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CFD Study on the Distribution of Fertilizer in the Fertigation Plant

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Abstract: *Population growth and the reduction of freshwater resources suitable for agriculture bring forward the use of high performance irrigation systems with minimum water consumption. Drip irrigation is characterized by the distribution of water slowly, dropwise, to the plant roots. Increasing soil fertility in a more intensive agriculture requires judicious application of fertilizers along with irrigation water, called fertirigation process. Drip fertigation installations have proven their effectiveness also in orchards.*

Studying the distribution of irrigation water has been achieved in the past by analytical and numerical methods; currently, it is based on the known relations of hydrotechnics calculation for pipeline networks operating at atmospheric pressure or overpressure. The study of the distribution of primary solution of fertilization and irrigation water in the final solution for a drip fertigation system has been less well studied in the literature.

In this article, based on mathematical models which have successfully simulated fluid flow pipeline there have been made CFD (Computational Fluid Dynamics) simulations to a fertigation plant through drip with droppers used in horticulture, to determine distribution of fertilizing solution. The diffusion of fertilizers in irrigation water solution is more difficult to track due to very low concentrations and its variation with pressure pipeline network. The mathematical model was built based on the assumption that the fertilizer is in the form of solid spherical with a diameter of 100 µm which do not chemically interact with water. In this mode is a hydraulic transport of particles from the main pipe to the dropping watering. The concentration and distribution of fertilizer granules and velocity field inside fertigation system is achieved by the CFD simulation, considering turbulent flow with the k-ε model.

Keywords: *drip irrigation, chemigation-fertigation, CFD*

1. Introduction

The need for food security in the context of population growth, brings to the fore the issue of agriculture and hence the effectiveness of the soil. Expanding and intensifying crop areas as a measure does so, entails the use of natural resources that can depleting. Soil is the main source of mineral nutrients and water for plants, its ability to provide plant nutrients needed varies according to the level of fertility. Historically, where soil tillage is done with intensity, along with soil tillage technique, it has a special role fertilizer application. The application of fertilizers taking into account the characteristics of the soil and plant physiological response to, some fertilizers acidify the soil pH and other changes - to the base. Fertilizer requirement varies by species during plant growth and development. In addition to providing nutrients, a fruit tree culture can survive without water. Crop yields may increase by a good fertility management, weed and disease control especially of consumption, preferably water economically and efficiently. Drip irrigation is characterized by the distribution of water slowly, dropwise, to the plant roots. Drip watering method is beginning its development in Germany in the 1860s, when researchers began experimenting watering with underground pipes, clay, to create a combination of irrigation and drainage system. Research has evolved in the 20s by applying a system of perforated tubes and the use of plastics for water accumulation and distribution was developed in Australia after it emerged PVC pipes [1].

Using a plastic dropper in the drip equipment was developed in Israel, which, instead of distributing water through tiny holes practiced pipe watering that easily block water was distributed through channels larger and broader a constant flow. Types of chemigation include fertilization (a process known as fertirigation), herbicides, fungicides and insecticides application. Fertigation is distributing fertilizers through irrigation water soluble fertilizers and chemicals. The method is advantageous due to fertilizer use at maximum efficiency.

Applying fertilizer as chemical solution in irrigation water - fertigation - can run in two ways: drip (drip lines with plastic dropper) and micro aspersion (micro aspersions Super fogger). The drip fertigation installations are currently used arrangements by dropping (using dripper watering the tab) and ramps (localized watering perforated pipes).

Drip fertigation installations with dropper were developed a wide range of dropping the needs of water and fertilizer plant.

Studying the distribution of irrigation water has been accomplished in the past by analytical methods known relationships based on the hydraulic engineering the calculation of the duct and pipe networks operating at atmospheric pressure or overpressure. Currently these calculations are performed by numerical methods using performance computers. Calculation of all components of a drip irrigation facilities in hydro schemes shall take into account the functional considerations, slope, soil characteristics, type of dropper used of different sizes, available pressure.

Studying the distribution of fertilizer primary solution irrigation water and the final solution in fertigation system has been studied less in literature.

In this paper, based on mathematical models which have successfully simulating fluid flow pipeline were simulations CFD (Computational Fluid Dynamics) to a equipment fertigation through drip with droppers used in horticulture, to determine distribution fertilizing solution. The mathematical model is CFD simulation users fully in discrete phases of DPM (Discrete Phase Model) for tracking the trajectory of the fertilizer particles in fertigation system. The paper assumes that the fertilizer is in the form of solid spherical with a diameter of 100 μm, and does not interact chemically with water. In this mode is a hydraulic transport of particles from the dripper watering pipelines. The concentration and distribution of fertilizer granules and velocity field inside fertigation system is achieved by considering the CFD simulation with the k-ε model at turbulent flow.

2. Numerical Methods

2.1 Geometry and Meshes

CFD requires defining geometry drip fertigation system, as shown in Fig.1.

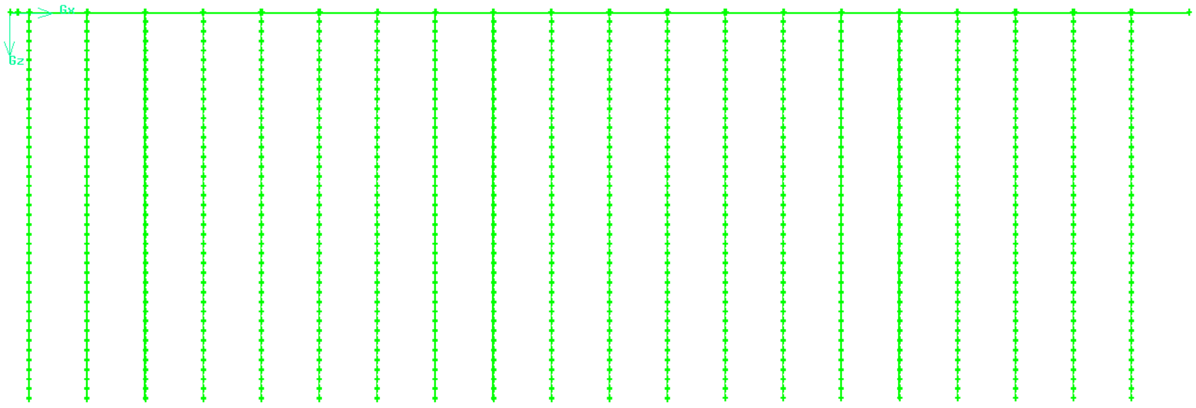

Fig. 1. Geometry drip fertigation system

The detailed dimension has shown in Table 1. Dimensions fertigation system used in the CFD simulation were reduced compared with those used in the experiment stage of fruit tree plantation, without affecting the physical phenomena occurring in the flow of irrigation water and fertilizer.

TABLE 1: Dimensions of the drip fertigation installations with dropper used in the CFD simulation

Dimension	mm
Diameter pipelines	28
Diameter injection pipe for fertilizer particles	12
Diameter pipe with droppers	16
The inner diameter dropper	0.8
The length of pipelines	61000
The length of pipe with droppers	20000
The distance between the pipes with droppers	3000
The distance from the injection pipe to the first pipe droppers	600

A grid independence study was carried out with three different mesh densities with mesh sizes varying from 1,250,000, 4,440,000 to 6,453,000. A mesh density of 4,440,000 cells (volumes) was optimal for good simulation and reasonable computational time. Optimizing the meshing had as main objective to avoid errors occurring in calculation stage. Meshing of the fertigation system was of the unstructured type with tetrahedral elements at quality 0.8, developed with Gambit v. 2.2.30 software, shown in Fig. 2.

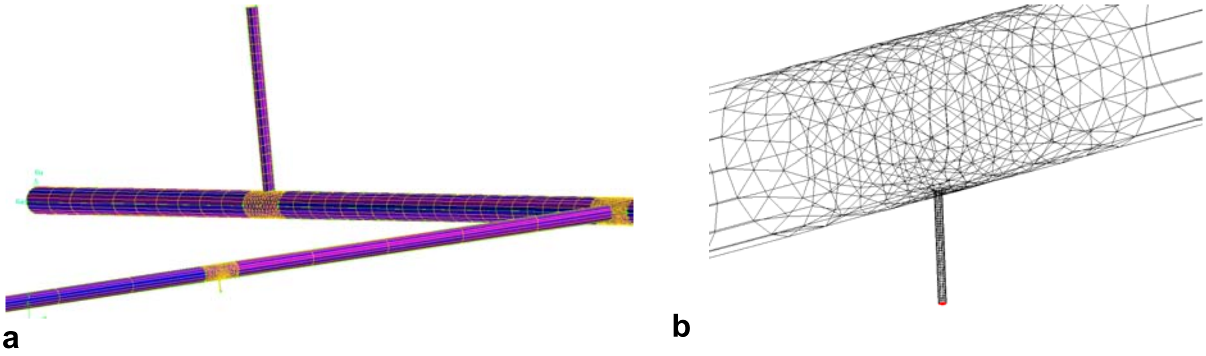

Fig. 2. Tetrahedral mesh model of the drip fertigation installations with dropper.
a. Meshing quality **b.** Meshing the dropper

2.2 Turbulence Model

The model is a simplified form of the original reduction and efficient operators, or its inclusion in mathematical equations for analysis. A mathematical model is a system of algebraic and/or differential equations describing the process behavior studied. To study a particular process establishes a mathematical model which is based on laws and principles known under the action of external factors known [2].
In developing the mathematical model of the process of working specific fertigation system, are the equations of flow of irrigation water, fertilizer particle trajectory equations, working conditions, hence the fundamental parameters and process variables and process restrictions.
Fertigation process specific parameters are obtained by experimental tests on existing fertigation plant fruit tree plantation. Stokes equations describe the Navier-principle all flows occurring in the continuum mechanics (Newtonian). They express equal amount of variation in the volume of fluid motion and considered external forces (mass) combined with those due to pressure or elastic and superficial forces. The mathematical model used is based on the general Navier-Stokes equations averaged Reynolds (if turbulent):

$$\rho\frac{Du_i}{Dt}=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]+\frac{\partial}{\partial x_j}\left(-\rho\overline{u_i'u_j'}\right)+\rho g_i \tag{1}$$

and continuity equation (mass conservation) averaged Reynolds

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}\left(\rho \overline{u_i}\right) = 0 \tag{2}$$

where: *ρ* - density of the liquid; *μ* - viscosity fluid; *p* - pressure in one direction; *g* - acceleration of gravity; $x_{i,\, j,\, k}$ - considered as a remote position; *t* - time; $u_{i,\, j}$ - the liquid velocity on direction i end j respectively.

In equations (1 and 2) u_i is decomposed into the average component of velocity $\overline{u}_i$ and fluctuating component u_i', and (= 1, 2, 3) represents the three directions. Relationship velocity is:

$$\mathrm{u_i} = \overline{\mathrm{u_i}} + \mathrm{u_i'} \tag{3}$$

Considering the turbulent fluid flow in fertigation system, equations (1) and (2) a further two equations, resulting in k-ε model proposed standard for CFD simulation. The k-ε standard model is the "full" of turbulence simplest model. It is turbulence shape with two transport equations, which allows independent assessment of the turbulent velocity and length scale of turbulence. This model works well technically in a wide variety of fluid flow. Values k turbulent kinetic energy dissipation rate and ε are obtained from the transport system of equations:

$$\rho \frac{Dk}{Dt} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\Pr_k}\right)\frac{\partial k}{\partial x_i}\right] + G_k + G_b - \rho\varepsilon - Y_M \tag{4}$$

and

$$\rho \frac{\mathrm{D}\varepsilon}{\mathrm{Dt}} = \frac{\partial}{\partial \mathrm{x_i}}\left[\left(\varpi + \frac{\mu_\mathrm{t}}{\Pr_\varepsilon}\right)\frac{\partial \varepsilon}{\partial \mathrm{x_i}}\right] + \mathrm{C_{1\varepsilon}}\frac{\varepsilon}{\mathrm{k}}\left(\mathrm{G_k} + \mathrm{G_{3\eta}C_b}\right) - \mathrm{C_{2\varepsilon}}\rho\frac{\varepsilon^2}{\mathrm{k}} \tag{5}$$

where G_k - term generation turbulent kinetic energy; G_b - the term that takes into account the effect of buoyancy; Y_M - The term that takes into account the effect of compressibility. $\Pr_k$ and $\Pr_\varepsilon$ - turbulent Prandtl numbers for *k* and *ε* respectively.

The kinetic energy per unit mass is given:

$$\mathrm{k} = \frac{1}{2}\overline{\mathrm{u_i'u_j'}} \tag{6}$$

The term generation turbulent kinetic energy is:

$$\mathrm{G_k} = -\rho\overline{\mathrm{u_i'u'_j}}\frac{\partial \overline{\mathrm{u_j}}}{\partial \mathrm{x_i}} \tag{7}$$

The term buoyancy in this case is neglected because it considered that the density is variable temperature or otherwise and gravity forces also appear neglecting. The effect of compressibility on turbulence occurs at higher flow velocity of sound, resulting in the neglect to the present model. The calculation is done with the relationship for turbulent viscosity:

$$\mu_\mathrm{t} = \rho \mathrm{C}_\mu \frac{\mathrm{k}^2}{\varepsilon} \tag{8}$$

Original constants k-ε model has been determined by experience with water, similar results to the experiment ($C_{1\varepsilon}$ =1.44; $C_{2\varepsilon}$ =1.92; C_μ =0.09; $\Pr_k$ =1.0; $\Pr_\varepsilon$ =1.3).

All equations (1, 2, 4, 5) of the system obtained will vary depending on certain terms and imposed assumptions.

2.3 Discrete Particle Model

The mathematical model which can simulate particles trajectory of discrete phase with the FLUENT software in a liquid-solid mixture is achieved by integrating the force balance on a particle [3].
The dispersion of particles due to turbulence can be predicted using the stochastic tracking model, which includes the effect of instantaneous turbulent velocity fluctuations on the particle trajectory.
The force balance between floatability and drag forces in a Lagrangian reference frame can be written as:

$$\frac{d\overrightarrow{u_p}}{dt} = F_D\left(\vec{u} - \overrightarrow{u_p}\right) + \frac{\vec{g}\left(\rho_p - \rho\right)}{\rho_p} + F_z; \tag{9}$$

where F_z is the sum of the force of particle acceleration and the force of gravity that in the simulation it was considered very low, taking into account the particle size of the order of micrometers; $F_D\left(u - u_p\right)$ is the drag force per unit particle mass and

$$F_D = \frac{18\mu}{\rho_p d_p^2 C_c} \tag{10}$$

where: ρ density of fluid medium (kg/m^3); ρ_p density of solid particles (kg/m^3); μ molecular viscosity (Pa s); d_p particle diameter (μm) and C_c Cunningham coefficient.
Cunningham correction coefficient is given by Stokes transport law and calculated with the relationship:

$$C_c = 1 + \frac{2\lambda}{d_p}\left(1.257 + 0.4e^{-\left(1.1\,{}^{d_p}\!/_{2\lambda}\right)}\right) \tag{11}$$

where: λ- molecular viscosity between free particle surface and water as a transport medium.
The coupling between the dispersed phase (the fertilizer particles) and continuous phase (water) in the CFD simulation of the proposed mathematical model is carried out by, provided that the continuous phase to the dispersed phase influence, the reverse is not true. To achieve this it is necessary to first deal with the flow of the continuous phase to achieve a stability of the solution, after which solves the discrete phase model.

2.4. Processing

In the step of processing the mathematical models are used to define the purpose of obtaining the flow field of the irrigation water and the trajectory of the fertilizer particles, from the set of equations and equations describing part physical properties of substances. In FLUENT simulation program to create an algorithm that is based on a mathematical model, which is added in addition to the contour conditions defined in the pre-processing (table 2).

TABLE 2: Boundary conditions for the CFD simulation

Boundary sections	***Status***	***Boundary conditions***	
		Fluid	***Fertilizer particles***
Inlet water	normal	u =*constant*	-
Inlet fertilizer	normal	-	u_p = constant
Outlet dropper	open	$p = 0$	catch
Wall pipe	close	$\frac{\partial u}{\partial n} = 0*$	-

* n = normal to the surface

Since the current of water that reaches the outline of input water is generated by the pump for accuracy simulation input section was considered at a sufficient distance from the pump so that the input speed of irrigation water remain constant over time (u = 0.715 m/s). The input section of the fertilizer particles differing from water inlet section of the particle velocity is assumed constant (u_p = 0.636 m/s). At 800 droppers, output is imposed on the outline provided free exhaust air (outflow type), where there than atmospheric pressure (101325 Pa = 1 atm.) And overpressure is considered null (p = 0). The water flow through the pipe walls or plant fertilizer is void.

Particles of fertilizer (Magnisal) of the primary solution with a concentration of 0.25 g/l are introduced into the plant through the fertigation vertical pipe with a diameter of 12 mm (Fig. 2 a). These particles are considered solid spherical shape with a diameter of 100 µm. Knowing that the density of fertilizer is 800 kg/m^3 calculate the number of particles introduced (about 4170) to the concentration primary solution.

The conditions for solving systems of equations for the fertigation system simulation are shown in table 3.

TABLE 3: Terms of solving differential equations

Terms of solving differential equations		**Algorithm/Scheme**	**Order**
Velocity- pressure coupling		Simple	-
Mesh equations	Pressure	upwinding (meshing scheme)	1
	Moment		1
	Turbulent kinetic energy		1
	Turbulent dissipation rate		1

When connecting velocity-pressure parameters and time between equations of continuity was performed using SIMPLE algorithm [4,5,6].

The meshing pressure and other conservation equations were used for meshing upwind scheme (velocity value *u* is "transported" to the edge of the volume relative to local velocity purposes) first order [3]. It was used in the simulation scheme linear (first order kinetics) for solving the equation of pressure in order to maintain the stability of the final solution. Quadratic scheme is more sensitive to pressure deformation, leading to instability in the calculation of the solution for the multiphase flow field (water plus particles) and the density of the mesh required.

All the simulations carried out were steady. Flow regime for the simulation is tested in order to obtain a steady state of convergent evolution residues.

Density and viscosity of water were considered constant for a given temperature (25˚C) with the conditions of boundary.

For the stability of the calculation flow of water applications was under-relaxation following factors: pressure - 0.3; moment - 0.7; density - 1; turbulent kinetic energy - 0.8; turbulent dissipation rate - 0.8; turbulent viscosity - 1. Simulated movement of fertilizer particles in water is achieved by Lagrangian particle trajectories tracking probabilistic model, called the DPM model (Discrete Particle Model) [7].

The trajectory of the particles is accomplished in several steps to a volume of fluid. Factor step length is initially set to value 5 and later for a more precise trajectory choose value 10 (Fig. 3).

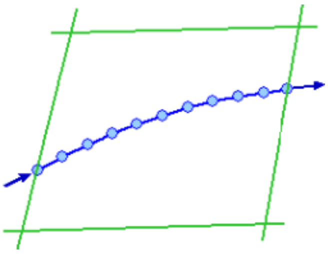

Fig. 3. Representation of the fluid volume and the step length of the fertilizer particle trajectory

The convergence of the solution through the stationary server was performed using the coefficients of the sub-relaxation time of 0.35 to 0.5 for the equation of equations turbulence. The convergence criterion used for all variables was imposed solutions to the value of 0,001. The number of iterations required for convergence equation system solutions in the processing was 555 (Fig. 4).

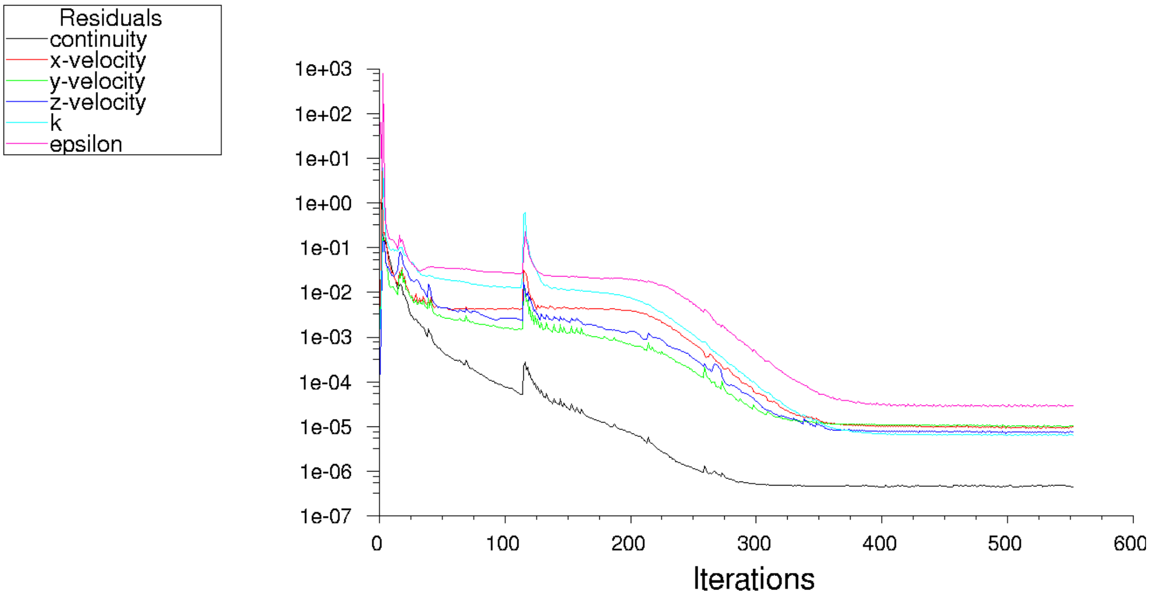

Fig. 4. Evolution of the processing residues for steady state

Processing subjected model simulation was performed with TYAN Workstation (Intel Xeon 2XCPU-3.33GHz; RAM - 16 GB DDR3 2600). The numerical solution tends to converge when analytic solution and the mesh step tend to zero. A numerical solution converges if the values of variables in the field of computing nodes tend to approach the exact solution. Also, the process of solving numerical errors is considered stable if not growing significantly discreet solution that the result is not real.

3. Results and Discussion

The results are presented as the processing velocity field, and that the trajectory of the fertilizer particles in the simulation of fertigation system. The ultimate goal is to present trajectory and mode dispersion of particles of fertilizer at the level of 800 droppers, and a tendency to move to their installation. The advantage of three-dimensional simulation of flow and particle motion is that it provides an overview as close to real fertigation process in fruit tree plantation. Plus adding a new dimension to the two-dimensional patterns lead to a more complex model but more realistic, given the turbulent flow of the simulated and the opportunity to observe the evolution of particle trajectories.

The distribution of the fertilizer particles is carried out uniformly in all of the 20 pipes of the drip fertigation system (Fig. 5). Following the loss of reducing the linear load and velocity of the final solution and fertilizer particles in the entire system, it appears that the last and penultimate dropping pipe the particles are distributed fairly evenly over all 40 dropping.

The pipes 18 and17 moving the fertilizer particles to droppers 36 and 25 respectively. It is noted that a non-uniform and incomplete is observed at the droppers from pipes 1 to 4. The particles are moving into pipe 1 up to the dropper 33, on pipe 2 to the dropper 35 and the pipes 3 and 4 particles are up to droppers 25 and 22.

This non-uniform distribution in the first 4 pipes can be explained by moving too quickly fertilizer particles, the first drip as it did enter into them. The smaller number of dropping fertilizer used for the first 4 pipes is due to the high velocity of the particles in the main pipe to let in a small number of particles in the first half of the installation and a larger number in the last half. The pipes 11 and 12 to register a total of only 27 or 25 droppers with fertilizer, but with a more uniform distribution in each dropper.

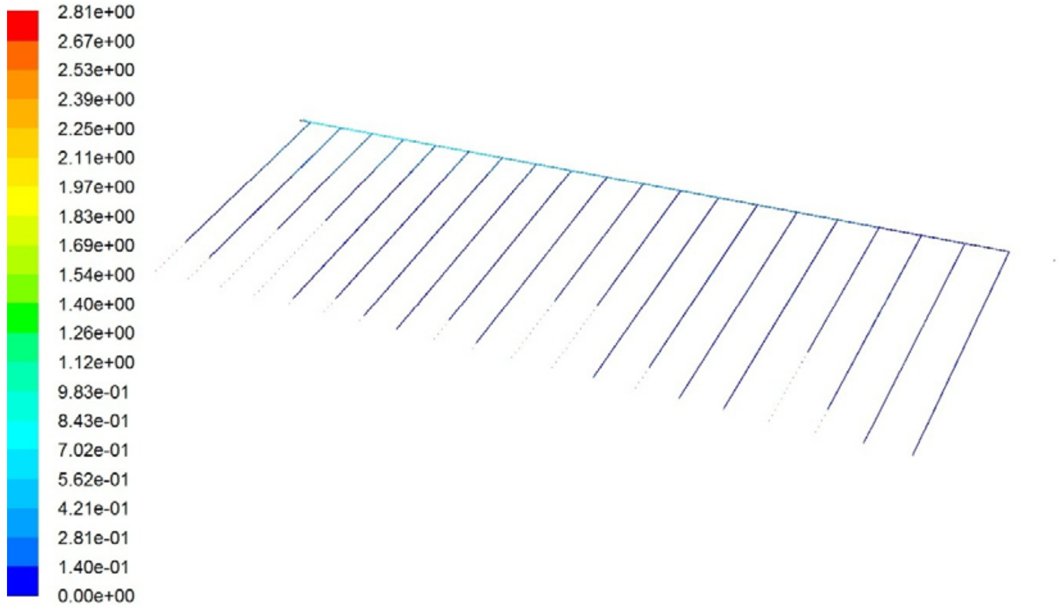

Fig. 5. Distribution of fertilizer particles in the system (color bar - fertilizer particle velocity)

By analyzing the particle distribution of fertilizer in the plant it is observed that only a percentage of 15% of fertigation pipes have fertilized all 40 dropping. The remaining pipes have a lower or higher percentage of the fertilizer dropping. Furthermore fertilizer particle distribution is non-uniform distribution in droppers in the first half compared to the last half of the plant.

Knowing the distribution of the fertilizer particle, in all the 800 droppers in the installation can be carried out in a similar way an analysis of the same type with the fertilizer solution. The concentration of the fertilizer follows the pattern of fertilizer particle distribution in the fertigation system.

Since the distribution is uneven fertilizer particles on the first pipe with dropping as a result of the great length of pipelines (61 m) relative to its diameter (0.028 m) was presented velocity field only to the first line with dropping (fig. 6).

The distribution of the velocity field in the median plane of the main pipe to the fertilizer ranges from 0 to 0.72 m/s in the pipe wall to the center flow and the vertical pipe of the fertilizer input velocity varies from 0 to 0.64 m/s from wall to the flow center.

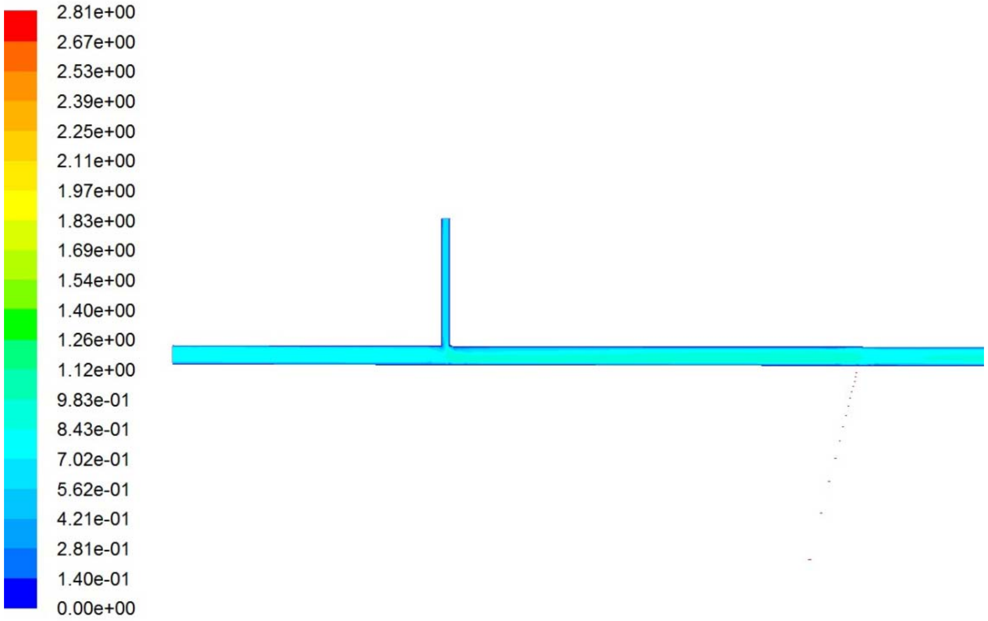

Fig. 6. Velocity field of fertilizers into the main pipe to the first pipe with droppers

4. Conclusions

By simulating CFD (Computational Fluid Dynamics) to a drip fertigation system with drippers used in horticulture has been taken to determine the distribution of fertilizing solution. The diffusion of fertilizers in irrigation water solution is more difficult to track due to very low levels and variation of pressure pipeline network. The mathematical model was built based on the assumption that the fertilizer is in the form of solid spherical with a diameter of 100 μm which do not chemically interact with water. The concentration and distribution of fertilizer granules and velocity field inside fertigation system is achieved by the CFD simulation, considering turbulent flow with the k-ε model. The advantage of three-dimensional simulation of flow and particle motion is that it provides an overview as close to real fertigation process in fruit tree plantation, plus adding a new dimension to the two-dimensional patterns, leading to a more complex model but more realistic, given the turbulent flow of the simulated process and the opportunity to observe the evolution of particle trajectories.

By analyzing the particle distribution of fertilizer in the plant it is observed that only a percentage of 15% of fertigation pipes have fertilized all 40 dropping. The remaining pipes have a lower or higher percentage of the fertilizer dropping. Furthermore fertilizer particle distribution is non-uniform distribution in droppers in the first half compared to the last half of the plant.

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