Flame chemiluminescence image processing using operator Canny

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Abstract. The need to design more eco-friendly combustors is due to the development and implementation of technologies and combustion methods aimed at reducing polluting emissions. The lean premixed flames use is more preferable from the point of view of NO_x emissions reduction. Due to the low stability and the need for a detailed study of various combustion modes of such flames at present, there is an increasing interest in methods of flame front dynamics analysis. The standard operators Sobel and Prewitt are often used to study the flame front dynamics, but the application of such filters is limited to a narrow range of flame parameters. The current study compares the results of image processing of the V-shaped methane-air flames by the operators Canny, Sobel and Prewitt. A set of advantages of Canny operator using were shown.

1. Introduction

Modern combustors are considered the main source of nitrogen oxide pollution in the atmosphere. NO_x emissions cause photochemical smog and the destruction of the ozone layer [1,2]. Over the last years, there has been increasing interest in new combustion methods aimed at reducing NO_x emissions, such as low-temperature combustion [3,4] and the lean premixed one [5]. However, lean premixed flames are less stable than diffusion ones, so it is necessary to develop methods that increase stability. Therefore it is important to understand the nature of the onset and development of instabilities. For that, it is necessary to study the flame front dynamics. The premixed flames dynamics issues have been repeatedly studied [6–8]. There are various methods for the flame front dynamics study: image analysis of radicals luminescence—CH, OH, HCO, HCHO [9] and chemiluminescence [10,11]. The latter has a set of advantages: high reliability, simplicity of implementation and versatility. In practice, various techniques are used for flame chemiluminescence image processing. Image analysis is performed using filters such as Otsu, Sobel, Savitzky-Golay, Prewitt, and Median, each with limited applicability. For example, the Otsu filter is good at detecting a front that does not have significant curvatures [11]. The Sobel filtering method is used to isolate the edges of a high-contrast image [12]. The Savitsky-Golay filter is mainly used for image smoothing [13]. The Prewitt operator has a high processing rate, but it is not suitable for images with jumps in the intensity gradient. The Median filter is effective in eliminating impulse noise and reducing the noise level [14]. This work aims to demonstrate the advantages of using the Canny operator for premixed flames chemiluminescence images processing.

2. Operator Canny

John Canny created the Canny operator in 1986 and it is applied to detect edges of a contrasting image [15]. The algorithm consists of several stages. Firstly, the initial image is translated into grayscale and smoothed. The filter mask is a square matrix of order n is filled according to the Gaussian distribution law. Parameter σ affects the degree of smoothing. The matrix dimension of the Gaussian operator affects the filtration rate. Filter with large kernel size very insensitive to noise. But with an increase in the dimension, the edge detection error will increase. After this stage, the maxima in gradient magnitude of a Gaussian-smoothed image are estimated. Canny's algorithm uses four directions: horizontal, vertical, and diagonal to detect edges of the gaussian-smoothed image. To estimate the modulus of the gradient is applied difference scheme. The angle of the gradient vector is rounded and can take four values: from 0 to 135 with step 45°. So the gradient and direction of the edge can be calculated. To find the edges with jumping in the module of the gradient, non-maximum suppression is used. Non-maximum suppression is divided into two stages. First, the gradient modulus of the current border pixel comparison with the gradient modulus of the border pixel in two orthogonal directions of the gradient. Then if the gradient modulus of the current border pixel is larger than the modulus of the other border pixels in one direction, the gradient magnitude of that pixel will be saved, otherwise, the value is cleared. After applying non-maximum suppression, the image contains noise edges. It is necessary to detect the border pixels with a low gradient magnitude and save the border pixels with a high gradient magnitude. For this, the double thresholding is applied. If the gradient module of a pixel is above the high threshold, that point is immediately output. If the gradient module of a border pixel is below the high threshold and above the low threshold, this is a weak pixel and it is output too. If the gradient magnitude of the border pixel is below the low threshold value, it equals zero. However, weak edge pixels can be both true edge and noise edge. To eliminate inaccuracy around a weak pixel, adjacent 8 pixels are considered. If at least one of them is strong, then the original weak pixel is preserved.

3. Image processing with Canny filter

The Matlab environment with the package Image Processing Toolbox, was used to process the flame chemiluminescence images. The software function "edge" with certain parameters (filters) was applied to the original image. The choice of a specific filter depends on the tasks at hand. The "edge" function has three arguments: the image supplied to the input, the operator used for filtering, and the threshold τ. Operators Sobel and Prewitt are most often used filters for the study premixed flame front dynamics [16–19]. The Sobel operator [12] calculates the image intensity gradient module in each pixel using the convolution operations of the kernel matrix size 3×3 and matrix of the original image. Further, the values of the modulus of the gradient that are less than τ are set to zero. The Prewitt operator [20] also calculates the image intensity gradient module and performs thresholding, but a different difference scheme is used to calculate the gradient. This difference significantly speeds up the image processing, however, for images in which the gradient jumps, the used approximation provides a worse processing quality compared to the Sobel operator. Canny's filtering technique is not as widely used for flame chemiluminescence image processing as Prewitt and Sobel. The argument τ of the function "edge" for the Canny filter is the upper value in the thresholding stage. The lower value is 40% of the upper one. The feature of the implementation of the Canny operator in Matlab is that for the Canny method, one more argument σ is added to the edge function, which affects the degree of smoothing of the image by the Gaussian filter. The Gaussian filter kernel size is calculated based on the σ value as rounding to an integer value of 4 σ. Software implementations of these filters were tested at the same value τ. A flame chemiluminescence image processing results were compared. The object of the study was the inverted conical premixed methane-air flame under the flow rate $V = 2$ m/s and equivalence ratio $\phi = 0.7$. The original image is presented in

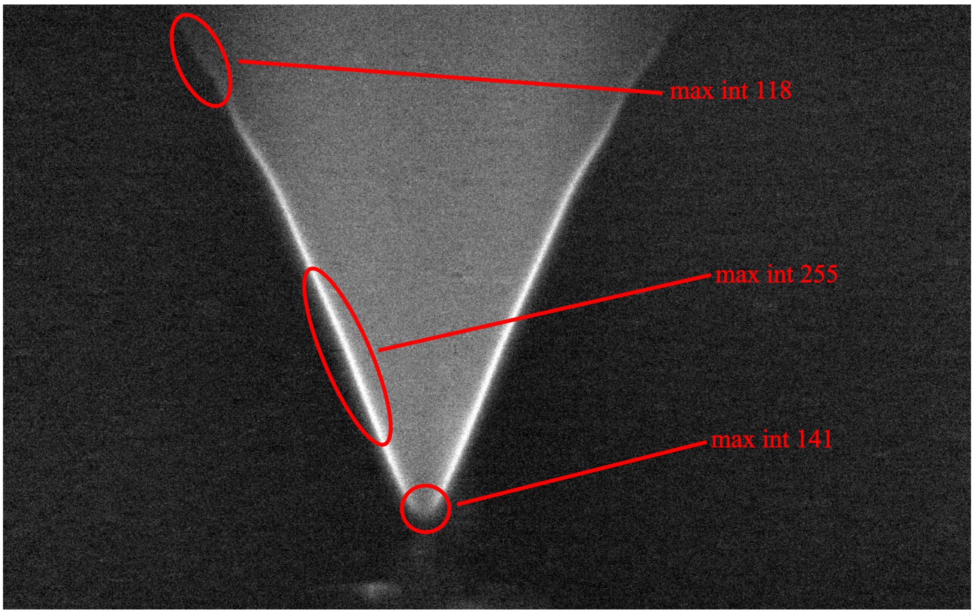
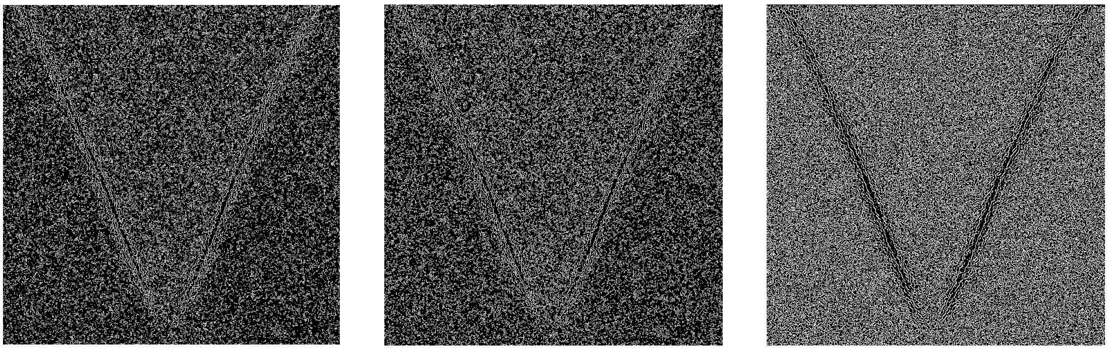


Figure 1. The initial image of the flame front with different intensity of the glow.

figure 1. The value $\tau = 0.1$ for all three filters was chosen based on the following considerations. At low value $\tau = 0.05$, the processing results of the Prewitt, Sobel and Canny filters are presented in figure 2(a), (b) and (c) respectively. The results are prectically identical due to the fact that filters are sensitive to interference. Noise pixels, in which the value of the gradient exceeds the set value, are not removed from the image. At high values—there is a risk of not seeing the results of processing, because the filter will save some the most brightest pixels. Due to the fact that the flame front realizes in areas with different equivalence ratio [21] the front glow intensity is not the same in various parts of the image (see figure 1). It leads to the fact that the resulting image contains noise pixels, because filter's algorithms are based on calculating image gradient. Filters effectiveness depends on how accurately the filter removes noise and estimates edges. That was chosen as a criteria for comparing the results of filters application. The flame front as an important object of the combustion dynamics study was chosen as an object of interest. The result of Sobel filter application to the original image using value $\tau = 0.1$ is presented in figure 3. There is a noise in the image in the form of separate white pixels.The absence of Gaussian smoothing in the algorithm of this operator, as a consequence, increases the filter's sensibility to noise. Also, the flame front is not a continuous line, it consists of a set separate pixels. The result of another common Prewitt filter application using the same value $\tau = 0.1$ is presented subfigure 4(a). This filter slightly improves the image processing quality. The noise pixels have become less, but the flame front contour is still undefined. It is not possible to estimate the thickness of any area of the contour and to obtain a continuous line. Furthermore increase of τ value does not lead to a significant image processing quality improvement. The results of processing are presented in subfigures 4(b, c). When we try to remove noise pixels by increasing τ, we also lose the flame front contour. Using the Canny operator with the same value $\tau = 0.1$ gives a better result (see subfigure 5(a)). The resulting image is has less noise pixels in comparison with using Sobel or Prewitt operator. The flame front is a continuous line. An additional advantage of Canny filter is the fact that all the noise is not separate pixels, but curves of different shapes and sizes. Futhermore using of software function "bwareaopen" of the Image Processing Toolbox package significantly improves the quality of image processing (see subfigure 5(b)). The argument of function "bwareaopen" is a nonnegative quantity. Objects in



(a) (b) (c)

Figure 2. Image processing with $\tau = 0.05$ (a)—Prewitt filter, (b)—Sobel filter, (c)—Canny filter.

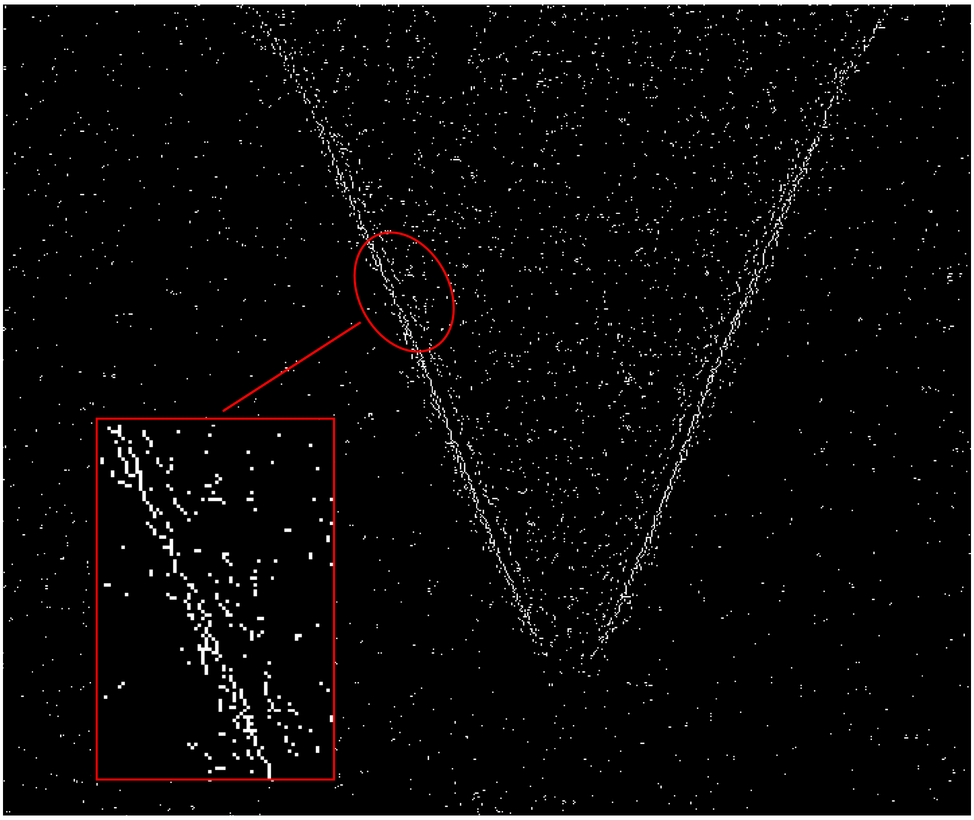
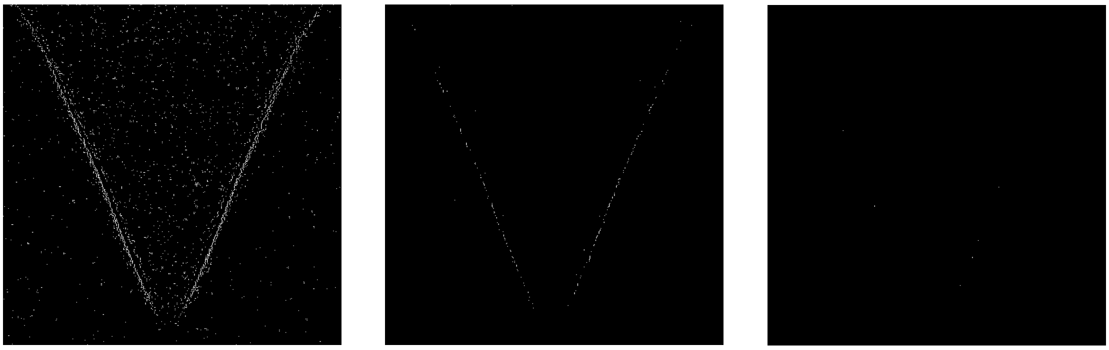


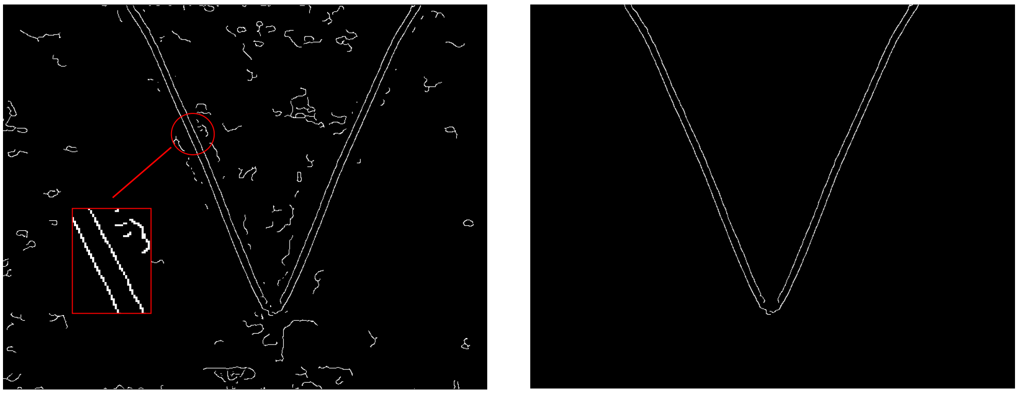
Figure 3. Image processing with Sobel filter with $\tau = 0.1$.

the image with a pixel length less than the value of the argument are removed from the image. The result of image processing by the Canny filter is more suitable for further analysis of the flame front dynamics. In this case, the flame front is a continuous line and noise is a variety of curves. Selection of filter parameters for specific flame characteristics even will slightly improve the accuracy of the analysis of the flame front shape and dynamics.



(*a*) (*b*) (*c*)

Figure 4. Image processing Prewitt filter with (a)—$\tau = 0.1$, (b)—$\tau = 0.15$, (c)—$\tau = 0.2$.



(*a*) (*b*)

Figure 5. Image processing Canny filter with $\tau = 0.1$ and $\sigma = 3$ (a)—processing result, (b)—the result of the subsequent application of the "bwareaopen" function.

4. Conclusion

The manuscript demonstrates the advantages of using the Canny filter for flame chemiluminescence image processing over the more widely used Sobel and Prewitt operators. The result of image processing by the Canny operator is more suitable for further analysis of the flame front dynamics. High processing quality and processing rate, the ability to regulate the sensitivity to noise are its advantages. The combined using of the Canny filter in the Matlab package and the software function "bwareaopen" allows to get the flame front as a continuous line one pixel thick.

References

[1] Canaani F, Fazli M and Ezzatian V 2016 *Iranian journal of geophysics* **10** 75–84

[2] Larin I 2017 *Russ. J. Phys. Chem. B* **11** 189–94

[3] Maurya R K, Maurya R K and Luby 2018 *Characteristics and Control of Low Temperature Combustion Engines* (Springer)

[4] Reijnders J, Boot M and de Goey P 2016 *Fuel* **186** 24–34

[5] Nemitallah M A, Abdelhafez A A and Habib M A 2020 Global warming and emission regulations *Approaches for Clean Combustion in Gas Turbines* (Springer) pp 1–12

[6] Wan J, Shang C and Zhao H 2018 *Fuel* **232** 659–65

[7] Wan J and Zhao H 2020 *Fuel* **279** 118473
[8] Wan J and Zhao H 2017 *Energy* **139** 366–79
[9] Tropea C and Yarin A L 2007 *Springer Handbook of Experimental Fluid Mechanics* (Springer Science & Business Media)
[10] Souflas K, Psarakis E Z, Koutmos P and Egolfopoulos F N 2019 *Combust. Sci. Technol.* **191** 1123–38
[11] Kojima J, Ikeda Y and Nakajima T 2005 *Combust. Flame* **140** 34–45
[12] Sobel I and Feldman G 1968 *Presented at a talk at the Stanford Artificial Project* 271–2
[13] Haq M, Sheppard C, Woolley R, Greenhalgh D and Lockett R 2002 *Combust. Flame* **131** 1–15
[14] Skiba A W, Wabel T M, Carter C D, Hammack S D, Temme J E and Driscoll J F 2018 *Combust. Flame* **189** 407–32
[15] Canny J 1986 *IEEE Transactions on pattern analysis and machine intelligence* **PAMI-8** 679–98
[16] Jie A C H, Zamli A F A, Zulkifli A Z S, Yee J L M and Lim M 2018 Flame analysis using image processing techniques *IOP Conf. Ser.: Mater. Sci. Eng.* vol 342 p 012060
[17] Canepa E and Nilberto A 2019 *Energies* **12** 2377
[18] Ahmed M and Birouk M 2020 *J. Eng. Gas Turbines Power* **142**
[19] Apeloig J, Gautier P, Salaün E, Barviau B, Godard G, Hochgreb S and Grisch F 2016 Plif measurements of nitric oxide and hydroxyl radicals distributions in swirled stratified premixed flames *18th International Symposium on the Application of Laser and Imaging Techniques to Fluid Mechanics*
[20] Prewitt J M 1970 *Picture processing and Psychopictorics* **10** 15–9
[21] Krikunova A 2019 *Phys. Fluids* **31** 123607