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Turbulent Kinetic Energy Distribution of Nutrient Solution Flow in NFT Hydroponic Systems Using Computational Fluid Dynamics

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Abstract: Hydroponics is crucial for providing feasible and economical alternatives when soils are not available for conventional farming. Scholars have raised questions regarding the ideal nutrient solution flow rate to increase the weight and height of hydroponic crops. This paper presents the turbulent kinetic energy distribution of the nutrient solution flow in a nutrient film technique (NFT) hydroponic system using the computational fluid dynamics (CFD) method. Its main objective is to determine the dynamics of nutrient solution flow. To conduct this study, a virtual NFT hydroponic system was modeled. To determine the turbulent kinetic energy distribution in the virtual NFT hydroponic system, we conducted a CFD analysis with different pipe diameters (3.5, 9.5, and 15.5 mm) and flow rates (0.75, 1.5, 3, and 6 L min⁻¹). The simulation results indicate that different pipe diameters and flow rates in NFT hydroponic systems vary the turbulent kinetic energy distribution of nutrient solution flow around plastic mesh pots.

Keywords: CFD; NFT hydroponic system; nutrient solution flow; turbulent kinetic energy

1. Introduction

Food production is increasingly becoming a major worldwide concern [1]. Hydroponics is an innovative strategy to produce more with less, and it plays an important role in areas unsuitable for conventional farming, such as arid and degraded soils [2]. Key aspects of hydroponics are weather protection and labor-intensive activity reduction, such as weeding and soil preparation [3]. One of the main advantages of hydroponics is that it reduces the amount of water and nutrients used for crop cultivation. The nutrient film technique (NFT) is a key technique used in hydroponics proven to be a feasible and competitive alternative to transport nutrients continuously to the roots through channels with no loss of quality.

Previous researchers have shown a growing interest in studying the impact of nutrient solution flow in NFT hydroponic systems. Helbel et al. [4] studied the effect of three nutrient solutions with two different flow rates (0.8 and 1.2 L min⁻¹). To evaluate the experiment, they cultivated lettuce (*Lactuca sativa* L.). Their experimental results did not show a significant correlation. Genuncio et al. [5] studied the accumulation of fresh weight in different ionic concentrations (50, 75, and 100%) and flow rates (0.75, 1, and 1.5 L min⁻¹). The authors proposed three different types of lettuce (Lucy, Izabela, and Veneza). Their experimental results revealed that the application of nutrient solution flow with a flow rate of 1.5 L min⁻¹ and a 100% ionic concentration increased the fresh weight of Izabela and Veneza. Al-Tawaha et al. [6] investigated the effect of three different nutrient solution flow rates (10, 20, and 30 L min⁻¹) in lettuce growth. The flow rate set at 20 L min⁻¹ increased the lettuce weight.

However, one of the limitations of these previously published articles is that there is no explanation of why some flow rates improved the lettuce growth in terms of computing technology.

Computational fluid dynamics (CFD) is progressively becoming a design-oriented tool in many engineering fields to solve and predict engineering problems that involve liquids and gases [7]. CFD has several attractive features: (a) easy variation of flow parameters, (b) fast changes to the geometry, and (c) detailed insight into flow behavior. CFD has proven to be accurate and beneficial in many engineering fields, including aeronautics [8], engine modeling [9], heat exchanger design [10], cooling systems [11], and wind turbines [12]. However, few studies have addressed CFD in NFT hydroponic systems. Bougoul and Boulard investigated the dynamics of water and nutrients in rockwool slabs that are used as growing substrates for sweet pepper crops [13]. They used CFD to solve the water movement equations numerically in three dimensions. Niam et al. proposed the design of a root-zone cooling system using CFD [14]. They conducted simulations to find the optimal distance between coolant pipes considering a uniform temperature distribution.

This paper presents the turbulent kinetic energy distribution of the nutrient solution flow in an NFT hydroponic system using CFD. Its main objective is to determine the dynamics of nutrient solution flow when it passes through the channel and around plastic mesh pots. The purpose of the current study is to provide a starting point for further investigations that use CFD simulations, featuring practical development in real NFT hydroponic systems. Thus, the main contribution of this study is to present a new point of view for determining the ideal nutrient solution flow rate to increase the weight and height of hydroponic crops. It will contribute to the field of hydroponics by exploring new ways to calculate the turbulent kinetic energy with different pipe diameters and flow rates. To the best of our knowledge, this has not been done before in this field. This approach represents an innovative, feasible, and economical alternative for monitoring the turbulence around the plant roots. Due to practical constraints, this paper will not provide the experimental results from a real NFT hydroponic system. Nevertheless, the methodology described here can be extrapolated effectively. The structure of this paper is as follows: Section 2 contains a description of the materials and methods, Section 3 shows the simulation results, and finally, Section 4 concludes the paper.

2. Materials and Methods

2.1. Modeling the Virtual NFT Hydroponic System

The virtual NFT hydroponic system relied on commercial polyvinyl chloride (PVC) channels for lettuce production. Figure 1 shows the NFT hydroponic system dimensions. The overall channel dimensions were 1000 mm (length) \times 103 mm (width) \times 74 mm (height). The channel's walls were 3 mm thick. The dimensions of the plastic hydroponic mesh pot were 50 mm (height) \times 45 mm (diameter). In addition, two plastic caps were included. The study used computer-aided design (CAD) to model the virtual NFT hydroponic system. The design parameters were obtained and are shown in Figure 1. The virtual NFT hydroponic system was designed to be used with plastic mesh pots and caps. In addition, inlet and outlet flow ducts were placed at the center of each plastic cap.

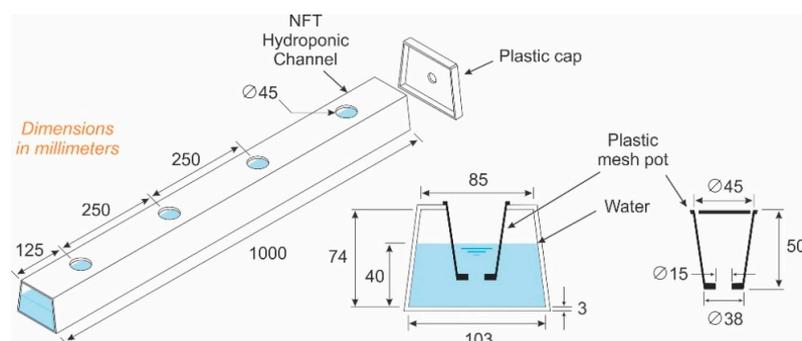


Figure 1. The nutrient film technique (NFT) hydroponic system dimensions.

2.2. Governing Equations

CFD relies on the governing equations of fluid dynamics—continuity, momentum, and energy [15]. These equations are given below:

Continuity

$$\nabla \cdot (\rho \vec{u}) = 0 \tag{1}$$

Momentum

$$\nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \cdot (\bar{\bar{\tau}}) + \rho \vec{g} \tag{2}$$

$$\bar{\bar{\tau}} = \mu \left[\left((\nabla \vec{u}) + (\nabla \vec{u})^T \right) - \frac{2}{3} \nabla \cdot \vec{u} \bar{\bar{I}} \right] \tag{3}$$

Energy

$$\nabla \cdot (\rho \vec{u} H) = \nabla \cdot \left(\frac{k_t}{C_p} \nabla H \right) + S_h \tag{4}$$

$$H = \int_{T_0}^T C_p dT \tag{5}$$

where \vec{u} is the velocity vector, ρ is the density, p is the pressure, \vec{g} is the gravitational acceleration, μ is the viscosity, H is the enthalpy, k_t is the thermal conductivity, C_p is the specific heat, S_h is a source term, T is the temperature, $\bar{\bar{I}}$ is the identity matrix, and $\bar{\bar{\tau}}$ is the stress tensor.

2.3. Reynolds Number

The Reynolds number (Re) is used in fluid mechanics to predict flow patterns. It can be used in experimental or empirical estimations as well as simulations [16]. Applications range from transition of laminar to turbulent flow in complex flow scenarios. Re is defined as:

$$Re = \frac{\rho v D_H}{\mu} \tag{6}$$

where ρ is the density of the fluid (kg m^{-3}), v is the velocity of the fluid (m s^{-1}), D_H is the hydraulic diameter (m), and μ is the dynamic viscosity of the fluid (kg ms^{-1}).

2.4. Boundary Conditions

Every CFD analysis requires boundary conditions, which define the upper and lower limits of the simulation variables, and the inlet and outlet details of the virtual NFT hydroponic system. Table 1 shows the boundary conditions for CFD simulations.

Table 1. Boundary conditions for CFD simulations.

Parameter	Value
Inlet temperature	20.05 °C
Environment pressure	101 kPa
Inlet volume flow rate	Variable
Number of cells in X, Y, Z	16
Number of cells in Y	10
Number of cells in Z	72
Total cells	67,401
Fluid cells	67,401
Fluid cells containing solids	28,496

2.5. CFD Simulations

To solve the governing equations with boundary conditions, a commercial CFD software package (SolidWorks Flow Simulation®) and a desktop PC (Intel® Core™ i7 CPU at 2.67 GHz with 8 GB of RAM) were used. Figure 2 shows a brief description of how the CFD software package works. During the pre-processing stage, the volume occupied by the virtual NFT hydroponic system is divided into very small volumes called cells (the mesh). The boundary conditions specify the initial conditions and properties of all bounding surfaces of the fluid domain. During the solving stage, the CFD software package reads the mesh, solves the governing equations iteratively, and produces result files. Finally, in the post-processing stage, the software interprets the result files to obtain useful information such as the turbulent kinetic energy distribution of the nutrient solution flow. Figure 3 shows the nutrient solution flow direction for CFD simulations.

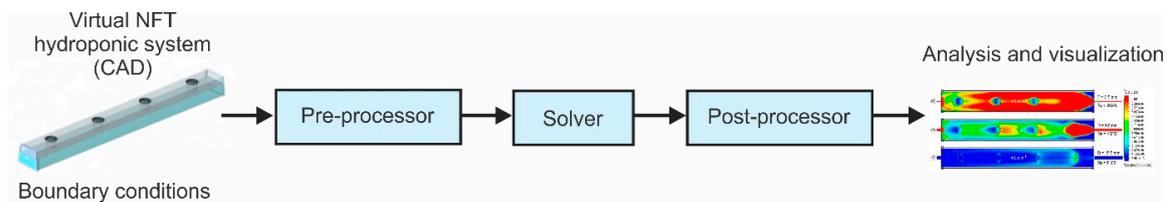


Figure 2. Brief description of how the CFD software package works.

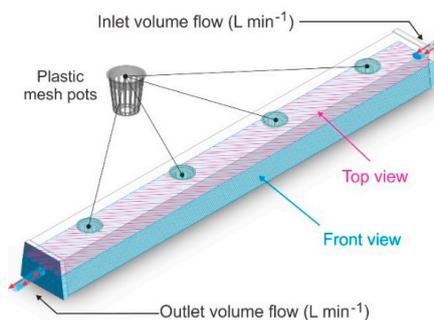


Figure 3. Nutrient solution flow direction for CFD simulations.

3. Simulation Results

The proposed inlet pipe diameters and flow rates were set to 3.5, 9.5, and 15.5 mm and 0.75, 1.5, 3, and 6 L min⁻¹, respectively. The pipe diameters were selected based on the commercial NFT hydroponic hoses available on the market [17]. The flow rates were selected taking into account previous studies proposed in the literature [4–6]. Figures 4–6 show the turbulent kinetic energy distribution using the three constant inlet pipe diameters.

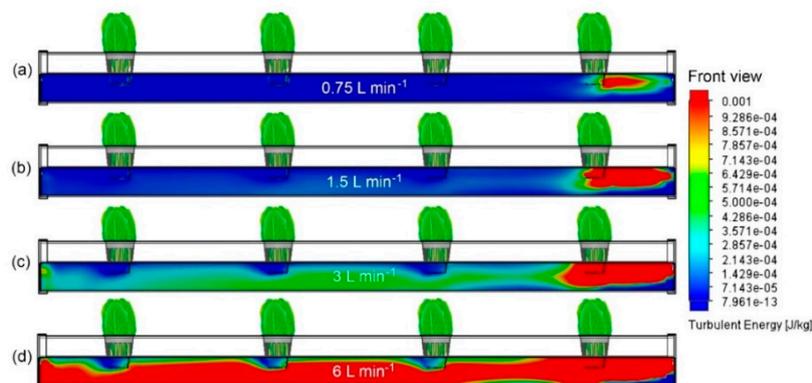


Figure 4. Turbulent kinetic energy distribution using a constant inlet pipe diameter of 3.5 mm.

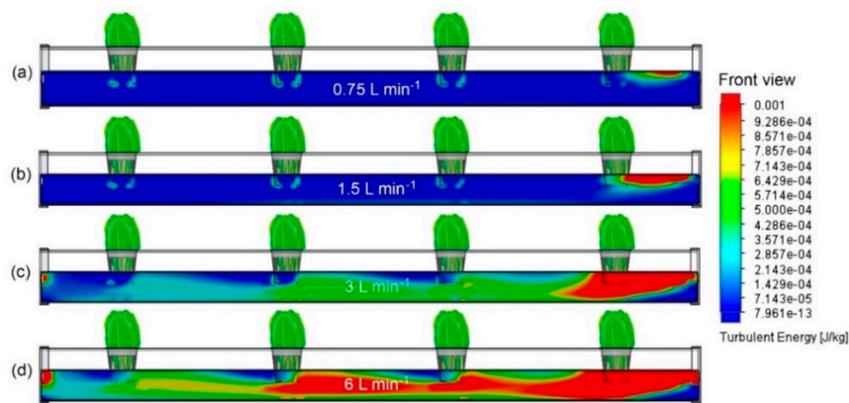


Figure 5. Turbulent kinetic energy distribution using a constant inlet pipe diameter of 9.5 mm.

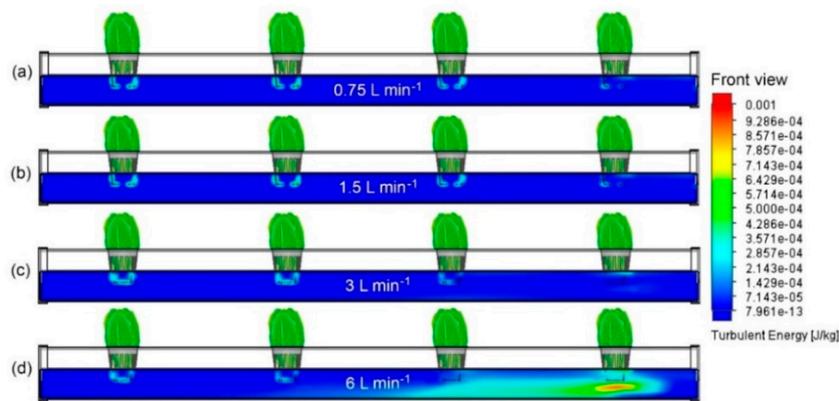


Figure 6. Turbulent kinetic energy distribution using a constant inlet pipe diameter of 15.5 mm.

When comparing Figures 4–6, turbulent kinetic energy decreased around the plastic hydroponic mesh pots when the pipe diameter was increased (15.5 mm). In contrast, turbulent kinetic energy increased when the pipe diameters were decreased (3.5 and 9.5 mm). Notice that only Figures 5a and 6a,b showed $2.857 \times 10^{-4} \text{ J kg}^{-1}$ of turbulent kinetic energy around the plastic mesh pots. Figures 7–10 show the turbulent kinetic energy distribution using the four constant inlet flow rates.

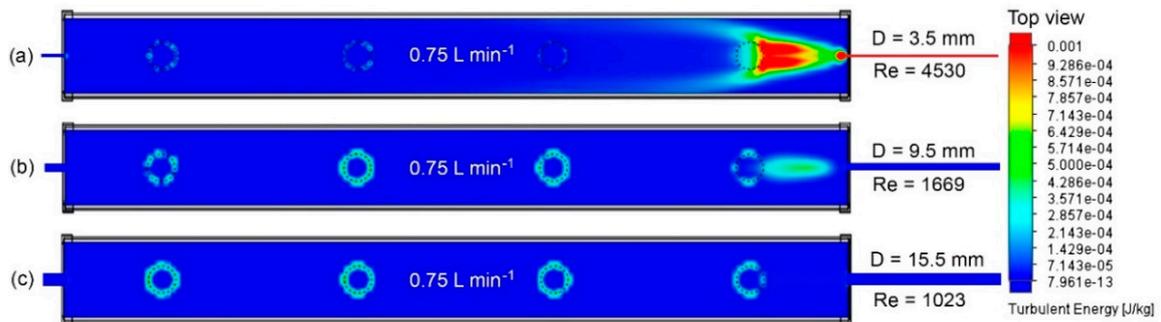


Figure 7. Turbulent kinetic energy distribution using a constant inlet flow rate of 0.75 L min^{-1} .

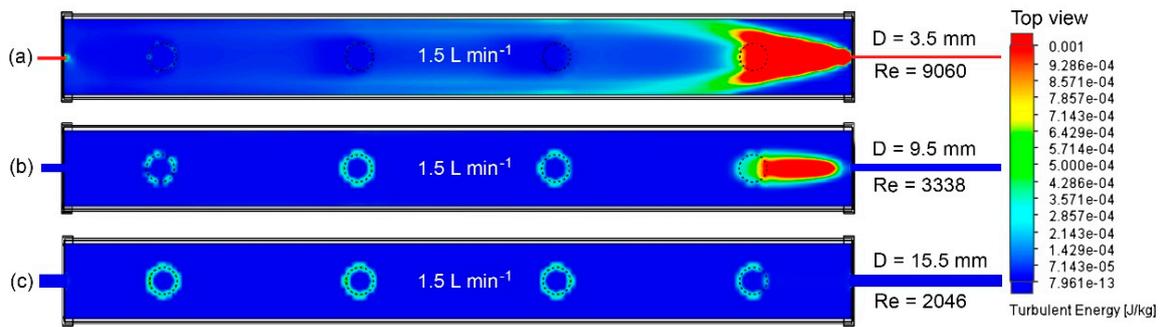


Figure 8. Turbulent kinetic energy distribution using a constant inlet flow rate of 1.5 L min⁻¹.

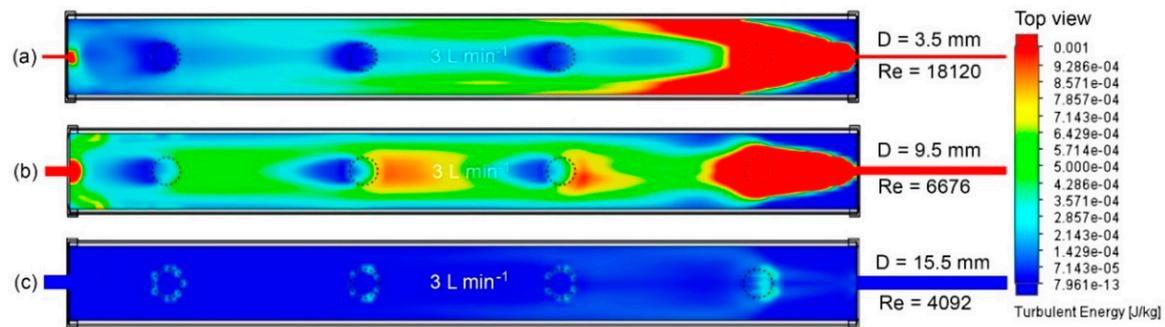


Figure 9. Turbulent kinetic energy distribution using a constant inlet flow rate of 3 L min⁻¹.

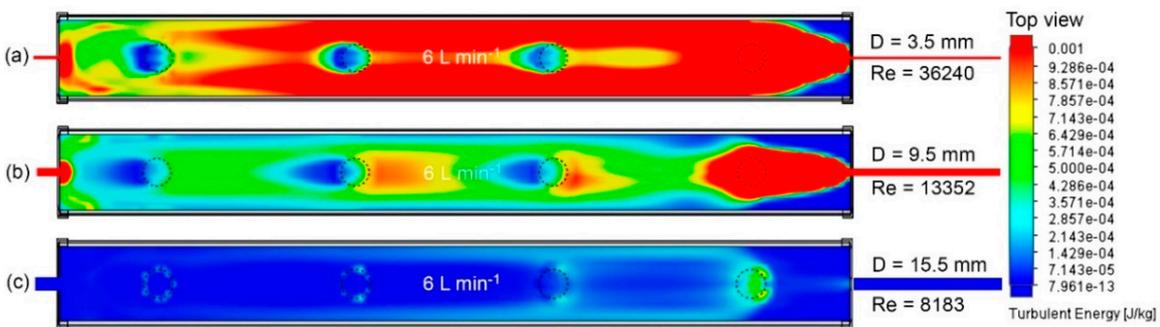


Figure 10. Turbulent kinetic energy distribution using a constant inlet flow rate of 6 L min⁻¹.

Table 2 shows the Reynolds number analysis—the Reynolds number was calculated at the inlet duct. In this study, the density of the fluid was set to 998.2 kg m⁻³ and the dynamic viscosity of the fluid was set to 10.02 × 10⁻⁴ kg ms⁻¹. At low Reynolds numbers—less than 2100—the turbulent kinetic energy tends to be decreased around the plastic hydroponic mesh pots, while at high Reynolds numbers—greater than 4000—the NFT hydroponic system tends to produce flow instabilities. Thus, the nutrient solution flow pattern was established. The Reynolds number could be used as a design tool when selecting pipe diameters and flow rates in NFT hydroponic systems.

Table 2. Reynolds number analysis.

Pipe Diameter (mm)	Volumetric Flow Rate (L min ⁻¹)			
	0.75	1.5	3	6
3.5	4530	9060	18120	36240
9.5	1669	3338	6676	13352
15.5	1023	2046	4092	8183

This study found that different pipe diameters and flow rates in NFT hydroponic systems vary the intensity of the turbulent kinetic energy of nutrient solution flow around plastic mesh pots. Pipe diameter and flow rate are determinant variables of the turbulent kinetic energy distribution of nutrient solution flow in NFT hydroponic systems.

4. Conclusions and Future Work

This paper presents the turbulent kinetic energy distribution of the nutrient solution flow in an NFT hydroponic system using CFD. To conduct the simulations, a virtual NFT hydroponic system was modeled using CAD. Simulation results were presented to understand the dynamics of nutrient solution flow. CFD was used to determine the turbulent kinetic energy distribution of the nutrient solution flow around plastic mesh pots considering different pipe diameters (3.5, 9.5, and 15.5 mm) and flow rates (0.75, 1.5, 3, and 6 L min⁻¹). Based on this virtual NFT hydroponic system, the designs for real NFT hydroponic systems should consider the Reynolds number. At low Reynolds numbers (<2100), the nutrient solution flow tended to be stable around plastic hydroponic mesh pots (<2.857 × 10⁻⁴ J kg⁻¹). For example, assume that a real NFT hydroponic system has D = 9.5 mm and a flow rate of 1.5 L min⁻¹ (the calculated Re = 3338). If the pipe diameter remains constant, then the maximum flow rate (calculated) must be set to 0.95 L min⁻¹ to maintain a stable nutrient solution flow (Re < 2100). Therefore, the Reynolds number may be used as a design tool when selecting pipe diameters and flow rates in real NFT hydroponic systems. These straightforward calculations make a clear application of the simulation results obtained to the field of applied hydroponics.

On the other hand, this study found that the distribution of nutrient solution flow around plastic mesh pots was not uniform. Therefore, the turbulence greatly depends on the location of the plant—this is an important issue for future research. Further studies need to consider the location of the plant. One of the issues that emerged from these findings was the experimental implementation. As mentioned in the literature review, researchers have studied the effect of different flow rates to evaluate lettuce growth. Genuncio et al. [5] claimed that 1.5 L min⁻¹ increased the weight of Izabela and Veneza lettuce and Al-Tawaha et al. [6] claimed that 20 L in⁻¹ was the ideal flow rate to increase the lettuce weight. One of the limitations of these previously published results is that there is no information about what input diameter was used for those experimental tests. The current study found that the ideal nutrient solution flow rate investigations to increase the weight and height of hydroponic crops should be expressed in Reynolds numbers instead of L min⁻¹. It is necessary to conduct future studies to experiment with the weight and height of hydroponic crops using the Reynolds number. It would be interesting to compare lettuce growth with the pipe diameters and flow rates proposed here.

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