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CFD Simulation of Cooling Pipes Distance in The Growing Medium for Hydroponic Substrate in Tropical Lowland

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Abstract: The precision agriculture paradigm has led to the effort to control environmental parameters based on suitability requirements, responsiveness and performance of the plant, where high temperature is a critical constraint for productivity and adaptability of plants in the tropical lowlands. This paper discusses the development a root zone cooling system using a CFD(computational fluid dynamics) simulation approach to optimize the distance of cooling pipes that can produce the optimal temperature distribution and uniformity in the planting medium for hydroponic substrate. The experimental results showed that the optimal horizontal distance of cooling pipes is 12 cm, where optimal temperature distribution and uniformity was obtained. The comparison between simulated and measured temperatures using linear regression produced correlation coefficient of determination, R^2 value of 96.5%. Hence, this underlies that the CFD approach for developing the root zone cooling can be applied in the hydroponic substrate tropical lowland.

Keywords:CFD-based simulation, cooling pipes distance, root zone cooling system, temperature distribution and uniformity.

I. INTRODUCTION

The challenges of cultivation in tropical climate is the high air temperature[1], where temperatures have an important role on the growth and production of plants[2], both in the root and canopy zone. High air temperatures is one of limiting factor of crop productivity and adaptation, because it can cause vary physiological problems such as delays in the initiation of tuber [3], stress on the growth of leaves [4], inhibition of nitrate uptake and reduction of nitrogen concentration [5], and reduction in photosynthesis rate and productivity [6], although the provision of water and nutrients are sufficient. For these reasons, many studies on temperature control around plant have been conducted in order to identify the effects on the development of plant physiology and increasing the productivity of agricultural cultivation.

In connection with the climate type in the tropics such as Indonesia, study of the temperature control for the crops is generally performed by a cooling treatment that restricted to root area. Past studies about root-zone cooling treatment concerned the following issue related to the issue under study: i) the effect of root zone temperature to dry mass of lettuce [7], ii) the effect of low root-zone temperature on potato bulb formation in aeroponic system [3], iii) the effect of cooling and electrical conductivity of nutrient solution on growth and development of lettuce [6], [8], [9], iv) possible effects of regulating hydroponic water temperature on plant growth [10], v) the accumulation of nutrients, metabolites production, photosynthesis rate, chlorophyll pigmentation and accumulation in plant tissues [11]. From these studies, it seems that the root-zone cooling treatment can be used as an option for microclimate control for crop growth in the tropical region.

Successful implementation of root-zone cooling system in hydroponic cultivation can be verified from the achievement of the temperature set point and the uniformity of the temperature distribution around the controlled zone, so that the observed parameters reflect a correlation from the cooling treatment. The temperature value and distribution uniformity can be analyzed using CFD-based software. Through numerical simulations based on the finite volume method and started from the equation of mass transport, continuity and momentum [12], heat transfer and temperature distribution of the growing media substrate can be described with a variety of visual forms, either vector, 2D and 3D, making it easier to understand the involved physical phenomena [13].

In this paper we illustrate a CFD-based simulation of temperature distribution and uniformity coefficient in hydroponic substrate in the tropical region. The primary goal of our simulation is to determine the optimal distance of the coolant pipes within root-zone cooling system on the medium substrate (porous), and to ensure the uniformity of temperature in the root-zone.

II. MATERIALS AND METHODS

Analysis using CFD was conducted to determine the temperature distribution as a critical parameter in the root zone of growing media substrate. The simulation was performed using a CFD software (Flow Simulation available in Solidwork® Premium 2011 interface). A computer with CPU Intel ® Core TM i7, 8 GB RAM, with 64 bit operating system was used.

2.1. Assumptions and initial conditions

Cold water circulation patterns in the cooling pipes is the part that affects the quality of the temperature distribution in the planting medium. In addition, the position of falling droplets of water from a hose drip was also instrumental in the spread of water in the growing medium, where the temperature distribution in the planting medium is wet, potentially more effective than the temperature distribution in the planting medium dry conditions. The hypothesis is based on the value of the heat capacity of water is greater than the value of the heat capacity of air. However, in the first phase in the system design RZC to hydroponic substrate is determining the distance of coolant pipe with planting medium dry conditions without involving the nutrition water. So the factors that affect the results of this simulation only heat transfer characteristics possessed by materials like beds and the planting medium.

Therefore, the assumption and boundary condition defined in the simulation consists of:

1) flow and heat transfer phenomena occur in steady state conditions,
2) type of analysis on the simulation of an external analysis,
3) the fluid involved only air (single phase), does not take into account water or water vapour,
4) the air pressure is defined the same as the air pressure environment greenhouse,
5) the heat source comes from exposure to solar radiation plus reflection and transmission of radiation from the material structure like beds, either wall or frame,
6) the specific heat, conductivity and viscosity of the air remain constant during the simulation,
7) the type of thermal conductivity in all the solid material is isotropic.
8) each parameter's value in a grid is calculated by interpolating all boundary nodes of the grid that results from discretization.

In this case, planting medium as the focus of domain analysis is defined as porous material and solid. Fluid that involved in the porous material was only air, where planting medium defined by dry media without any water element. The initial conditions defined in this experiment include environmental temperature (°C), a solid initial temperature (°C), relative humidity (%), and solar radiation (W/m2) as depicted in Table 1.

Table 1 Initial condition

input parameters	value
environmental temp., (°C)	33
solid material temp., (°C)	26
relative humidity, (%)	57
solar radiation, (W/m²)	183

Simulations performed at various distances pipe *x* (10 cm - 20 cm), aiming to seek distance pipe value *x* which has the best distribution temperature and uniformity. Sketches of the simulation domain looks ahead further described in Figure 1.

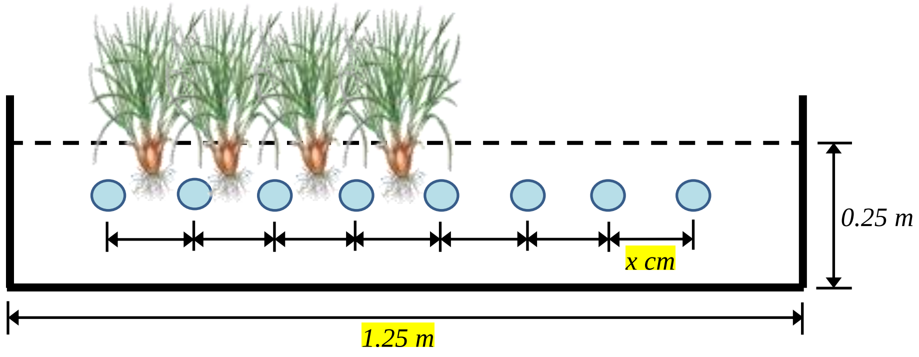

Figure 1 illustrations of cooling pipes distance at the substrate medium tube.

2.2 Governing equation

Temperature is strongly determining the growth of plants, especially in the phase of tuber formation [3], [14]. Therefore, analysis of the temperature distribution in the root zone must be done to find best cooling system structure with respect to layout of the cooling pipes and the required water temperature flown through the pipes. The distribution of temperature in the cooling pipes and the planting medium is simulated using numerical approach based on finite volume.

Numerical approach in Solidwork software uses the Cartesian mesh approach, where the numerical discretization equation is based on the finite volume method [15]. The basic equations in the CFD incorporates conservation law, momentum and energy [16], [17], and numerical approximation representing the principle of mass continuity expressed in the equation of Reynolds-Average of the Navier-Stokes [13], [18], [19] that iswritten as:

$\frac{\partial\rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0$ 1

where ρ is the density of the fluid (kg m^{-3}), t indicates the time (seconds), x is the distance in Cartesian coordinates (m), u is the air velocity (m s^{-1}), and i, j are Cartesian coordinates.

$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j) + \frac{\partial\rho}{\partial x_i} = \frac{\partial}{\partial x_j}(\tau_{ij} + \tau_{ij}^R) + S_i \, , i = 1,2,3$ 2

where τ is the tensor's viscosity due to the shear stress influenced by the dynamic viscosity of the fluid contained in the growing media; and S_i is an external force influenced mass distribution due to the resistance of porous media. This condition is influenced by the nature of gravity and the density of the material that can cause their buoyancy effect, and thus it can be expressed as:

$S_i^{gravity} = -\rho g_i$, which consist of three different elements, namely:

$S_i = S_i^{gravity} + S_i^{porous} + S_i^{rotation}$ 3

The planting medium (mixture of rice husk and cocopeat) is defined as porous domain, were the porosity is the fraction of the total volume occupied by pores, given by:

$\phi = \frac{V_g + V_w}{V}$ 4

where V_g and V_w are the volumes occupied by the gas and the liquid water phases, respectively, in an elemental volume V. Saturation degree of a phase is defined as the fraction of pore volume occupied by that particular phase. Saturation degree of the liquid-water and the gas phase are given by

$S_w = \frac{V_w}{\phi V}$ and $S_g = \frac{V_g}{\phi V}$..5

where:

$S_w + S_g = 1$ 6

The energy equation is derived from the first law of thermodynamics [20]. Discretization energy equation is presented as follows:

$\frac{\partial\rho H}{\partial t} + \frac{\partial\rho u_i H}{\partial x_i} = \frac{\partial}{\partial x_i}(u_j(\tau_{ij} + \tau_{ij}^R) + q_i) + \frac{\partial p}{\partial t} - \tau_{ij}^R \frac{\partial u_i}{\partial x_j} + \rho\varepsilon + S_i u_i + Q_H$ 7

where $H = h + \frac{u^2}{2}$..8

where h is the heat enthalpy, q_i is the diffusivity of heat flux and Q_H a specific heat absorbed per unit volume. However, the energy equation above is only to illustrate the interaction of the heat transfer among isotropic fluid media. The heat transfers and energy interactions in the porous medium constitute interaction between solid and gas. Therefore, the equation used is as follows:

$\frac{\partial\rho e}{\partial t} = \frac{\partial}{\partial x_i}\left(\lambda_i \frac{\partial T}{\partial x_i}\right) + Q_H$,...9

where e is the specific internal energy expressed from $e = c.T$,c is the specific heat, and λ_i are eigenvalues of the thermal conductivity tensor. For a medium that is isotropic, eigenvalues on each coordinate will be the same, that is: $\lambda_1 = \lambda_2 = \lambda_3 = \lambda_i$. In addition, heat transfer in porous media is approached by volumetric heat exchange. Hence, the specific heat of the material absorbed per unit volume is expressed by the following equation:

$$Q_H^{porosity} = \gamma.(T_p - T) \quad \text{.......10}$$

where γ is the volumetric heat transfer coefficient between the fluid with a porous matrix, whileT_p is the temperature in porous media, and T is the temperature of the fluid that interact with porous media.

The uniformities of temperature in the root-zone (between coolant pipes) is defined by:

$$U_T = 100 * \left(1 - \sum_{i=1}^{n} \frac{|\bar{T} - T_i|}{(n\bar{T})}\right) \quad \text{.......11}$$

whereU_T is the uniformities of temperature in the root-zone (%),$\bar{T}$ is the average value of temperature, i is a number of point parameter where temperature evaluated, and n is the total number of point parameters.

2.3.Hydroponic substrate system concept with planting medium cooling

Cooling in the root zone is produced by cooling pipes carrying cold water around the root area. The planting medium, consisting of a mixture of rice husk and cocopeat (4:1), was placed on on a 6,26 m x 1,25 m x 0,25 m sized growing bed as shown in Figure2.

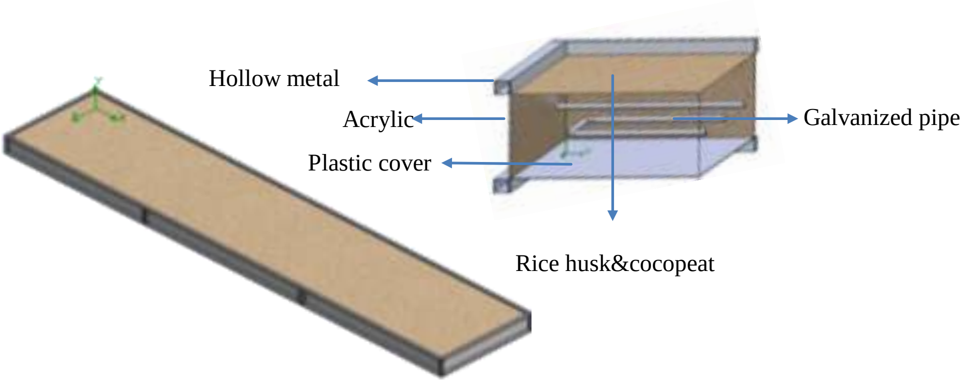

Figure 2 A growing bed

The wall of growing bed is made of acrylic and the pipe material is made of galvanized. Given the heat transfer process occurring in planting medium predominantly influenced by walls, pipes and planting medium, thus the thermal properties of solid materials that being considered are only in the form these materials, which are presented in Table 2.

Table 2 Thermal properties of solid material

parameters	material		
	acrilic	porous medium	galvanize steel
density, ρ (kg/m³)	1190	178.17	7870
specific heat, Cp (J/kgK)	1250	2378	382
thermal conductivity, k (W/mK)	0.21	0.068	18

III. RESULTS AND DISCUSSION

The goal parameters set up in this simulation include fluid temperature (air), and temperature of the solid material. Temperature fluid is used to determine the temperature distribution over the planting medium which also the environmental temperature of green house.

The simulation of the conjugate heat transfer between fluid and solid phases was addressed considering the full set of equations 3, describing the heat-conduction in a solid. In this case, a multi-region framework is required, adopting different computational grids for the solution of the governing equations relative to the fluid and the solid media

Settings the mesh affect the number of cells in the grid. The more the number of cells in the grid, the more precise the solution but requires a large enough memory [15]. Iteration has been performed at 3.00GHz speed computers consisting of eight CPUs run in a parallel mode. The iteration process stopped until all parameters reached the state of convergence and it took 2728 seconds (about 46 minutes) to stop.The meshing processtook only 8 seconds with total number of mesh of 280 038, representing the domain area of 1:26 m x 0.4 m x 1:35 m.

Mesh discretization process was performed using TDMA(Tri Diagonal Matrix Algorithm) to form a uniform mesh, that is the cuboid or tetrahedral. This method was first introduced by Thomas in 1949, and therefore it is called Thomas Algorithm[21].Iteration results of the domain geometry meshing shown at the front view orientation is presented in figure 3.

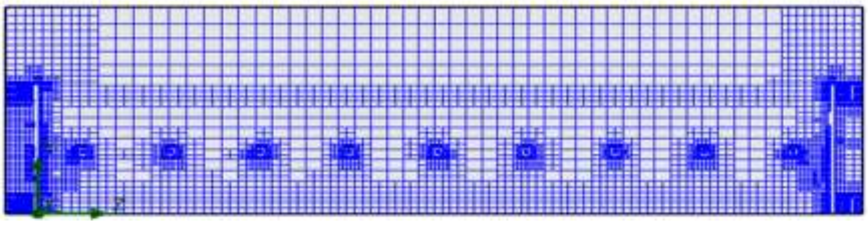

Figure 3 mesh for domain region at the front view orientation

The simulation using the CFD model was applied in order to characterize the heat-transfer properties with different coolant pipes distances. The characteristic of temperature distribution and uniformity on planting medium is highly related with the capacity of cooling effect radius of pipe. However, the dry porous medium with thermal conductivity, low k (0,0068 W/mK), planting medium can act as a barrier in spreading the effect of cold (insulator) from the pipe in to the planting medium. The cooling effect can reach more distant radius through water thermal characteristic in the planting medium, where water has high thermal capacity.The observed parameters in this simulation included air and solid material temperatures.The air temperature is used to determine the temperature distribution over the substrate medium,and the ambient temperature plants, whereas the solidmaterial temperature is used to observe volumetric heat exchange in the substrate medium.Referring to temperature distribution shown in figure 4, the closer the distance between the cooling pipes (blue circles), the lower the planting medium temperature at the horizontal line.

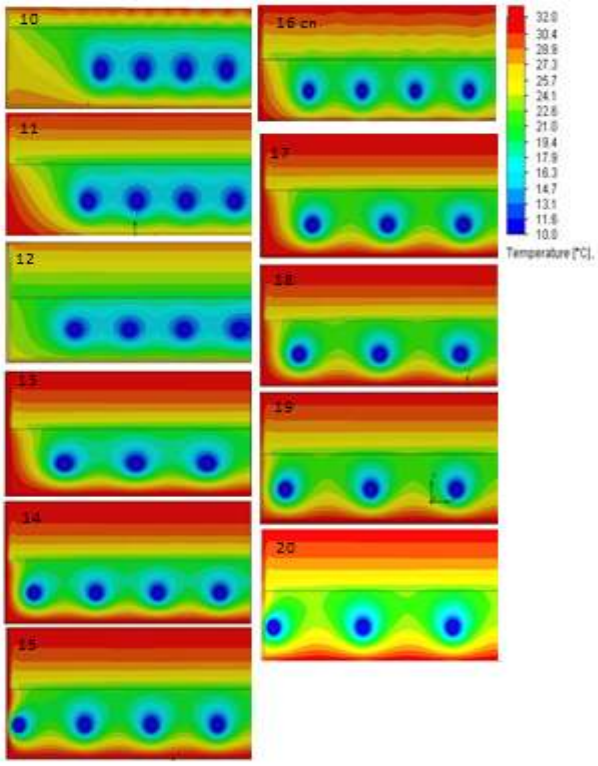

Figure 4 The temperature distribution in the growing bed

The point that represents the range of the cooling effect of the growing media is the midpoint of the horizontal distance between the pipe. Therefore, the cooling effect of the growing media can be plotted on a graph distance relationship coolant piping to the value of the lowest temperature at the midpoint between the pipes, as shown in figure 5.

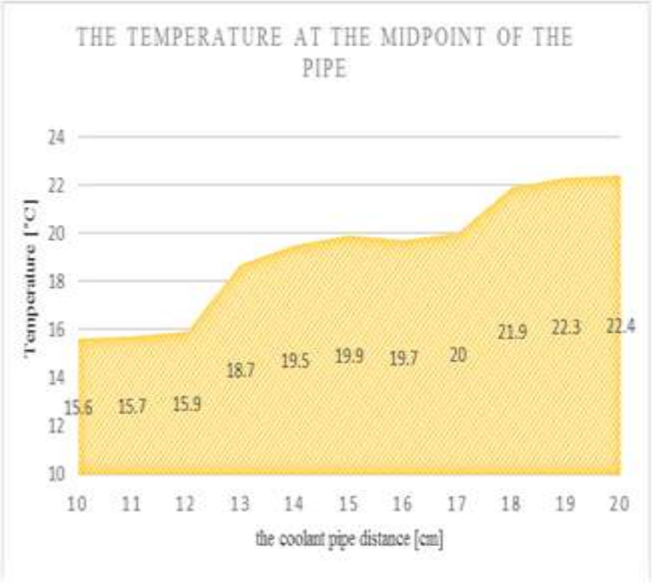

Figure 5 The temperature at the midpoint of the pipe

The target temperature required for shallot bulb formation in the plant media in the RZC system was set up to be in the range of 16-18 ° C, which is the common temperature average of root zone for shallot cultivation in highland [22]. Referring to figures 4 and 5, the target temperature was obtained by the distance cooling pipes of 10 cm, 11 cm and 12 cm.With respect to the pipes installation, the distance of 12 cm is the best choice. It is shown in figure 4 that the maximum temperature in the planting medium with a distance of 12 cm cooling pipes was 15.9 ± 0.17 ° C.

Distance between cooling pipes also influences the temperature distribution uniformity in the planting media. The temperature distribution uniformity is computed using equation (11), to show the correlation between the distance of the pipes to the temperature uniformity, as shown in Figure 6.The cost of pipes installation can be calculated based on the price of galvanized pipes with 0.5 in size, thickness 2.6 mm and a length of 6 m, is Rp. 150 000,00 per rod. The estimated cost is shown as green curve in Figure 6.

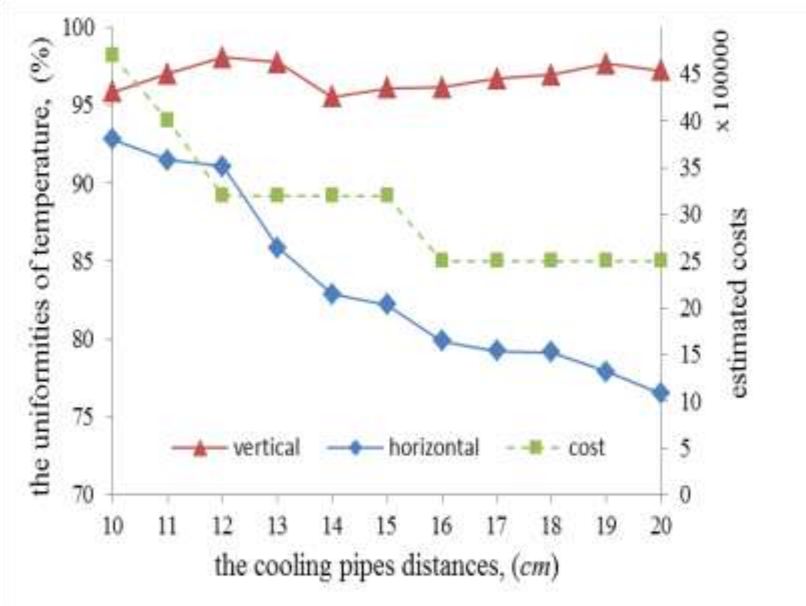

Figure 6 The correlation distance between the pipes against the uniformities of temperature and estimated costs.

Observe that the percentage of temperature distribution uniformity in the planting media is still maintained above 90% with the pipes horizontal distance of 12 cm, as shown with the blue curve in figure 6. It is important to note that temperature distribution and uniformity are two important parameters in the development of root-zone cooling system.Using a CFD simulation-based approach, the optimum distance between cooling pipes for the root-zone cooling system in the hydroponic substrate can be determined. In addition, variations of the temperature distribution in the planting medium from the simulation results can also be classified based on the value of optimum temperature requirements for different types of plants.

Validation was conducted to determine the precise value between simulation results with measurement results. There are 10 validation points that are placed in the planting medium is presented in Figure 7.

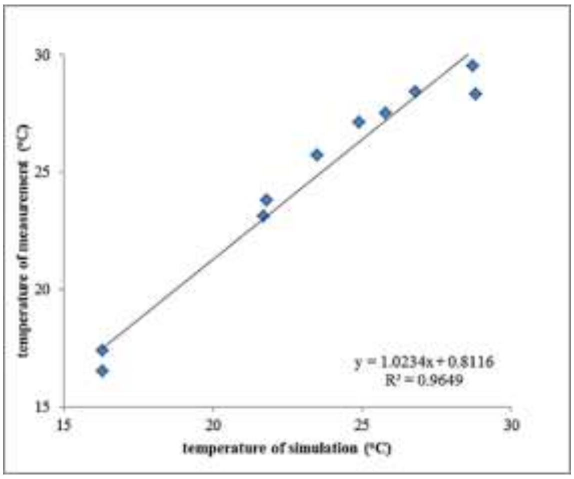

Figure 7 The linear correlation between the temperature of simulation of the temperature of measurement.

The regression analysis showed that the linear equation *y = ax +b*, value *a*at 1.0234 and *b* at 0.8116 with determination coefficient R^2 at 0965.

IV. CONCLUSIONS AND FUTURE WORK

The root zone cooling system has been developed using a CFD simulation approach to optimize the distance of cooling pipes that can produce the best temperature distribution and uniformity in the planting medium. It has been shown that the optimal horizontal distance of cooling pipes is 12 cm, where optimal temperature distribution and uniformity was obtained. The comparison between simulated and measured temperatures using linear regression produced the an R^2 of 96.5%. This underlies that the CFD approach for developing the root zone cooling can be applied in the hydroponic substrate tropical lowland. For future work it is important to calculate the total energy consumption for the cooling system since it will influence the implementation cost for real applications and shallot crop production using hydroponic substrate.

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