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μ -PIV characterization of the flow in a milli-labyrinth-channel used in micro-irrigation

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Abstract The baffle-fitted labyrinth-channel is largely used in micro-irrigation systems. The existing baffles, which play an important role for generating pressure losses and ensure the flow regulation on the irrigation network, produce vorticities where the velocity is low or zero. These vorticities favor the deposition of particles or other biochemical development causing emitter clogging. Flow topology characterization in this labyrinth-channel must be described to analyze emitter clogging sensibility which drastically reduces its performance. This characterization can be performed experimentally using the micro-particle image velocimetry (μ -PIV) technique. In this study, μ -PIV experiments are performed to visualize the flow in tenpattern repeating baffles used in micro irrigation emitter. Cross section is 1mm². Reynolds number varies from 400 to 800. This investigation allows analyzing the flow regime. It helps to fix the baffle number from where the flow is developed. Finally, the μ -PIV and modeling results comparisons are presented. The global objective of this study is to identify and analyze the sensitive areas in order to reduce them thanks to geometry optimization.

List of symbols

d _h	Hydraulic diameter (m)
d _p	Particle diameter (m)
f	Frequency (Hz)
k	Coefficient
р	Pressure head (m)
q	Flow rate (m^3/s)
Re	Reynolds number
St	Stokes number
u	Velocity module (m/s)
u _m	Mean flow velocity at the inlet (m/s)
Х	Exponent
u'	The root-mean-square of the turbulent velocity fluctuations (m/ s)
$\overline{u^{\prime 2}}$, $\overline{v^{\prime 2}}$,	Reynolds stresses
$\overline{w'^2}$, $\overline{u'v'}$	
V _x	Velocity component in the direction x (m/ s)
V _y	Velocity component in the direction y (m/s)
x, y, z	Cartesian coordinates
Δt	Time between pulses (s)
$\lambda_{abs}, \lambda_{em}$	Absorption and emission length (m)
η	Kolmogorov length scale (m)
ν	Kinematic viscosity (m ² / s)
3	Dissipation rate of turbulent kinetic energy (m^2/s^3)
τ_{p}	Characteristic time of a particle(s)
τ_{k}	Kolmogorov time scale (s)

 ρ_{p} Particle density (kg/m³)

μ Dynamic viscosity (Pa.s)

1. Introduction

Micro-irrigation is a technique characterized by low-velocity water flows. The water drops near the plants through emitters. This type of irrigation improves efficiency by reducing evaporation, drift, runoff and deep percolation losses when compared with the other techniques such as sprinkler irrigation. In this technique, emitters are the most important and critical components [6]. They generate low flow rate between 0.5 and 8 l/ h for pressure between 0.5 and 4 bars. Emitter flow rate increases with static pressure in a lateral pipe according to a power-law (Karmeli 1977) [6]:

 $q = k P^{x}$ (1)

where q is the emitter flow rate, K the proportionality coefficient that characterizes each emitter, P the pressure head and x the emitter discharge exponent. The value of this exponent depends on emitter conception. Indeed, manufacturers try to design emitters whose flow rate is not directly dependent on the pressure head (x < 0.5). To reach this goal, they introduce some elements in the emitter such as a labyrinth-channel which generates local pressure head losses. The main drawback of this technique is clogging. There are a few studies where labyrinth-channel was investigated experimentally. Some researchers employ numerical modeling to study the flow in the labyrinth-channel. The numerical studies emphasize that emitter performances are related to hydraulic conditions; [2], [7], [8]. Clogging occurs in low-velocity regions and vortex as it is experimentally found [5], [11]. When designing emitters, clogging can be prevented or at least significantly reduced by decreasing, as much as possible, vortices size. Thus, anti-clogging properties and consequently micro-irrigation efficiency are strongly related to hydraulic performance. Previous numerical studies [5] and [7] analyze flow in several geometries in order to choose the best design or to optimize an existing geometry [3] and [9]. Depending on the model used [1], flow is strongly different. It is thus necessary to validate these results. In this work, we propose to overcome with this challenge in performing micro particle image velocimetry (µ-PIV) experiment to analyze the flow within such a labyrinth-channel. This analysis is focused on the vortices. The velocity fields and profiles are presented along the labyrinth-channel in the directions x, z. The results obtained by μ -PIV are compared to those calculated, numerically, by [1] in order to validate the numerical hypothesis and choose the best turbulence model adapted to the labyrinth-channel flow.

2. Materials and method

2.1 Hydraulic pilot

2.1.1. The labyrinth-channel

Ten-pattern labyrinth-channel has been fabricated by machining and a second plan plate is used to seal the prototype. The material is transparent PMMA. Sealing is assured in pressing the two PMMA plates between two 5mm thick steel plates. This geometry is the most widespread in micro-irrigation. That is why this first study has been performed on it. The labyrinth-channel geometry is shown in Fig. 7. The labyrinth-channel unit length, maximum width and depth are 3 mm, 2.7 mm and 1mm respectively. The cross-section is equal to 1mm².



Fig. 1 Prototype support

2.1.2-Hydraulic circuit

The hydraulic scheme which provides the flow fluid (water) with PIV seeding particles is shown in Fig. 2. It is composed of a diaphragm metering pump (SIMDOS 10), pump accuracy of 2% of the set value, pumps water from a 1 liter tank. The flow rate is adjusted by the pump. Just before the pump, there is a filter to protect it, especially during seeding. Then, two dampers, a hand-made damper (which is constituted by a pipe which contains air) and a commercial damper (type: PML 9962-FPD10, with a maximum efficiency of 97%), absorb the flow pulsations, before going through a flow meter (Mc Millan, accuracy of ± 3 ml/min) and the labyrinth-channel prototype. The pressure at the inlet as well as the pressure drop is measured by two highly precise pressure transmitters (PR-33x/ 80794 and PD-33x/ 80920, accuracy of 0:01 %).



Fig. 2 General scheme of experiments and experimental set-up.

2.2 Optic components

Optical scheme or μ -PIV equipment is composed by a laser source which is a Litron Nd-YAG Laser of 135 MJ, doubled in frequency (532 nm). A HiSence 4M camera with the resolution of 2048 \times 2048 pixels equipped with a Canon MP-E 65mm f/ 2.8 lens was mounted inside of the labyrinth-channel.

2.3 Experimental setting

2.3.1 **µ-PIV**

a. Time between pulses and frequencies

There are several parameters to adjust before starting the μ -PIV experiments. Firstly, time between two laser pulses. This time is defined by flow velocity. The flow in labyrinth-channel is complex. According to [1], it consists in two different regions: one is the main flow and the other is the vortices zones. The modeling is carried out by k- ε models and RSM. The flow is supposed to be turbulent. The velocity profile is plotted in Fig. 3. This profile corresponds to the modeling results by the standard k- ε model for a flow rate of 48ml/min. We chose two velocities corresponding to the peaks for estimating Δt . Δt is calculated in order that a particle moves a quarter of interrogation window, which is equal to 64 pixels (0.93 mm). This step is repeated to calculate the time between two laser pulses for the three flow rates imposed during the experiment (Tab 1). Tests are carried out to determine which time will be better for μ -PIV experiments. The tests began from the largest time of each flow rate, Tab.1 (which corresponds to vortex velocity) to the smallest time (which corresponds to the main flow velocity). It has been observed that the velocity profiles measured do not evolve anymore when the time is lower than that of the main flow (for example 17µs for flow rate of 48ml/min). Therefore, the smallest time has been taken. Secondly, frequency between two image couples is calculated by taking into account that images have to be non-correlated, i.e. the particle which has a low velocity leaves the image. We thus choose to fix f = 1 Hz. Thirdly, image number is chosen to ensure convergence criteria toward mean velocity and two fluctuating velocity second-order moments components. In these experiments, we analyze 250 image series. The residue values obtained (Fig. 4) are 10^{-2} and 10^{-5} , for respectively mean and fluctuating velocities.



Fig. 3 Velocity profile for the flow modeled in 3D by the RSM model, flow rate=48ml/ min

q	Velocity	Time	
ml/ min	m/ s	μs	
24	0.65	36	
	0.11	222	
36	1	23	
	0.21	110	
48	1.35	17	
	0.34	69	

Tab. 1 Times between two laser pulses



b. Seeding particles

During the experiment, the particles concentration is added to the water until there are four particles by 64×64 pixels interrogation window. This concentration was 10 ml solution charged with fluorescent particles added to 150 ml pure water. The particles added are polystyrene covered with red fluorescence. Particle density is nearly equal to the water density (1.05 kg/m³). Typical dye wave lengths used in red fluorescent particles are $\lambda_{abs}=530$ nm and $\lambda_{em}=607$ nm. These particles have a diameter of 5.2 µm. The choice of particle diameter is made to ensure that it is inferior to the Kolmogorov length scale. The Kolmogorov length scale is calculated (Eq. 2), according to the results of [1], where the dissipation rates ε for the flow rates 24 ml/min (Re=400) and 48 ml/min (Re=800) were 8 and 100 m²/s³ respectively.

$$\eta = \left(\frac{v^3}{\varepsilon}\right)^{1/4} \tag{2}$$

The Kolmogorov length scale varies from 9 μ m to 13 μ m for these flow rates based on the numerical results. Stokes number (Eq. 3) is also a parameter determining the particles choice. This number is defined as the ratio of the characteristic time of a particle (Eq. 4) to a characteristic time of the flow or the Kolmogorov time scale (Eq. 5).

$$St = \frac{\tau_p}{\tau_k}$$
(3)

$$\tau_{\rm p} = d_{\rm p}^2 \frac{\rho_{\rm p}}{_{18\mu}} \tag{4}$$

$$\tau_{\rm k} = \left(\frac{\upsilon}{\varepsilon}\right)^{1/2} \tag{5}$$

Stokes number for the same flow rates tends toward zero. This means that the particle behaves like a tracer. The particle seeding image is shown in Fig. 5.



Fig. 5 Particles seeding

c. Alignment and perpendicularity

Prototype support, Fig. 1, is installed to be parallel to laser light sheet and perpendicular to the camera. The fact of being perpendicular is to have a clear view of fields in the channel bottom maintaining the same distance between the camera and the prototype. Then, the distance between laser source and prototype support is adjusted. This distance allows having the finest laser highlight at the nearest prototype side. This distance is equal to 40 cm. Afterwards, by moving the camera, lens focal length changed, it was set to cover a full baffle. Lens focal length was 48 μ m. At this position, a pixel is equivalent to a distance of 1.45 μ m. Thus, acquisition window has the dimension of 2.98 ×2.98 mm. Finally, the channel middle is defined measuring the distance between the channel bottom and the side between the two plates which was 0.65 mm equivalent to 1 mm (channel depth). As a consequence, this distance will be divided by two to have the channel middle at the prototype inlet and outlet thanks to velocity profiles in the z-direction. This profile has been obtained from the maxima of velocity profile in the (x, y) plane taken at different z-values Fig. 6.



Fig. 6 velocity profile in the middle of line a in the direction z

2.3.2 Experiment post-treatment

The μ -PIV system analysis software used is commercial software provided by Dantec (Dynamics Studio). During the treatment, a mask is used to eliminate the area outside of the labyrinth-channel flow. Then, the mean image is calculated for 250 images. An arithmetic image is then deduced. Finally, an adaptive correlation is applied to the arithmetic images with final interrogation area size of 64 × 64 pixels and overlap of 50%. As an option, high accuracy subpixel refinement is chosen. The adaptive correlation data are exported to Matlab in order to continue and illustrate the treatment results (velocity fields and profiles, fluctuating velocity second-order moments, turbulence intensity).



Fig. 7 Labyrinth-channel

Velocity and Reynolds stresses are deeper analyzed on field and lines as represented in Fig. 7 whose coordinates are grouped in (Tab. 2). x1, x2, y1, y2 are the boundaries coordinates of each line. z=0.5, this mean that the results are presented in the channel middle according to the z axis.

Dimensions in mm	x1 (mm)	x2 (mm)	y1 (mm)	y2 (mm)	Z
Line a	0	1	-1.23	-1.23	0.5
Line 1	2	2	0	2.75	0.5
Line 2	5.3	5.3	0	2.75	0.5
Line 3	8.6	8.6	0	2.75	0.5
Line 4	11.8	11.8	0	2.75	0.5
Line 5	15	15	0	2.75	0.5
Line 9	28.3	28.3	0	2.75	0.5
Line 10	31.6	31.6	0	2.75	0.5



3. Results and discussion

The μ -PIV has been performed on the ten patterns labyrinth-channel of emitter. Three flow rates have been imposed, namely, 48 ml/min, 36 ml/ in and 24 ml/min. Based on the mean velocity and inlet cross-section, the Reynolds numbers are 400, 600 and 800 respectively.

$$Re = \frac{U \, d_h}{v} \tag{6}$$

Then, the images recorded are treated by Dantec software (Dynamics Studio). The mean and fluctuating velocities are calculated and traced by Matlab software.

3.1 Inlet flow

The labyrinth-channel prototype is designed taking into account that the flow has to be established before the entrance in the baffle curve. Velocity profiles, before the baffle curve, are plotted to determine whether the flow was developed or not. These profiles are shown Fig. 8 for Re=800 and Re=400. The velocity profiles do not evolve. Therefore, the flow is considered to be established. The parabolic shape of velocity profile for Re= 400 ensures this fact.



Fig. 8 Velocity profiles for various y positions at the inlet.



Fig. 9 Dimensionless velocity profiles in line a.

Then, dimensionless velocities in line **a** (Fig. 7) for the two Reynolds numbers are plotted in Fig. 9. The dimensionless velocities have the same tendency near the wall. The difference is important in the flow core. At Re=400, the parabolic behavior confirms that the flow is laminar whereas at Re=800, the curve is more homogenized which can be attributed to a transitional regime or an influence of the downstream turn. The Reynolds stresses are calculated. The fluctuating velocity second-order moments show that the turbulence is weak; about 10⁻⁴ for $\overline{u'^2}$ and $\overline{u'v'}$. 10⁻² for $\overline{v'^2}$ (for Re=800 and Re=400) which is important comparing with the other terms ($\overline{u'^2}$ and $\overline{u'v'}$) Fig. 10 and Fig. 11.

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The turbulence intensity, at the inlet, is calculated from the following formula:

$$I = \frac{u'}{U_m}$$
(7)

where:

$$\mathbf{u}' = \sqrt{\left(\frac{1}{3}\left(\overline{\mathbf{u}'^2} + \overline{\mathbf{v}'^2} + \overline{\mathbf{w}'^2}\right)\right)} \tag{8}$$

As only two components of the fluctuating velocity are measured by 2C μ -PIV, the third component has to be estimated from the first two. Comparing the two components measured by μ -PIV, the fluctuating velocity $\overline{v'^2}$ is greater than $\overline{u'^2}$. The ratios are 20 (30) for Re=800 (Re=400). Therefore, the fluctuating velocity perpendicular to the main flow axis is 20-30 times lower than in the main flow direction. Therefore, it was decided to calculate the turbulent intensity by assuming axisymmetric flow [4], i.e. the two components perpendicular to the main flow direction are considered equal. For Re=800 (Re=400), the turbulence intensity is large near the wall about 15-35 % (20-60%). Nevertheless, it is very small, 3-3.5% in the channel middle (1.5-2.5%).

3.2 Flow characterizations in the labyrinth-channel

The flow streamlines and velocity fields obtained for the fifth baffle are shown in Fig. 12 and Fig. 13 for respectively Re=800 and 400. The flow in the labyrinth-channel is composed of a main flow where the velocity is high (reaching 2.8 and 1.2 m/s) and vortex zones at very low velocity. The velocity in the vortex zone varies from 0.3 to 0.6 m/s for Re=800 (respectively 0.1 to 0.3 m/s for Re=400). The vortex form is not changed when increasing the flow rate. The vortex center moves a little towards the wall for Re=400.



Fig. 12 Streamlines and velocity fields in the fifth baffle, Re=800.



Fig. 13 Streamlines and velocity fields in the fifth baffle, Re=400.

Fluctuating velocity second-order moment fields $\overline{u'^2}$, $\overline{v'^2}$ and $\overline{u'v'}$ are also calculated and plotted for the fifth baffle for Re=800 and Re=400 (Fig. 14 and Fig. 15). It can be observed that the Reynolds stresses are three times higher for Re=800 in comparison with Re=400. For both, $\overline{u'^2}$ and $\overline{v'^2}$ are maximum in the main flow near the separation zone. Reynolds stresses is close to zero at the vortex zones, thereby facilitating the particle deposition and emitter clogging.









3.3 Axial development of the flow

The vortex zone, as mentioned above, has the same form for all baffles, for both cases Re=800 and Re=400. However, the question is how the flow develops along the ten baffles. In order to answer to this question, the velocity profiles are plotted at the beginning (third baffle), the middle (fifth baffle) and the end of labyrinth-channel (ninth baffle) (Fig 16). At Re=800, in the main flow, velocity magnitude is the same for all positions but in the swirl zone, some differences are observed (34% in the vortex zone). For Re=400, a greater dispersion is observed (40% in the vortex zone).



Fig. 16 Velocity profiles in 3^{rd} , 5^{th} and 9^{th} baffles for Re=800 and Re=400.

One of the measurement errors is related to the flow meter. In fact, tests are performed to calculate this error. The volume of water is collected for a period of time imposed, and then the flow rate is calculated. Comparing with the flow meter values, the errors were 4% (8%) for Re=800 (respectively Re=400). This partially explains the dispersion.







Fig. 18 Velocity profiles for the first three baffles Re=600, at the lines 1,2 and 3 in Fig. 7

No conclusion about establishment can be thus emphasized. Therefore, we focus on the velocity evolution on the first three baffles plotting the velocity components profiles v_x , v_y and v module on the first three baffles in order to understand how the flow changes from one baffle to another (Fig. 17 and Fig. 18). v_x is negative in the vortex zone and positive in the main flow when v_y is positive in the vortex zone and negative in the main flow. The flow velocity reaches the maximum value at y=1.95mm from the low wall. In the first baffle, the main flow and vortex zone are not well clear. It is difficult to distinguish them. Flow structure is more or less established from the third baffle but small evolution is observed until the tenth baffle.



Fig. 19 Dimensionless velocity profiles Re=600, Re=800.

Regarding dimensionless velocity for Re=800 and Re=600 (Fig. 19), it appears that the flow is developed in the third baffle.



Fig. 20 and Fig. 21 show the fluctuating velocity second-order moments profiles which are slightly different. $\overline{u'v'}$ values are close to zero in the vortex zones and higher in the main flow. Smaller particles should be used in future experiments to better predict this profile. In general, fluctuating

velocity second-order moments profiles confirm that third baffle is the baffle where the flow is developed. It can be concluded that the flow properties do not change after the third baffle, for the different flow rates.

3.4 Vertical evolution of the flow

As mentioned above, the labyrinth-channel is fabricated by machining and thus this surface is not smooth. The surface roughness has not yet been characterized. The velocity profiles are plotted in Fig. 22, for the third baffle at z=[0.25; 0.5; 0.75] mm above the rough wall. Velocity profiles for 0.25mm and 0.75mm are superimposed; the flow is symmetric about the z axis for this range. At this distance from the wall, the roughness has no effect on velocity.



Fig. 22 Velocity profiles, Re=800.

3.5 Comparison of µ-PIV results with CFD modeling

The flow modeling has been performed by commercial software (ANSYS/Fluent) [3], several models were tested such as k-e and RSM models. It must be noted that k-e model assumes that the flow is isotropic. $\overline{u'^2}/\overline{v'^2}$ is calculated within the third baffle to know whether the flow is isotropic or not; shown in Fig. 23. In order to better distinguish contour values, the high scale is fixed to be 2.5. However, the maximum value of $\overline{u'^2}/\overline{v'^2}$ reaches 1000 near the wall. It is due to the low value of $\overline{v'^2}$. The red zones highlight the zone where $\overline{u'^2}/\overline{v'^2}$ is greater than 2.5. It confirms that the flow is not isotropic. Therefore, the PIV results will be compared with those of RSM model only.



Fig. 23 $\overline{u'^2}/\overline{v'^2}$ ratio in the third baffle, Re=800.

Streamlines obtained with μ -PIV are compared with the modeling by RSM model in Fig. 24 for Re=800. This model does not predict the vortex zone form as μ -PIV: vortex center is not at the same position and velocity magnitude is greater in the μ -PIV results (1.6 times greater) Fig. 25.



Fig. 24 Velocity streamlines in the second baffle, Re=800.



Fig. 25 µ-PIV velocity profiles comparing to RSM model at the line 3, Re=800.

Regarding the Reynolds stresses (Fig. 26) $\overline{u'^2}$ is also under-predicted in the main flow by RSM model. Nevertheless, $\overline{v'^2}$ is the same order and $\overline{u'v'}$ is negative in the main flow for both cases (µ-PIV experiments and RSM model results). The RSM model does not predict the flow in the labyrinth-channel. Therefore, the choice of another model or an option modification of this model is advised for the following modeling.



Fig. 26 µ-PIV Reynolds stresses profiles comparing to RSM model at the line 3, Re=800.

Conclusion

The main objective of this work was to better understand and characterize the flow inside labyrinth. This understanding helps to design the labyrinth-channel in order to avoid the emitter clogging. The flow within the labyrinth-channel experimentally is investigated by μ -PIV on tenpattern repeating of emitter. The velocity fields and profiles show that the flow, which is composed of a main flow and vortex zones, is developed from the third baffle and that the flow is symmetric about the z axis. The flow is not isotropic. Experimental and numerical results predicted more or less the same structure but intensities are greater from μ -PIV data. Further investigations are needed in order to predict this flow structure. Experiments using smaller particles in order to describe more precisely the flow are in construction. Afterward, particle tracking velocimetry (PTV) method will be developed to analyze the particle path and agglomeration processes, in interaction with such a complex flow. Such a study is important in order to optimize emitter conception to limit particle deposit inside swirling zones.

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