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FLAME FRONT TRACKING IN IMPINGING JET FLAMES

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Abstract: *Flame tracking is important in the study of flame-wall interaction. Based on flame area, stretch angle and flame thickness the wall effect on the flame can be evaluated. The proposed tracking method is based on differences in seeding particle density in unburnt and burnt gases. Particle images are recorded with a high-speed Particle Image Velocimetry (PIV) system that consists of a high speed CMOS camera and high-repetition rate, diode-pumped Nd:YLF laser. The instantaneous flame front is recognizable in the raw PIV images and the key task is to detect it automatically with image processing tools. Interaction with the wall and an unexpected shift of the wall position during the measurements (due to heating) makes this task very challenging. This paper presents a procedure for entire flame front tracking which utilizes generally available image processing tools. Several issues in the measurement of the flame front are highlighted and their solution or elimination is proposed.*

Keywords: Flame Tracking, Impinging Jet, PIV, Image Processing.

1. Introduction

Flame-wall interaction is important topic for process industry. Its effect is utilized e.g. in impinging jet flames for enhancing wall heat flux (Chander and Ray, 2005). It is used for rapid increase in heat flux when compared to conventional heating separated to radiant and convective sections. Proper understanding can improve design of combustion devices and improve prediction of wall lifetime. The flame front itself does not usually reach the wall due to the loss of energy. The wall temperature tends to be significantly lower than the ignition temperature of the gas mixture. Therefore, the reaction zone cannot reach the wall and the flame is quenched in the thin layer near the wall. Quenching has significant influence on the pollutant formation (Li et al, 2010). Effects of quenching can be investigated by varying the wall temperature which influences the layer thickness.

1.1. Flame tracking

Flame analysis can be performed in several ways. One is to track the flame front via image processing algorithms. The flame front tracking is based on differences in seeding particle density in unburnt and burnt gases. This difference in density can be clearly seen in Fig. 1. Some authors have suggested to use seeding particles, such as oil or incense smoke, (Jeanne et al., 2000) that are visible only in unburnt region of the flame or using threshold value with no further details on their procedure (Tachibana et al., 2004; Hartung et al., 2009). Some advanced methods for flame front tracking based on Canny filter edge detector were developed (Coron et al., 2004), but did not show convincing improvements. Our procedure proposes using

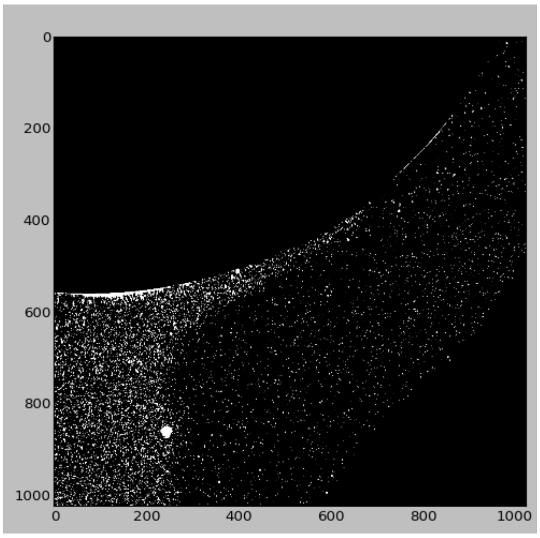

Fig. 1: PIV image of an impinging jet flame.

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general filters available in many libraries for image processing and therefore is easy to implement.

2. Experimental |Facility

The experimental setup consists of a horizontal cylindrical stainless steel pipe with an outside diameter of 88.9 mm which is convectively cooled by air on the pipes' inner surface. The pipe axis is oriented perpendicular to the vertical jet axis. The burner fires natural gas premixed with air from a copper pipe with an inner diameter of 26 mm with open end – see Fig. 2. Seeding particles (aluminum oxide) are injected into the mixture by using a cyclone seeder.

Fig. 2: Experimental set-up.

The particle image velocimetry system consists of a high-speed CMOS camera (LaVision High Speed Star) with 1024×1024 pixels and 12-bit resolution. The laser is a dual oscillator/single head diode pumped Nd:YLF Darwin Duo 527-80-M emitting green light with a wavelength of 527 nm. The duration of a laser pulse is about 150 ns. The PIV system collected double frame images at a frequency of 1500 Hz. The laser sheet is perpendicular to the cooled cylindrical pipe axis and stretches in vertical direction from the cooled impingement pipe to the jet exit.

3. Measurement

Two different cases were considered in this study. The first is a "cold" case with full (internal) cooling of the horizontal pipe which is heated by the impinging flame. The second is a "hot" case without cooling of the horizontal pipe. The highest wall temperature as measured by a thermocouple mounted just below the inner surface of the pipe is 580 °C for the "hot" case and 178 °C for the "cold" case. For each case several data sets were obtained to ensure repeatability and to allow evaluation of statistical quantities.

Several problems had to be solved to capture satisfying images. One problem was the apparent shift in the wall position observed in the images for the cold and hot wall temperature. Even when the camera remains in a fixed position the wall highlighted by laser sheet appears to have increased in diameter by 1.6 mm (36 px). This effect can be clearly seen when cold and hot sets of images are compared. The shift is not large, but it significantly disturbs the image processing and pipe edge detection. This shift might be caused by two physical effects, i.e. thermal expansion of steel and optical distortion of light rays due to different air temperatures. Another difficulty for image processing is the masking of wall reflections prior to application of filters. Masking is performed by using circles with slightly larger diameter than the pipe itself to hide all reflections. Among hot and cold wall cases the circle diameter may differ by up to 142 px (6.5 mm). It is not only due to wall shift, but also due to differences in deposition of the seeding particles on the walls which scatters more light towards camera.

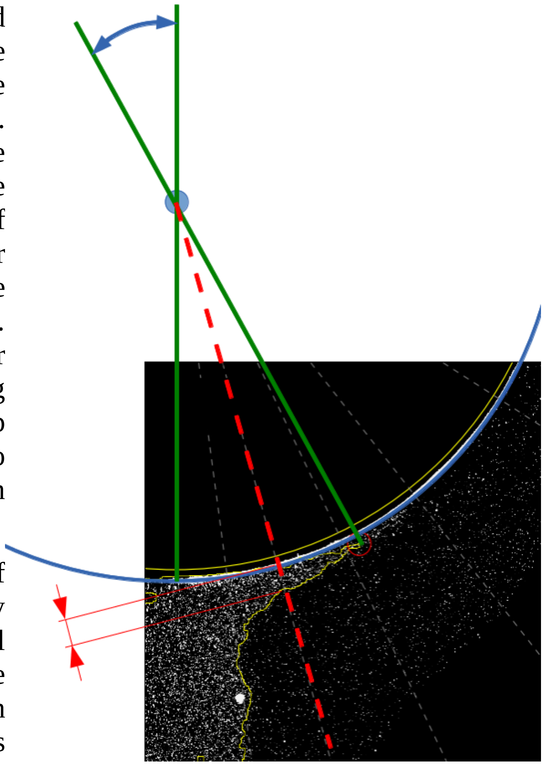

Fig. 3: Properties of the stretched flame.

Limiting the amount of laser light reflected by the wall of the horizontal pipe was also the key issue. It was solved by decreasing the angle between the camera axis and horizontal pipe axis. The final setup can be seen in Fig. 2. The thickness of the overexposed reflection from wall on captured image was reduced to 10 px (0.46 mm). This allowed more accurate imaging of seeding particles in the near wall region.

A limiting factor of the proposed image processing method is the variation in time of the seeding particle density. Ideally, the same seeding density should be used for all cases to achieve comparable tracking of flame. The most challenging region for accurate tracking is the far side of the flame stretching around the horizontal pipe where the stretch angle is measured (see red circle in Fig. 3).

4. Image Processing

The aim of image processing is tracking of the flame front and extracting characteristics of the flame such as: flame area, stretch angle, thickness of the stretching flame, distance of the flame from the cooled wall (quenching layer) as indicated in Fig. 3. We aim at assembling the set of generally available methods which provide the best results. The suggested procedure of the image processing method is illustrated in Fig. 4. It can be implemented with e.g. Python SciPy library (Jones et al., 2001) and its extension for image processing Scikit-image (Walt, 2013).

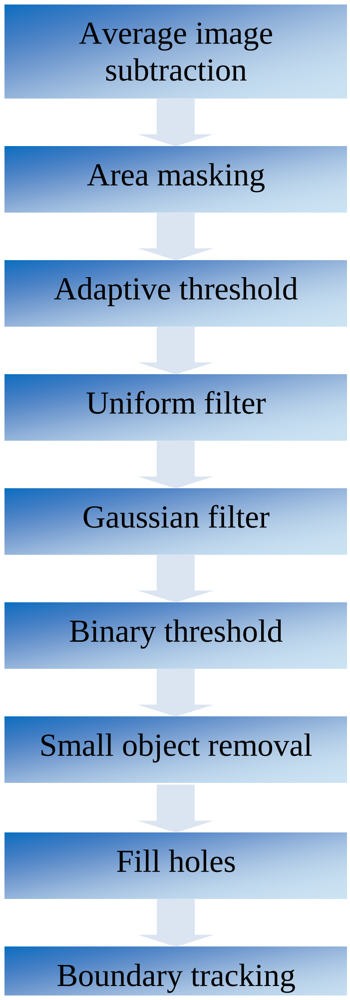

Fig. 4: Procedure of the flame front tracking.

The first step is to remove the background by creating an average image from a set of 1000 images followed by its subtraction from each individual image. In the second step the overexposed region (caused by reflections from the horizontal pipe) and unimportant areas (such as area inside the horizontal pipe) of the images are masked (erased). Adaptive threshold follows with the lower threshold value obtained from an averaged intensity value from rows 500 to 1024 (in bottom part of the image). Threshold value is then calculated as:

$$T_h = \bar{I} \cdot 2.87 - 7.67 \qquad (1)$$

where $\bar{I}$ is average intensity.

Equation 1 was obtained by experimental fitting the threshold value to the average intensity value in several data sets. All pixels with an intensity lower than T_h are set to 0 and all pixels with intensity higher than 20 are set to 20. This narrows the range of intensity values and improves behavior of uniform filtering.

The uniform filter is a two-dimensional filter implemented as a sequence of one-dimensional uniform filters with size 30 px in each axis. This blurred image is than further smoothed by a Gaussian filter with standard deviation set to 3.

A binary threshold produces a single solid area of the flame with intensity 1, while rest of image has intensity 0. Smaller artifacts, not

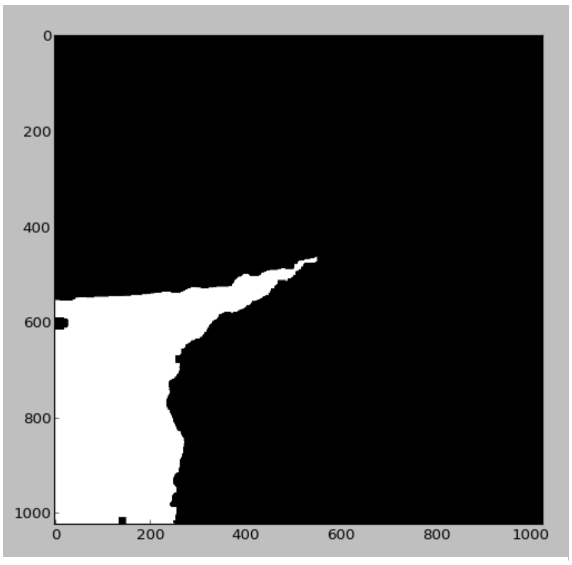

Fig. 5: Binary image of the flame.

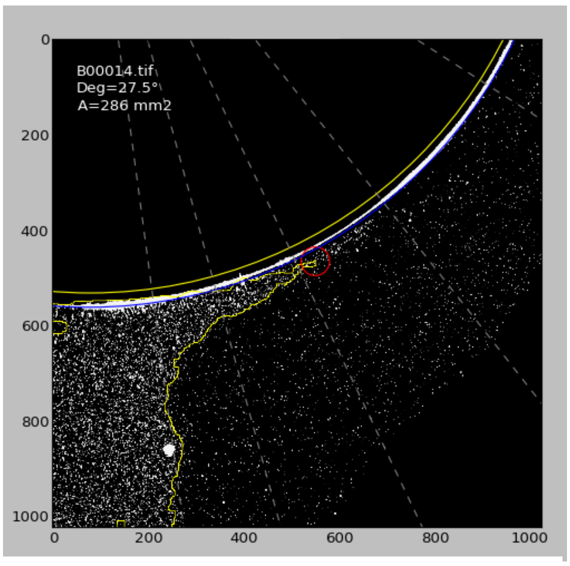

Fig. 6: PIV image with highlighted flame boundary.

connected to the core of the flame, are removed by small object removal method. The maximum size of the object to remove is 15000 px. Only the flame itself remains in the image. However, there may be small holes inside the flame due to disturbances in seeding density. Those are removed by fill holes method based on binary dilation. The final binary image is shown in Fig. 5. The last step is boundary tracking performed on the cleaned binary image. This step highlights the boundary (see final image in Fig. 6) and allows us to label the flame with appropriate properties.

The core body of the flame is tracked well, however, in the stretched part of the flame there are separated areas of unburnt gases travelling away from the flame. Those structures influence the detection of the stretch angle and may cause a significant overestimation of its value.

5. Conclusions

A method is proposed to derive instantaneous flame fronts from raw PIV images. The method enables the extraction of valuable data on impinging flames such as: flame area, stretch angle, thickness of the stretching flame, distance between the flame and the cooled wall (quenching layer). The method is based on the variation of the particle seeding density between (cold) unburnt gases and (hot) combustion products. The data processing method was applied to sets of raw PIV images and flame front could be detected accurately in both cases.

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