

Post-Processing of Schlieren Images

Emilia PRISACARIU^{*1}, Tudor PRISECARU², Valeriu VILAG¹, Cosmin SUCIU¹,
Cristian DOBROMIRESCU¹, Marius ENACHE¹, Razvan NICOARA¹

*Corresponding author

¹COMOTI – Romanian Research & Development Institute for Gas Turbines,
B-dul Iuliu Maniu 220D, Bucharest 061136, Romania,
emilia.prisacariu@comoti.ro*, valeriu.vilag@comoti.ro, cosmin.suciu@comoti.ro,
cristian.dobromirescu@comoti.ro, marius.enache@comoti.ro,
razvan.nicoara@comoti.ro

²Politehnica University of Bucharest,
Splaiul Independentei No. 313, Bucharest 060042, Romania,
tudor.prisecaru@upb.ro

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Abstract: *In general, the Schlieren visualization method is used to qualitatively describe phenomena. However, recent studies have attempted to convert the classical Schlieren system into a quantitative method to describe certain flow parameters. This paper aims at analysing pictures from a qualitative and a quantitative point of view. The post-processing of images for both situations is described based on different applications. Real examples are used and both methodologies and logical schemes are explained. The article focuses on image processing, and not on the studied phenomena.*

Key Words: *calibrated schlieren, quantitative image processing, qualitative image processing, data acquisition*

1. INTRODUCTION

Schlieren is a visualization method and can be defined as visible streaks produced in a transparent medium (such as air, water, gas, etc.) as a result of density variation which produces changes in the refractive index.

The simplest configuration that a Schlieren system can have is attributed to Auguste Toepler. This configuration is based on the properties of ray distribution of a point-like light source on a parabolic mirror. There can be many optical path variations, but as a functioning principle, all can be reduced to the single mirror setup. Other optics can be added in order to increase system sensitivity and contrast or to expand and modify the testing area, adapting the system to the experiment. The versatility and simplicity of the system are the main properties that give it an advantage over other visualization techniques. It can be adapted to almost all applications with optical access and transformed into a quantitative measuring system.

In the recent decade, many ways to quantify information from the images have been described, but all implied altering the system by introducing different elements into the optical setup. The most popular method is Schardin's calibrated Schlieren, which uses a small diameter lens with a very large focal distance (placed in the testing area) to compare the

intensity of the pixels found on the lens to the intensity of the phenomenon attributed pixels [1]. Another method that helps quantify the result is using a calibrated coloured filter. The importance of the post-processing software can be seen in the type of the analysed phenomena. High-speed flows can now be quantified using a charge-coupled camera (CCD), which allows the capture of details of a very fast-growing phenomenon. In terms of post-processing techniques, high-speed cameras and software updates allow the processing of large batches of images in a very short time, are the novelty in the field of processing.

Given that no more than a decade ago, high-speed cameras were very difficult to find and expensive because high-maintenance and post-processing software were not included in the work package, it can be concluded that image processing came a long way to reach the current situation. The included high-speed camera software allows the simplest operations to be performed, but a dedicated code has to be put in place in order for the post-processing to fit perfectly the experimentally obtained images.

Usually, in-house developed software is the best choice, regardless of the programming language it is written in.

There are two types of post-processing in the case of Schlieren systems: qualitative post-processing (which focuses on underlining the phenomenon by making it more visible and clearer) and quantitative post-processing which, if done properly, can yield quantitative results and help characterize an entire subsonic flow or other studied phenomena.

2. QUALITATIVE POST-PROCESSING

Although the images have been used to qualitatively describe the phenomenon or to try and calibrate the system, the image post-processing steps have never been explained before. The system used is usually in the one-mirror configuration [1], or the Z-type that uses two parabolic mirrors with off axis orientation, similar to the one pictured in Fig. 1.

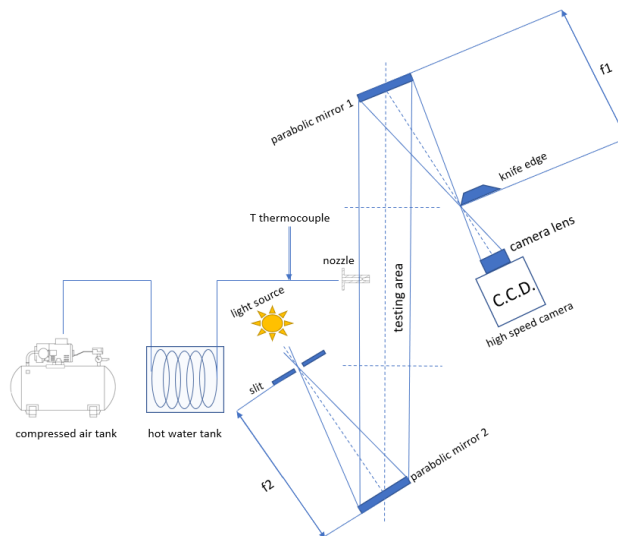


Fig. 1 Experimental setup for a heated jet [4]

The first images analyzed will be the images from Fig. 1 setup. These are the images of a supersonic flow coming out of a supersonic nozzle and having the exit velocity approaching 2.5 Mach [2]. The setup explanation can be found in [2]. Image processing applied in order to obtain a qualitative result implies following steps like: after acquiring raw images, set raw

images to gray scaling (normalizing the image matrix), apply a mask over the images, use contrast stretching and other operations.

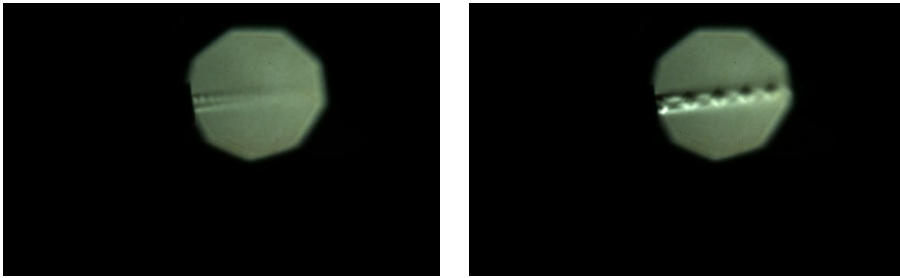


Fig. 2 Raw images of the supersonic jet

The raw image quality for the supersonic jet is poor because the Z-type configuration is done with two parabolic mirrors that have a very small focal length which does not allow the correct alignment, so that the light source is imaged through an insufficiently opened camera diaphragm. As it can be observed by taking a closer look, there are spots that indicate surface irregularities of the mirrors or of the camera lens and also, the phenomenon does not cover 90% of the picture resolution, as recommended. Another important issue is the color of the image. The Phantom VEO high speed cameras record RGB (red-green-blue) images. All high-speed cameras need special lightning conditions. If the number of frames increases, the light intensity decreases. The dark spectrum renders the green gradient of the image.

Taking into consideration the nature of the flow, the wanted qualitative result can be a post processed image or a movie.

In the case of a post-processing movie, the first step would be to use a function that opens a video file and then select the folder that contains the images, while specifying the root of the image name. The images will be named, for example from “scene_001” to “scene_500” with the “scene” root. The next step is to do a background subtraction in order to eliminate any lens/mirror surface shadows caused by debris, surface scratches and other defects (Fig. 3).

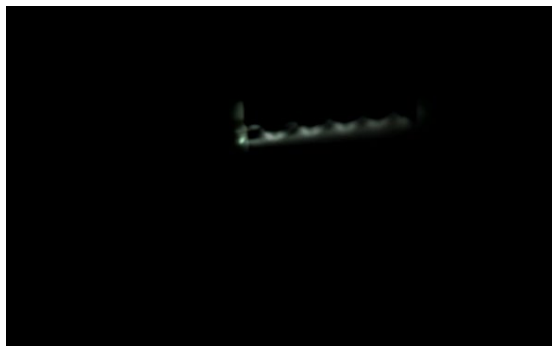


Fig. 3 Image after background subtraction

Because there was nearly no natural convection in the room, the background was almost identical to the frames; this is why instead of a gray resulting background, a black background was obtained. For a qualitative image, this is not good. The contrast is too high and even if it would be ideal for the quantitative analysis, another stage of processing must be applied for the qualitative one.

To make the process easier, the RGB to gray image transition should be done here. Normalizing the image means writing the image matrix as a pixel intensity map with values

between 0 and 1 and thus obtaining a simple matrix, instead of the 3D matrix given by the RGB matrix type. The “rgb2gray” function can also be applied to a batch of images.

As mentioned before, the image of the jet is very small compared to the resolution of the camera and there is no point in post-processing image batches with so many irrelevant pixels, so the next step is applying a circular mask to all images to reduce the analyzed area and only include the illuminated part of the mirror.

The mask is circular and Eq. (1) will describe the desired circle (here, r is the radius of the desired circle, x is the horizontal coordinate of the image and x_0 and y_0 are the coordinates that establish the circle origin), considering the radius of the drawn circle and the coordinates for the point of origin that can be identified on the picture.

$$(x - x_0)^2 + (y - y_0)^2 \leq r^2 \tag{1}$$

The circle will be plotted and the mask function will be called inside the main program. The circular mask is used in most Schlieren application because the area of the mirror represents the area from which the information must be extracted.

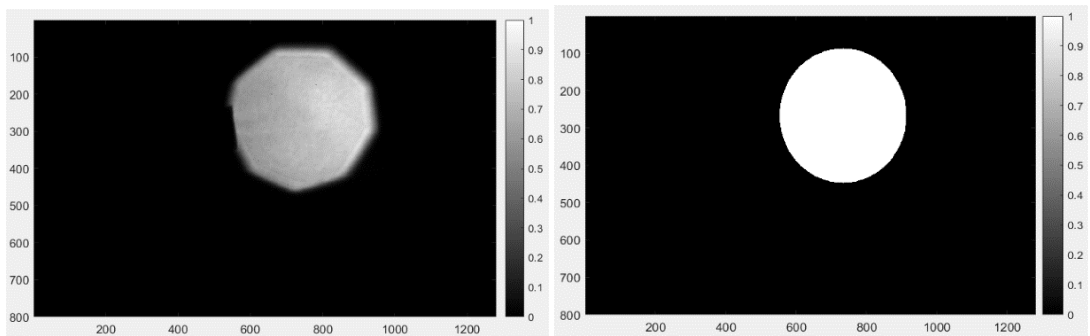


Fig. 4 Normalized image and circular mask (from left to right)

The background needs to be lighter in order for all the flows characteristics to be observed. In general, the background is replaced by a mean of pixel intensities located in the phenomenon, but at the same time, one can come across a background variation.

For example, in this case, starting with the 6th frame, the background becomes darker and for the last 6th frames, the background becomes lighter.

One must correct this by adding or diminishing the pixel intensity of the background. As seen in Fig. 4, a higher intensity belongs to a lighter zone, so adding to the intensity will increase the lighting for the first 6 frames. The process is reversed for the last 6 frames. The final result can be observed in Fig. 5.

One can always apply contrast stretching or unsharp masking to improve the images. For a better understanding, the complete code is listed in the Appendix below.

Post-processing of qualitative images can be also seen in [3]. Here, the image of the jet was double because of the self-intersecting light rays.

This issue was at that time impossible to overcome due to the limited physical space and optical access to the phenomenon.

The setup is described in Fig. 6. and the experiment in [3]. The raw image and the post processed image of the jet can be seen in Fig. 7. In this case, there are 2 options that can be considered.

One is to consider the flow to be axial-symmetric and only post-process the unaltered half of the image that contains information of a singular jet, after which the post-processing of the second half of the image can start.

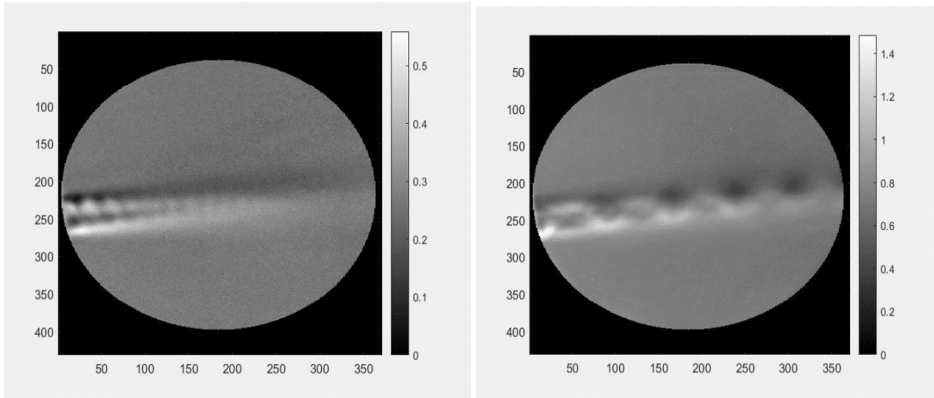


Fig. 5 Qualitative post-processed images of a supersonic jet

The second option refers to the fact that the second half of the image can suffer pixel intensities diminishing, based on the average performed on the first half, excluding the jet parts geometrically placed outside the phenomenon and replacing them with background intensity equivalency.

Fig. 7 (right), shows the result after applying the second option.

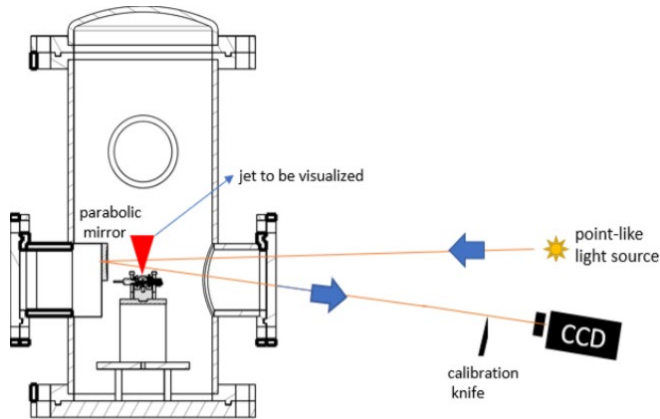


Fig. 6 Experimental set-up of a schlieren system for visualizing jet inside a vacuum chamber

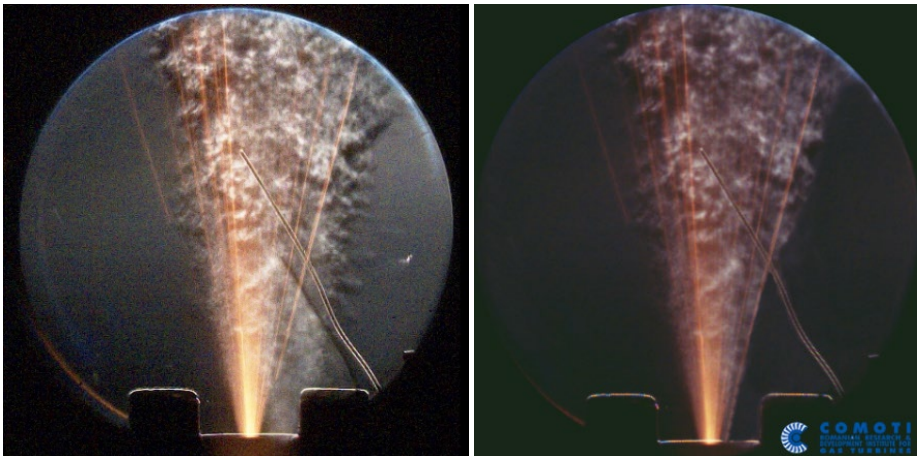


Fig. 7 The raw image and the post processed image of the hydrogen-oxygen jet (from left to right) [3]

3. QUANTITATIVE POST-PROCESSING

Quantitative post-processing relies on the pixel intensity matrix. The phenomenon needs to have the background removed and the image normalized to increase the accuracy of the data. Image processing varies as a function of the calibrating method. If the calibrated method is Schardin's, then pixel intensity correlation will have to be applied between the calibrating lens and the phenomenon [1].

If the method relies on the knife edge calibration, the important steps can be found in [2] for the same case explained before, and implies calibrating each point for a very specific knife edge cut off.

Basically, the image processing in this case is minimal and the process relies much more on the physical calibration method.

The BOS (background-oriented Schlieren) method is to be avoided in general because of the work load involved in post-processing and because of the fact that the images obtained through it are not qualitative or esthetic.

As seen in Fig. 9, the setup of this system is very simple and the images obtained require a high-density variation in order for it to result in displacement vectors.

A good code for generating a BOS background can be found in [7]. BOS can be achieved by using a single camera, but one has to take into account that the result is path integrated, or can use two different cameras and calculate 2 displacement angles like in Fig. 8, in order to obtain 3D results.

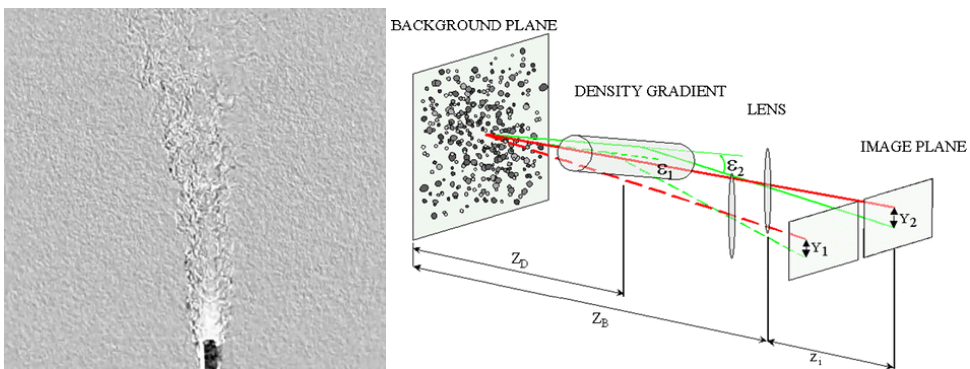


Fig. 8 Oscillating Bunsen Burner Flame (BOS) [5] and BOS setup [6] (left to right)

In order to post-process BOS images, one can use a cross-correlation function to spot the displacement of the particles, just like in the case of particle image velocimetry (Fig. 9).

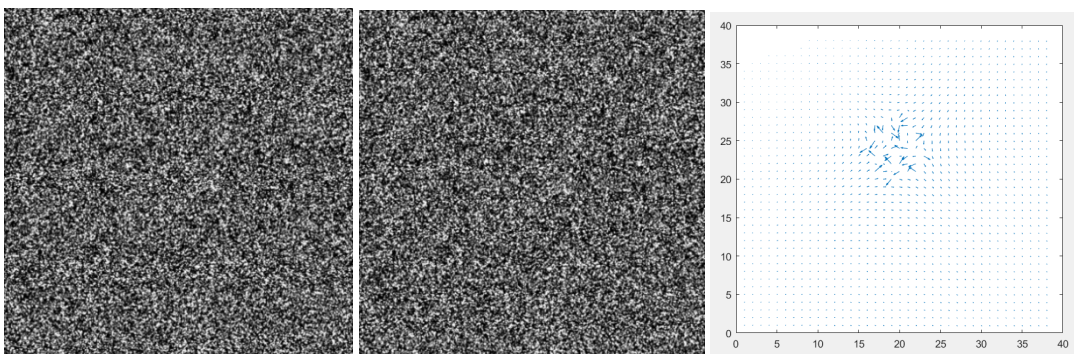


Fig. 9 Consecutive frames of a strong vortex (PIV) [8] and the resulting vectors

Applying the same program to BOS images has the same result (a displacement vector map), considering the points in the background particles, and making it easier to calculate the displacement angle, which can lead to a precise calculation of the refractive index map which can afterwards be transformed into a density map of the phenomenon by applying the Gladstone-Dale relation [9]. The refraction index and density map represent quantitative information. Depending on the nature of the studied flow, temperature can also be extracted, as well as pressure and other important physical quantities [10]. The logical process of applying the cross-correlation function is described in Fig. 10.

The process starts with reading the images and normalizing them. After that, the interest zone is delimited. This zone of interest refers, most of the times, to the entire image; in this case, x_{max} and y_{max} refer to image dimensions. If a mask is necessary, it shall be applied after the image is converted to gray scale. The mask is important not to alter the information by taking into consideration the dead pixel intensity, any reflection of the optical system, etc.

The next steps rely on centering the grid and generating it. The interrogation window is defined by choosing the appropriate x_{win} and y_{win} values. It is recommended that the size of the search window be 64 x 64 pixels, but for a rigorous search, it can be reduced to a minimum of 8x8 pixels.

This value has a lot to do with the particle size, usually the particle needs to represent 3 pixels or more to avoid peak locking [11]. Other parameters can be varied, but for BOS there is no need to correct for out-of-plane particle displacement or worry about choosing the right particles to follow the flow path.

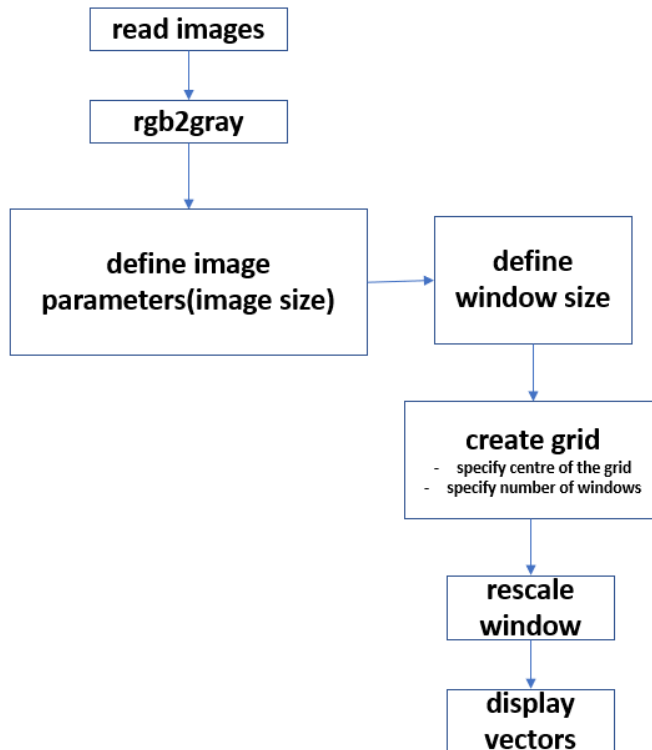


Fig. 10 Logical scheme of the vector generating program

Fig. 10 embodies the general form of the program and can be adapted to each particular situation.

4. CONCLUSIONS AND FUTURE WORK

Schlieren is a system that can be turned into a quantitative measurement tool by using a good calibration method and a post-processing code.

The code and the calibrating solution need to be adapted to the studied phenomena. Schlieren can offer both qualitative and quantitative information due to the advance in image post-processing.

Its versatility, the ease of use and small measurement error (2%-3%) [1] are the main advantages, while the main disadvantage is the need to correlate the system to a CFD simulation to solve the temperature and pressure in case of turbulent flows, starting from the Schlieren's density map [3].

For future work, the author envisions the development of a Matlab code coupled with a CFD simulation that can automatically result into a full characterization of a supersonic flow. A study regarding a thermally calibrated Schlieren is also in progress.

If successful, the calibration curve will be obtained and could be used to determine the temperature in optically accessible flows without intruding it with measuring equipment. This calibration curve will result out of the correlation of the temperature with the light intensity expressed in the recorded image matrix.

If needed, other calibrating factors will be used. The importance of in-house developed codes that can be applied to various experimental setups and can correct for possible system flaws is clearly underlined here.

In conclusion, the logic of post-processing and the code provided in this paper can represent a good starting point for how Schlieren image processing can be performed and can also inspire others not to view Schlieren only as a method of visualization, but also acknowledge its quantitative possibilities.

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APPENDIX

```

%% write frames to video
srcFile=dir('C:\Username\Desktop\1102\images\scene*.png');
gray=zeros(800,1280,length(srcFile));
bckg=imread('C:\Username\Desktop\images\bckg.png'); % reads background
%% 0. Open video file recorder/writer
movie = VideoWriter('name_of_movie.avi'); % opens video recorder
movie.FrameRate = 2; % select frame rate
open(movie)
for i=1:length(srcFile)
%% 1. Read image
    filename=strcat('C:\Users\C112\Desktop\1102\ims\',srcFile(i).name);
    Z=imread(filename);
    gray(:,:,i)=rgb2gray(Z);
gray_bckg=rgb2gray(bckg);
    F=mat2gray(gray(:,:,i));
    M=mat2gray(gray_bckg);
    %ifi>6
        %M=M+1.2; %*(1.1/1.4);
    %end
    J=F-M;
    %unsharp masking should be done here(or contrast stretching)
    %M=gray(:,:,i)+20;
%% 2. Plot image
figure(1)
imagesc(F);
colormap('gray');
colorbar
    %F=im2double(gray(:,:,i));
    %F=mat2gray(gray(:,:,i));
    V=size(J);
ximg=V(1);
yimg=V(2);
    if i<=6 %only req when background changes during measurements
        J=J+0.3; %background is lighter for first 6 frames
    else
        J=J+0.7+0.3; %background is darker for the >6 frames
    end
    [c]=mask_circle(ximg,yimg);
    K=J.*c;
% for i=1:ximg

```

```
%      for j=1:yimg
%      if K(i,j)<0
%          K(i,j)=0;
%      end
%  end
%  end
figure(3)
imagesc(K(50:480,550:920));
    colormap('gray');
colorbar
%  path=strcat('C:\Users\C112\Desktop\1102\ims\2\',srcFile(i).name);
%  imwrite(I,path);
%% 3. Get frame and store it (add frame)
    G = getframe(gcf);
writeVideo(movie,G);
    %ifi==20
    %break
    %end
    pause
end
close(movie);
```