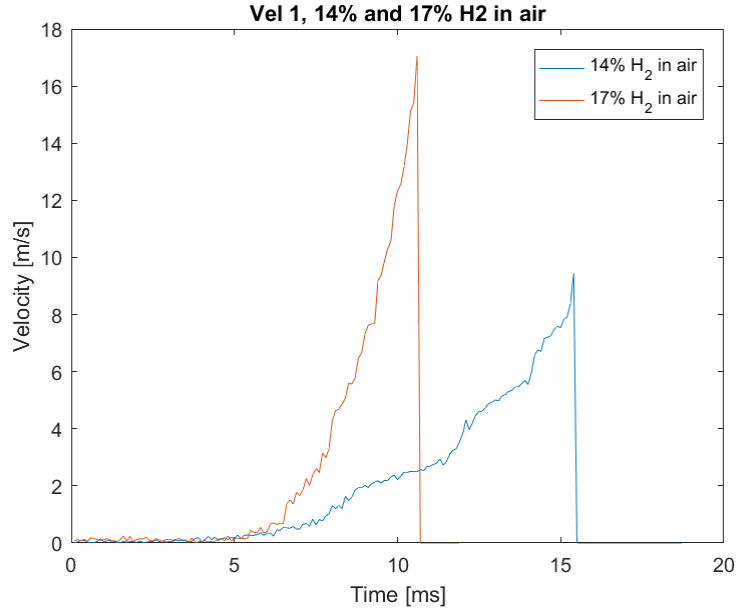


Figure 6: Plotted reactant velocities for 14 and 17% hydrogen in air at position Vel1 positioned just above the obstacle.

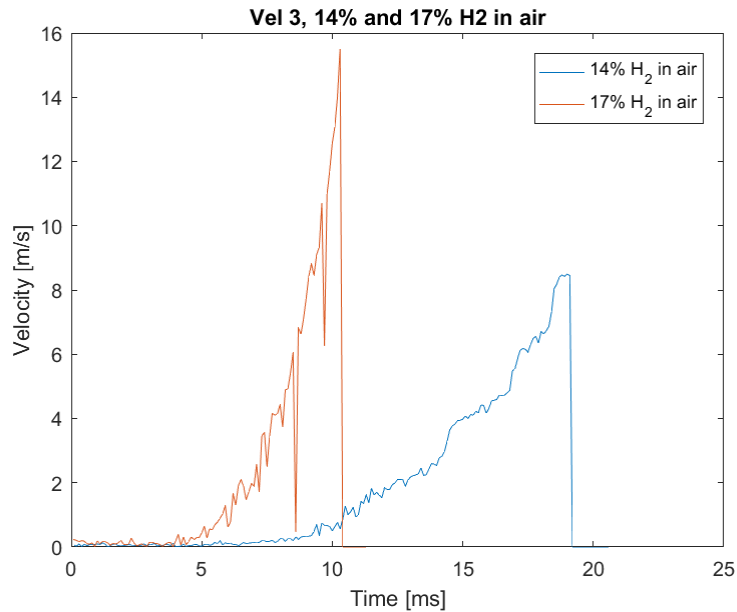


Figure 7: Plotted reactant velocities for 14 and 17% hydrogen in air at position Vel3 placed 4.5 cm behind the obstacle.

4.0 DISCUSSION

The obstacle of BR 1/3 will influence the flame and increase the overall reaction rate. The flow velocities are higher than what will be generated from a laminar planar flame. The propagation is probably close to laminar but the strained velocity field around the obstacle increase the flame front area. The flow velocity in front of the flame as it passes the obstacle is the same as the velocity in front of the flame one channel height behind the obstacle. This is probably due to the increased reaction rate due to the flame-vortex interaction behind the obstacle. The measured flow velocities of the

explosions in 17% hydrogen is about a factor two higher than in 14%. This ratio is the same as for a laminar flame.

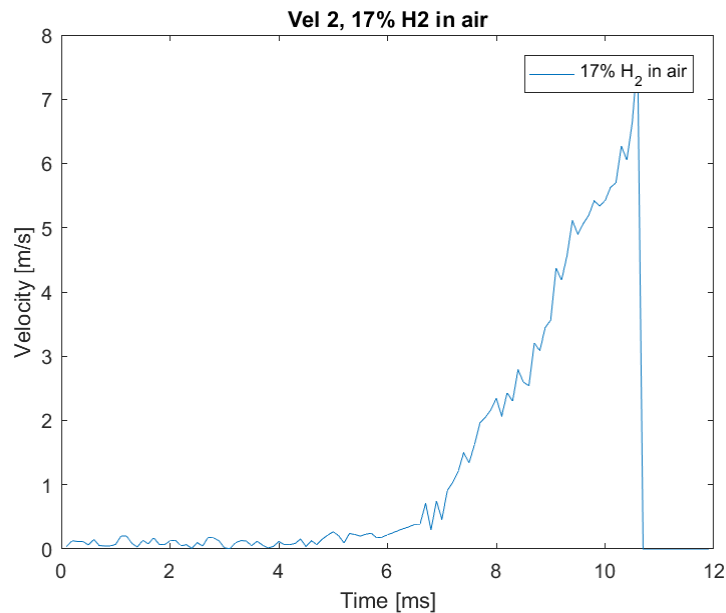


Figure 8: Velocity history at position Vel 2, 5 mm behind the obstacle inside one vortex.

Some indication of the droplets separating from the flow can be seen in the vortices behind the obstacle. This separation will produce a wrong vector field in that region. Figure 8 shows the measured absolute velocity 5 mm behind the obstacle and an offset above the centerline. This position measures the velocities in the vortex. A measured maximum velocity of 7 m/s in a vortex of about 1 cm diameter produces strong centripetal forces that will separate the liquid droplets from the gas flow. Even though the measured velocity in this position is wrong due to the separation, it will be an estimate of the vortex strength.

5.0 CONCLUSION

The propagating flame gives flow velocities higher than the reference laminar planar flame velocity. The strained flow field increase the flame surface area and increase total reaction rate. The present results of both flow velocities and flame position can be used for comparison for CFD-codes for validation purposes of showing capabilities in simulating slow explosions in lean hydrogen-air mixtures.

More detailed results can be extracted from the present results for use in modeling.

Even the low velocities resulting from a premixed flame in 17% hydrogen in air results in the droplets separating from the flow in the regions of highest vorticity.

ACKNOWLEDGMENTS

The authors would like to thank the Norwegian Research Council for funding this work under project Hy3DRM project number 245356.

REFERENCES

1. Hargrave, G.K., Jarvis, S., Williams, T.C., A study of transient flow turbulence generation during flame/wall interactions in explosions, *Meas. Sci. Technol.* 13 (2002), 1036-1042.
2. Di Sarli, V., Di Benedetto, A., Russo, G., Jarvis, S., Long, E.J., Hargreave, G.K., Large Eddy Simulation and PIV Measurements of Unsteady Premixed Flames Accelerated by Obstacles, *Flow Turbulence Combust* (2009) 83:227-250.
3. Long, E.J. and Hargrave, G.K., Experimental Measurement of Local Burning Velocity Within Rotating Flow, *Flow Turbulence Combust* (2011) 86:455-476.
4. Kahler, C.J., Scharnowski, S., Cierpka, C., On the resolution limit of digital particle image velocimetry, *Exp. Fluids* (2012) 52:1629-1639.
5. Taylor, Z.J., Gurka, R., Kopp, G.A., Liberzon, A., Long-Duration Time-Resolved PIV to Study Unsteady Aerodynamics, Instrumentation and Measurement, *IEEE Transactions on* , vol.59, no.12, pp.3262-3269, Dec. 2010 doi: 10.1109/TIM.2010.2047149