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# Optical-Flow based Analysis for Range Hoods captured Flow Measurement

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**Abstract.** The performance assessment of suction systems is a fundamental aspect in industrial field, and the quantitative estimation of their uptake is a still open challenge. This research proposes a measurement methodology for the quantitative evaluation of the steam uptake of a kitchen hood suction system through the definition of an uptake index, obtained by processing optical measurement using the Farneback dense optical-flow algorithm. The results and the uncertainty analysis show high reliability and consistency of the proposed approach.

*Keywords:* Steam flow; Uptake index; Farneback; Optical-flow

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## 1. Introduction

In the industrial field, a methodology for the evaluation of the performance of an absorption system in free environment is still needed. In fact, nowadays, no legislation regulates the uptake measurement and due to this, the implementation of an optimized method for the quantitative estimation of the uptake is a very topical issue. For this purpose, the measurement of the fluid velocity field during the suction process is necessary. One of the most established and commonly used techniques is the Particle Image Velocimetry (PIV) [1, 2]. The PIV technique is widely used in fluid-dynamics to obtain instantaneous velocity measurements [3, 4]: a plane of seeded flow is illuminated with a laser sheet and the motion of the seeding particles, captured with a camera, is used to calculate the velocity field through cross-correlation function. However, one of the limits imposed by this technique is the complexity of the measurement and the high



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costs of the instrumentation, due to theoretical considerations.

For this reason, in last years, computer-vision based approaches have been largely implemented in fluid-dynamics measurements in order to establish reliable alternatives to the classic methods [5]. In literature, several researches are found as validation of the technique through the comparison with the PIV, such as Corpetti et al. [6] and Liu et al. [7]. Among all the computer-vision methods, the optical-flow technique is one of the mostly employed approach in this field [8, 9, 10], but in general, it has been widely applied to research displacement fields in solid bodies [11, 12, 13, 14], liquid flows [15] and gas flows [16, 17, 18]. Optical-flow is related to the motion of visual-features, such as corners, edges, ridges and textures in two consecutive frames of a video scene [19, 20]. Within optical-flow methods, the differentiation between sparse and dense approach is fundamental [21]. The Lucas-Kanade algorithm is one of the most employed as gradient-based [9, 10, 22, 23], using the Shi-Tomasi corner detector approach [24]. The gradient-based methods depend on the assumption that the brightness of a point in the image is constant during a short time interval [25], while the location of that point in the image may change due to motion. On the other hand, region-based approaches rely on the correlation of different features [8, 26, 27], including normalized cross-correlation and Laplacian correlation of velocity, similarity, etc. [28, 29, 30]. In recent years, several dense optical-flow methods have been developed [31]. However, the Farnebäck algorithm [32, 33] is considered one of the most employed due to its high performances compared to the required computational effort.

For this reason, in this research, a low-cost approach based on the Farnebäck algorithm for the absorbed steam flow assessment is presented. In particular, with this study, a percentage index is proposed for the quantitative definition of suction systems steam flow uptake. An experimental campaign is performed on a kitchen hood system to test and verify the methodology.

The manuscript is organized as follows. In Sec. 2 the uptake index definition using Farnebäck algorithm is proposed and the experimental setup and the data elaboration are described. In Sec. 3 the results of the experiments are presented and Sec. 4 draws the conclusions.

## 2. Materials and methods

### 2.1. Farnebäck algorithm

The dense optical-flow approach, proposed by Farnebäck [32], is an iterative and multi-scale two-frame displacement estimation method based on polynomial expansion [33]. According to this method, the neighborhood of each pixel of an image can be approximated by a quadratic polynomial as:

$$f(\mathbf{p}) \sim \mathbf{p}^T \mathbf{A} \mathbf{p} + \mathbf{b}^T \mathbf{p} + c, \quad (1)$$

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where  $\mathbf{p}$  is the  $(x, y)$  pixel coordinators vector,  $\mathbf{A}$  is a symmetric matrix and  $\mathbf{b}$  and  $c$  are defined, respectively, as [32]:

$$\mathbf{p} = \begin{pmatrix} x \\ y \end{pmatrix} \quad \mathbf{A} = \begin{pmatrix} r_4 & \frac{r_6}{2} \\ \frac{r_6}{2} & r_5 \end{pmatrix} \quad \mathbf{b} = \begin{pmatrix} r_2 \\ r_3 \end{pmatrix} \quad c = r_1 \quad (2)$$

The approximating quadratic polynomial function  $h(x, y)$  can be seen as [32]:

$$f(x, y) \sim h(x, y) = r_1 + r_2 x + r_3 y + r_4 x^2 + r_5 y^2 + r_6 xy \quad (3)$$

The coefficients can be estimated through the weighted least square approach:

$$\arg \min_{r_1, \dots, r_6} \sum_{x, y} (w(x, y)(f(x, y) - h(x, y)))^2 \quad (4)$$

where  $w(x, y)$  is the weighting function [33].

The global displacement  $\mathbf{d}_{12}$  between two consecutive images  $I_1$  and  $I_2$  can be defined using Eq. (1):

$$f_1(\mathbf{p}) = \mathbf{p}^T \mathbf{A}_1 \mathbf{p} + \mathbf{b}_1^T \mathbf{p} + c_1, \quad (5)$$

$$f_2(\mathbf{p}) = f_1(\mathbf{p} - \mathbf{d}_{12}) = \mathbf{p}^T \mathbf{A}_2 \mathbf{p} + \mathbf{b}_2^T \mathbf{p} + c_2, \quad (6)$$

where  $f_1(\mathbf{p})$  and  $f_2(\mathbf{p})$  are the exact quadratic polynomials for the images  $I_1$  and  $I_2$ , respectively. Expanding the Eq. (6), it follows:

$$f_2(\mathbf{p}) = \mathbf{p}^T \mathbf{A}_1 \mathbf{p} + (\mathbf{b}_1 - 2\mathbf{A}_1 \mathbf{d}_{12})^T \mathbf{p} + \mathbf{d}_{12}^T \mathbf{A}_1 \mathbf{d}_{12} - \mathbf{b}_1^T \mathbf{d}_{12} + c_1. \quad (7)$$

By comparing the Eq. (6) and Eq. (7):

$$\mathbf{A}_2 = \mathbf{A}_1, \quad \mathbf{b}_2 = \mathbf{b}_1 - 2\mathbf{A}_1 \mathbf{d}_{12}, \quad c_2 = \mathbf{d}_{12}^T \mathbf{A}_1 \mathbf{d}_{12} - \mathbf{b}_1^T \mathbf{d}_{12} + c_1, \quad (8)$$

and then, if  $\mathbf{A}_1$  is not singular, the global displacement  $\mathbf{d}_{12}$  between two consecutive images  $I_1$  and  $I_2$  can be obtained [33]:

$$\mathbf{d}_{12} = -\frac{1}{2} \mathbf{A}_1^{-1} (\mathbf{b}_2 - \mathbf{b}_1) \quad (9)$$

The global displacement field  $\mathbf{D}$  estimated during the entire acquired video is thus defined as:

$$\mathbf{D} = (\mathbf{d}_{i,i+1}, \mathbf{d}_{i+1,i+2}, \dots), \quad i = 1, \dots, N - 1 \quad (10)$$

where:

$$\mathbf{d}_{i,i+1} = \begin{pmatrix} d_x \\ d_y \end{pmatrix}_{i,i+1}, \quad (11)$$

with  $d_x$  and  $d_y$  are the displacement components in  $x$  and  $y$  directions between the  $i^{th}$  and  $(i + 1)^{th}$  frames and  $N$  is the number of acquired frames. In this research, both iterative and multi-scale approaches were implemented. In particular, 3 converging iterations and 5 scale levels were found as proper compromise between computational efficiency and results accuracy.

*Optical-Flow based Analysis for Range Hoods captured Flow Measurement**2.2. Uptake Index*

In this research, an analytical model for steam suction systems uptake estimation is presented. In this particular application field, the resulting maps are generally preferred in terms of velocity respect to the displacement, due to technical and procedural considerations. For this reason, the velocity field  $\mathbf{V}$  can be derived from the spatially calibrated global displacement field  $\mathbf{D}$  obtained from the Farnebäck data elaboration (see Sec. 2.1). Thus, the velocity field is defined as:

$$\mathbf{V} = \mathbf{D} \cdot f_s \quad (12)$$

where  $f_s$  is the sampling frequency of the acquisition. Similarly to the global displacement field, the velocity field can be seen as:

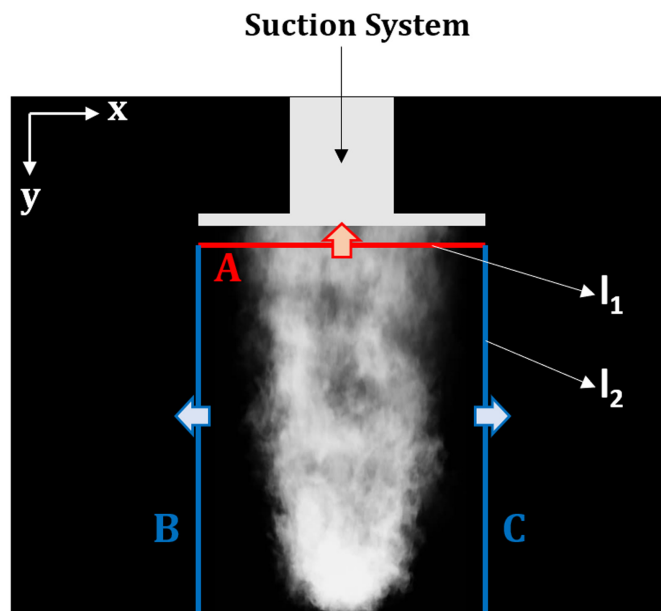
$$\mathbf{V} = (\mathbf{v}_{i,i+1}, \mathbf{v}_{i+1,i+2}, \dots), \quad i = 1, \dots, N - 1, \quad (13)$$

where:

$$\mathbf{v}_{i,i+1} = \begin{pmatrix} v_x \\ v_y \end{pmatrix}_{i,i+1}, \quad (14)$$

with  $v_x$  and  $v_y$  are the velocity components in  $x$  and  $y$  directions between the  $i^{th}$  and  $(i + 1)^{th}$  frames.

For a quantitative analysis, the uptake index (UPTI) is here proposed. A sample suction system is schematised in Fig. 1, where a closed surface incorporates the steam flow generated from the bottom.



**Figure 1.** Uptake index estimation scheme

The steam particles that come out from the B and C sections (*i.e.*, blue lines) are considered a negative contribution to the uptake while particles crossing the A section

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(red line) are assumed aspirated. Thus, the flows crossing out from the sections A, B and C are defined as:

$$Q_A = l_1 \sum_{i=1}^{N-1} v_{y,i,i+1}^-, \quad Q_B = l_2 \sum_{i=1}^{N-1} v_{x,i,i+1}^-, \quad Q_C = l_2 \sum_{i=1}^{N-1} v_{x,i,i+1}^+ \quad (15)$$

where  $l_1$  and  $l_2$  are the section lengths,  $v_x$  and  $v_y$  are the velocity components, perpendicular to the sections, obtained from Farnebäck computation. The velocity apices are referred to the reference system. Finally, the UPTI can be defined as the ratio between the flow out of the red line and the total flow out of the blue and red sections:

$$\text{UPTI} [\%] = \frac{Q_A}{Q_A + Q_B + Q_C} \quad (16)$$

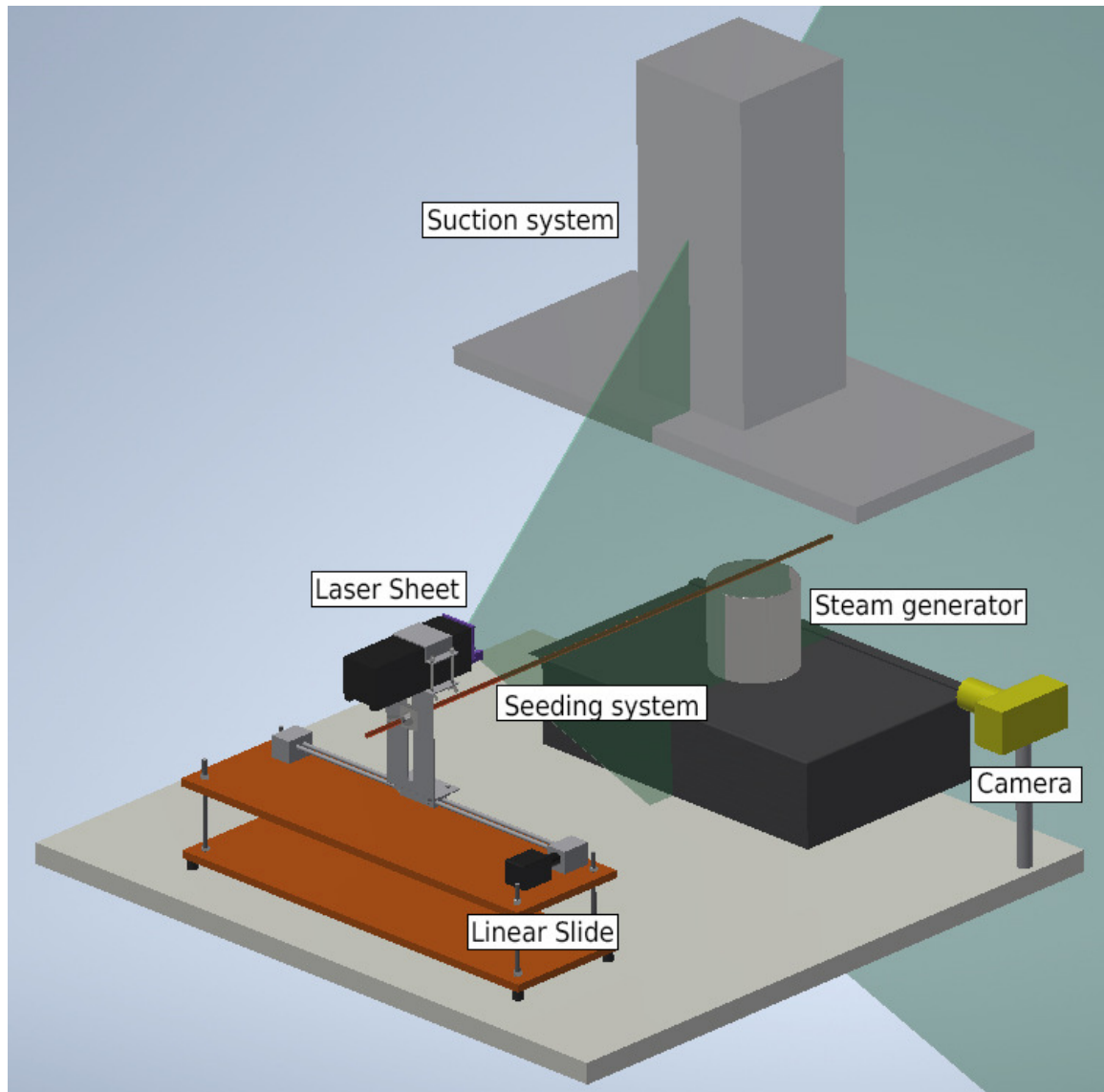
*2.3. Experimental setup*

The experimental campaign presented in this research was designed in order to estimate the uptake index, described in Sec. 2.2, for an industrial steam flow suction system. The system chosen is Elica Thin, a traditional T-shaped kitchen hood with 3 absorbing speed levels and 0.65 m<sup>2</sup> of complex suction surface, produced by Elica Spa. and shown in Fig. 2.



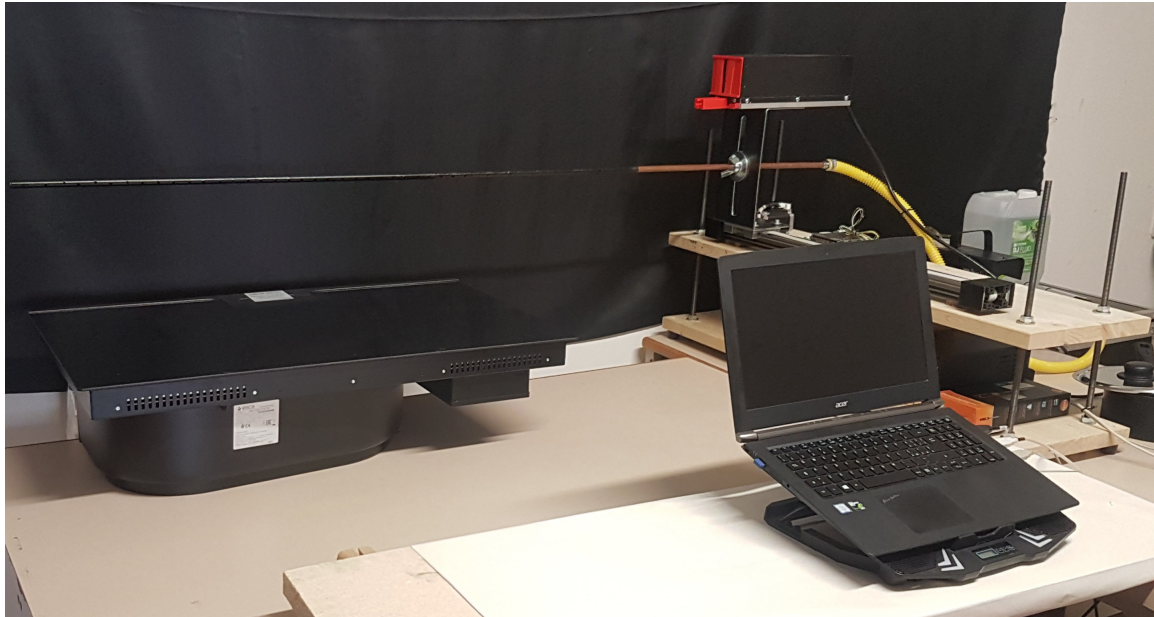
**Figure 2.** Elica Thin T-shaped suction system

The used test bench, shown in Fig. 3 and placed in a dark room in order to obtain higher contrast of the phenomenon, consists of: a steam generator (400 W of power); a glycol-smoke seeding system [34, 35]; a green laser sheet (wavelength 532 nm) controlled by a stepper motor on a linear slide in order to be able to analyze different focus planes; an acquisition device (Canon EOS 7D with F/1.4 optics mounted).

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**Figure 3.** Test bench for steam uptake index estimation

The seeding system was properly designed and realized with a 10 mm diameter copper pipe, connected to the steam generator, with 10 drilled holes of 2 mm of diameter in order to uniformly insemenate the measurement volume from the bottom of the test bench (see Fig. 4).

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**Figure 4.** Seeding system

The experiments are organized as follows: the laser sheet and the camera are placed orthogonally at 1.5 m and 2 m from the center of the hood, respectively; the three suction speeds of the hood are tested acquiring 5 seconds of suction process with the camera acquisition parameters settled at 50 fps and 1920x1080 pixels of resolution. Moreover, in order to estimate the uncertainty due to the measurement repeatability, each test was repeated 5 times [36] under the same conditions.

#### *2.4. Data elaboration*

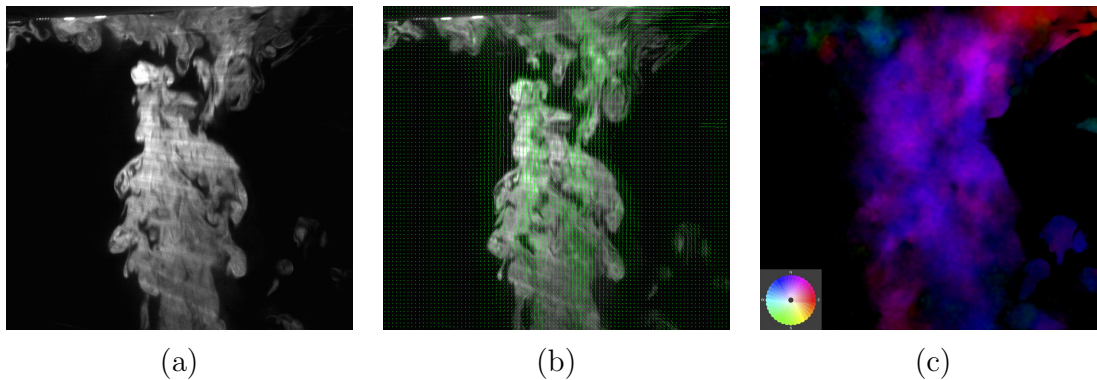
As discussed in Sec. 2.1, each acquired video is analyzed in pairs of frames. In the Fig. 5-(a), an original frame, extracted from the acquired video, is shown. The optical-flow algorithm is applied between this frame and the following one. The velocity fields calculated by Farnebäck algorithm expressed by magnitude lines and HSV-code colors are shown in the Fig. 5-(b) and Fig. 5-(c), respectively. In particular, in the HSV maps, the color indicates the direction of the motion while the intensity corresponds to the velocity magnitude.

The OpenCV Farnebäck optical-flow module has been exploited [37]. The following computational parameters were obtained after preliminary optimization experiments:

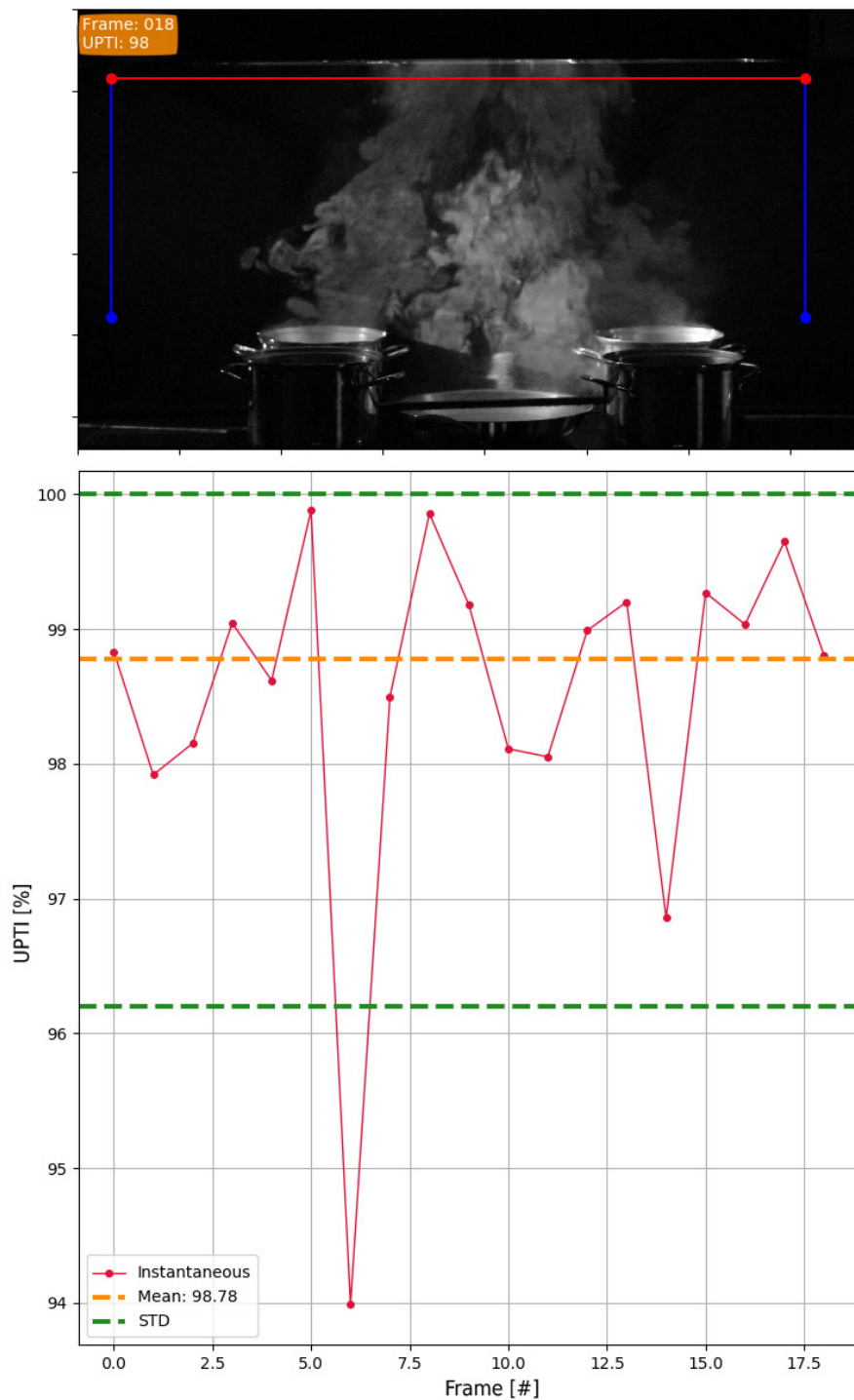


*Optical-Flow based Analysis for Range Hoods captured Flow Measurement***Table 1.** Computational parameters for Farneback algorithm

Parameters	Value
Pyramid scale	0.5
Pyramid levels	5
Iterations	3
Average window size	10
Poly- $n$	5
Poly- $\sigma$	1.15

**Figure 5.** Optical-flow frame computation: (a) original frame, (b) line map flow, (c) HSV map flow

The sections definition is then performed according to the scheme shown in Fig. 1. Iterating the Eq. (15) and Eq. (16) for each couple of consecutive frames, the UPTI index behaviour over acquire frames were obtained. The Chauvenet method is finally implemented in order to filter out the UPTI outlier values [38]. In this regard, based on a confidence interval calculated from the standard deviation of the results distribution, the algorithm evaluates the inlier values to be used to determine the average UPTI. This approach is fundamental in order to control the random and aleatory nature of the phenomenon analyzed. In Fig. 6, the UPTI behaviour (red line), the confidence interval (green lines) and the average UPTI value (orange line) are shown by means of the dedicated Python module-based GUI.

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**Figure 6.** Section definition and UPTI over time fluctuation: short video sample

### 3. Results

The experiments were conducted as described in Sec. 2.3 and the acquisition were elaborated as presented in Sec. 2.4. In Tab. 2, the results of each measurement are presented ( $V\#$  and  $S\#$  states for acquired video and suction system speed level).

*Optical-Flow based Analysis for Range Hoods captured Flow Measurement***Table 2.** Experiments results

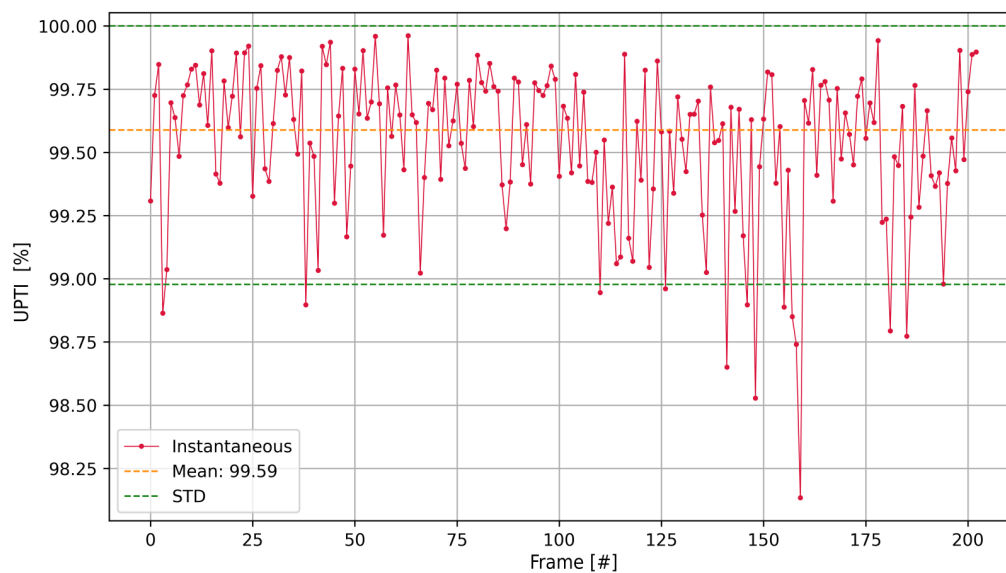
	UPTI [%]		
	S1	S2	S3
V1	99.59	98.60	98.24
V2	99.45	97.65	98.74
V3	99.35	98.71	97.94
V4	99.32	97.04	95.57
V5	99.22	97.93	95.57

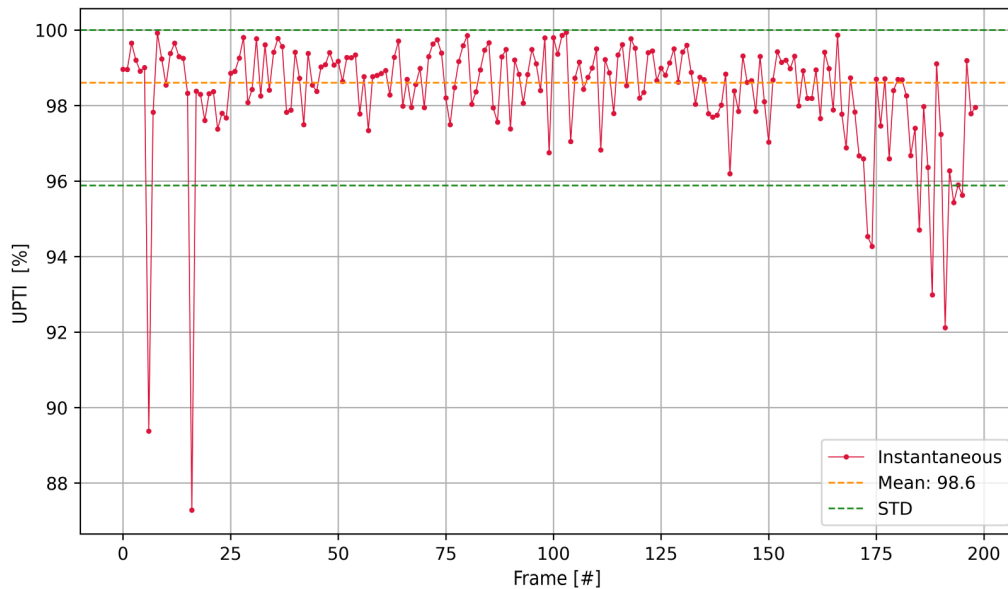
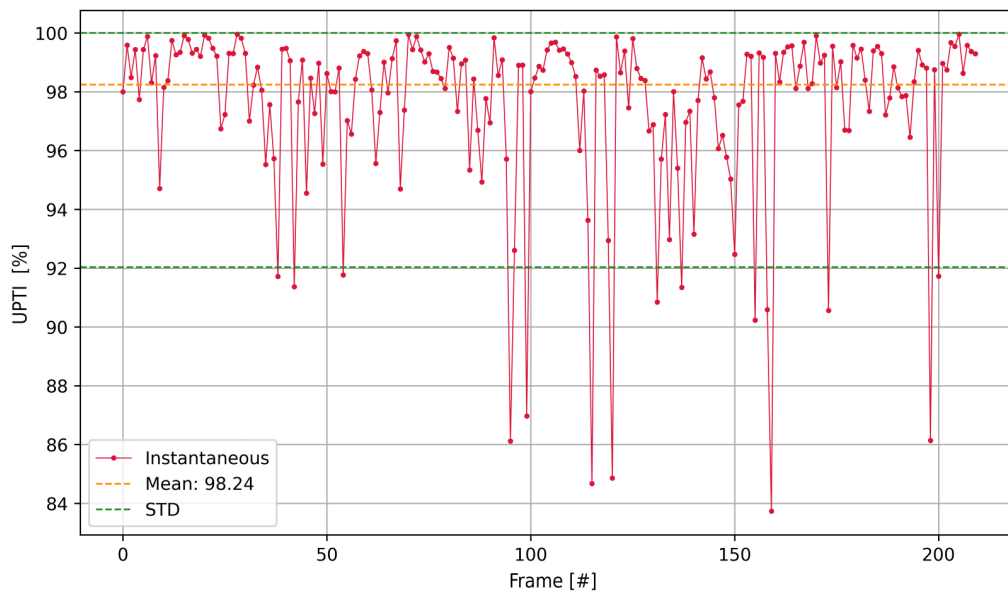
Then, the statistical analysis was carried out and the uncertainty due to measurement repeatability was evaluated, and the results are shown in Tab. 3.

**Table 3.** Uncertainty analysis

	Uncertainty [%]
S1	$\pm 0.14$
S2	$\pm 0.71$
S3	$\pm 1.14$

For the sake of clarity, the detailed results of the UPTI over time is shown only for acquisition V1 and speeds S1-S2-S3.

**Figure 7.** UPTI behaviour over acquisition: V1 - S1

*Optical-Flow based Analysis for Range Hoods captured Flow Measurement***Figure 8.** UPTI behaviour over acquisition: V1 - S2**Figure 9.** UPTI behaviour over acquisition: V1 - S3

The obtained results are in line with the expectations. In fact, considering the tested above-upright suction system, an high UPTI is awaited a priori. Furthermore, as the suction speed increases, the UPTI decreases, as proved by the results in Tab. 2. This behaviour can be attributed to the increasing in convection and turbulence phenomena that force the steam out of the suction area, while under S1 conditions, the flow is almost laminar and this phenomena are not appreciable. For the same reason, the results in terms of uncertainty are also acceptable. The uncertainty goes from 0.28% of the tests

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at speed S1 to 2.86% of those at speed S3.

## 4. Conclusions

This study researches the steam flow uptake of industrial suction system. Computer-vision algorithms are used for data processing. While the established methods give good results but with high-costs instrumentation, the implementation of dense optical-flow Farneback algorithm has shown reliable results with relatively low-cost instrumentation required. Moreover, in this research, an uptake index has been proposed for the quantitative estimation of the actual steam flow absorbed by a classic T-shaped kitchen hood. The experiments and the statistical and uncertainty analysis confirm the expectations of higher uptake in case of low suction speed. Further developments of this proposed method include the implementation of real-time computation of the uptake index, the reduction of the noise both for the acquisition and the computation process as well as the testing of more complex and non-conventional hoods.

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