Temperature Distribution in Aeroponics System with Root Zone Cooling for the Production of Potato Seed in Tropical Lowland

Eni Sumarni, Herry Suhardiyanto, Kudang Boro Seminar, Satyanto Krido Saptomo

Abstract—Expansion of potato cropping on lowland is an alternative for increasing potato production in Indonesia. Aeroponics cultivation system with limited cooling at root zone is one of the solutions in obtaining quality potato seed in tropical lowland. Problems in fluids flow for supplying nutrition need to be understood, either fluids movement inside a pipe or inside an aeroponics chamber. One of the methods to understand the distribution of air temperature in a chamber is by analyzing it by means of Computational Fluid Dynamic (CFD). The objective of this research was to find out the temperature distribution in an aeroponics system. Two treatments were applied, i.e., application of root zone cooling at 10 °C and no cooling as control. The temperature distribution inside the aeroponics chamber was analyzed using the CFD. The size of the aeroponics chamber used was 1.5 m length, 1.0 m width and 1.0 m height. The outer wall of the aeroponics chamber was made of plywood material of 12 mm thick .The inside part of the wall was insulated with Styrofoam of 2.0 cm thickness. This set up performed a good temperature distribution. The result of validation showed that air temperature simulated by using CFD agreed well with that of air temperature measured inside the aeroponics chamber.

Index Terms—Aeroponics system, CFD, potato seed, zone cooling, tropical lowland

1 INTRODUCTION

Increase of potato production in Indonesia faces some constraints, among others are : (1) still conventional cultivation technique, (2) limited hilly land area with air temperature suitable for potato cultivation, and (3) as a humid tropical country, Indonesia is an optimum region for potato pest and disease to develop [1]. Expansion of potato cropping on lowland is an alternative to support the effort to increase potato production in Indonesia. Aeroponics cultivation system with limited cooling at rooting area is one of the solutions in order to obtain quality potato seed for tropical lowland. Aeroponics cultivation system has more advantage compared to the conventional one with soil medium. Aeroponics technology utilizes the seed resulted from tissue culture (plantlet) which is good and free from disease [9]. This technology has been applied in China, Korea, and Peru, capable of producing 100 tubers per plant [15]. The aeroponics system can result in higher production (ten times that of the conventional system).Utilization of nutrition and water can be saved since it is manageable, and can produce clean and healthy tubers [9].

Growth of potato plant is strongly influenced by weather. High air temperature at tropical lowland can cause stress and retardation of tuber formation. The root zone cooling is intended only to cool the limited area of plant growth (root zone), not the whole space of a greenhouse. Mechanical cooling to lower the air temperature inside a greenhouse needs a large amount of energy. Cooling load required to lower greenhouse air temperature up to 6 ºC below the outside ambient temperature can reach 0.3 MJ/m² [13].Although the inside air temperature of a greenhouse is high, plants can grow in well condition provided that the root zone temperature can be maintained at lower level. Root zone cooling is capable of increasing the production of cucumber [7], salad [6], strawberry [16], and spinach [14].Greenhouse equipped with this cooling system can lower the daily maximum temperature of the root zone from 2 to 6 ºC below the air temperature above the plant [5]. It is important to know the fluids flow for the supply of nutrition, either fluids movement inside a pipe or inside aeroponics chamber.

The introduction of advanced ICT (Information and Communication Technology) in agriculture has enabled farmers to acquire huge amounts of site specific data for their farms, with the ultimate aim to improve their decision-making process [10]. The application of CFD in precision crop has been concentrated mainly on greenhouse system [3] and the optimization of sprayer [12]. CFD is a simulation method that can efficiently estimate both spatial and temporal field fluid pressure as well as other chemical and environmental scalars, and the method has proven its effectiveness in system design and optimization within the chemical, aerospace, and hydrodynamic industries [17]. The ubiquitous nature of fluids and their influence on system performance has caused a widespread take-up of CFD by many other disciplines. As a developing modeling technique, CFD has received extensive attention throughout the international research and industrial community. As a result, CFD became an integral part of the engineering design and analysis environment of many companies because of its ability to predict the performance of new designs or processes prior to manufacturing or implementation [2]. The motion of water in rockwool slabs used as growing substrate for a sweet pepper crop was simulated using CFD [11] but similar studies have not been found for water or nutrients motion in other growing medium or in the soil. Computational Fluid Dynamic (CFD) is one of the methods in analyzing air temperature distribution inside a chamber.CFD is a computer based system analysis comprising heat transfer flow [15]. The objective of this research was to obtain temperature distribution in an aeroponics cultivation system with the application of root zone cooling and no cooling treatment as control.

2 MATERIALS AND METHODS

This research was conducted at the Department of Mechanical and Bio-systems Engineering, IPB. The location is on the altitude of the 250 m *asl*, 106.42 E, and 6.33 S. An aeroponics box or chamber was built with the size of 1.5 m long, 1.0 m wide and 1.0 m high. The outer part of the box was made of12 mm plywood and the inside part was insulated with 2 cm Styrofoam sheet. The box cover was made of 3 cm Styrofoam sheet and used as plant holder (Figure 1).

Instrumentation and tools used in this research consisted of: weather station using Davis 6162 and 6163 for recording micro climate data of inside and outside of greenhouse. MV 2000 Type Hybrid Recorder with 48 channels and MV 1000 Type with 24 channels were used to record air temperature data inside the aeroponics chamber using T type thermocouples. Nutrition, cooled by chiller, was sprayed to potato plant roots through nozzles using high pressure pump. Timer was used to control nutrition supplying time. The treatments applied in this research were 10 °C root zone cooling and no cooling for control.

2.1 Computational Fluid Dynamic (CFD)

CFD simulation was conducted using Solidwork® Premium 2011 software. Three dimensional analyses were done towards fluids and thermal flow using desk top computer with specification: CPU Intel ® Core ™ i7, RAM 8GB, and 64bit operation system.

(a) (b)

Figure 1. Aeroponics system with root zone (a) and no cooling for control (b)

Equations for fluids were developed and analyzed on the basis of Partial Derivative Equation (PDE) representing the laws of mass conversion, momentum and energy. Solution for fluids flow like air in CFD simulation was described quantitatively in the magnitudes of temperature and velocity in the form of differential equations based on numerical analysis of finite volume method, especially Navier-Stokes equation.

- *Eni Sumarni. Department of Agricultural Techology.* General Soedirman University. *E-mail: arny0879@yahoo.com*
- *Herry Suhardiyanto. Department of Mechanical and Biosystem Engineering. Bogor Agricultural University (IPB). Bogor. Indonesia. E-mail: herrysto@yahoo.com*
- *Kudang Boro Seminar. Department of Mechanical and Biosystem Engineering. Bogor Agricultural University (IPB). Bogor. Indonesia. E-mail: kseminar@ipb.ac.id*
- *Satyanto Krido Saptomo. Department of Civil and Environmental Engineering. Bogor Agricultural University (IPB). Bogor Indonesia. E-mail : saptomo@ipb.ac.id*

The CFD method comprised three main components, i.e., pre-processor, solver and post-processor [4]. Pre-processor component was an input component of fluids into the CFD program. In the pre-processor phase, the followings were conducted: making of geometry of the system to be analyzed, formation of grid mesh on every domain or all, selection of chemical and technical phenomena needed, determination of fluids properties (conductivity, viscosity, specific mass, etc.), determination of appropriate boundary condition (inlet, outlet, velocity, pressure and other variables).

Solver provided mathematical solution process in CFD. The method used was finite volume developed from finite difference method. All results were displayed in the post-processor, which could be in the forms of geometrical display of domain and grid, plots of velocity vector, distribution of temperatures at every point, tracking or trajectory of particles, visualization, goals, etc.

2.3 Equation of Mass Conservation

Equilibrium of mass for fluids element was expressed as the mass increasing rate in the fluids element. All fluids elements were function of space and time, so that specific mass of fluids ϱ was written in the form of ϱ (x,y,z,t) and velocity components of fluids were written as dx/dt=u, dy/dt=v, and dz/dt=w. The mathematical equation was written as follows:

$$\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}=0 \qquad (1)$$

ρ is the specific mass of fluids (kg/m³) and x, y, z are the directions of Cartesian coordinates.

2.4 Equation of Momentum

Equation of momentum was developed from Navier-Stokes equation in the form compatible to the finite volume. Momentum in the x direction:

$$\rho\left[u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right]=\frac{\partial p}{\partial x}+\rho g_x+\mu\left[\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right]+S_{MX} \qquad (2)$$

Momentum in the y direction:

$$\rho\left[v\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right]=\frac{\partial p}{\partial y}+\rho g_y+\mu\left[\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right]+S_{My} \qquad (3)$$

μ is the dynamic viscosity of fluids (kg/m.s), g is the gravitational acceleration (m/s²) and S_{MX}, S_{My}, S_{Mz} are momentum from the body per unit of volume per time for x, y, and z coordinates, respectively.

2.5 Equation of Energy

The equation of energy was derived from First Law of Thermodynamics. Mathematically it can be written as [4] :

$$\rho\left[u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right]=k\left[\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right]+2\mu\left[\left(\frac{\partial v_x}{\partial_x}\right)^2+\left(\frac{\partial v_y}{\partial_y}\right)^2\right]+$$
$$\mu\left[\left(\frac{\partial v_x}{\partial_y}+\frac{\partial v_y}{\partial_x}\right)^z\right]+S_i \qquad (4)$$

T is fluids (K), k is fluids thermal conductivity (W/m.K), and S_i is the energy added per unit of volume per unit of time.

2.6 Equation of Equilibrium

Fluids flow seeks equilibrium thermodynamically. If it is related to variables of ρ and T, the equation of equilibrium for pressure (P) and internal energy (i) is as follows [4]:

$$\begin{aligned} P &= P\,(\rho, T) \\ i &= i(\rho, T) \end{aligned} \tag{5}$$

For ideal gas, P = ρ RT and i = C_vT

2.7 Validation

Validation was conducted by comparing the average air temperature measured inside the aeroponics chamber with the result of CFD simulation. The validation test was conducted using linear regression line between the measured average air temperature (x) and CFD results (y). Accuracy of simulation result and measured data was expressed in error percentage, which is written as the following equation:

$$Error = \frac{\left|T_{CFD\ simulation} - T_{measurement}\right|}{T_{measurement}} x\,100\% \tag{6}$$

3 Boundary Condition

The boundary conditions for the CFD simulation are presented in Figure 2 and Figure 3. The temperature value at each wall of the aeroponics chamber conforms to its boundary condition. Assumptions used in the simulation were: air moved in steady state condition; air was incompressible; specific heat, conductivity and viscosity of air were constant during the simulation; particles out from nozzles were of water, and greenhouse was assumed to have no big role in heat transfer process.

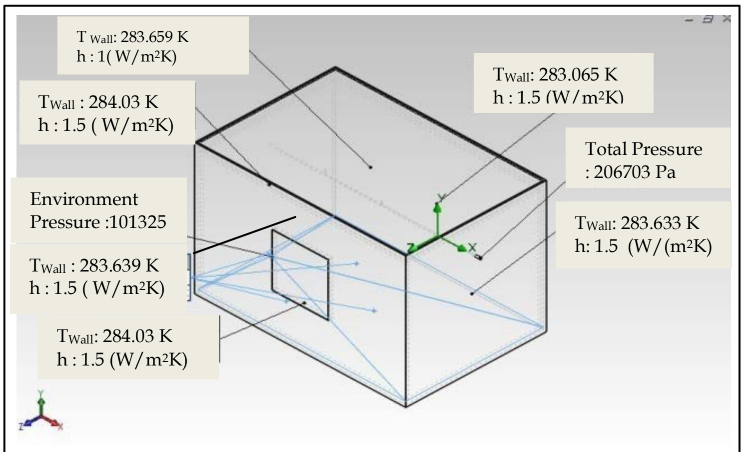


Figure 2. Boundary condition for CFD simulation in aeroponics chamber with 10 °C cooling temperature

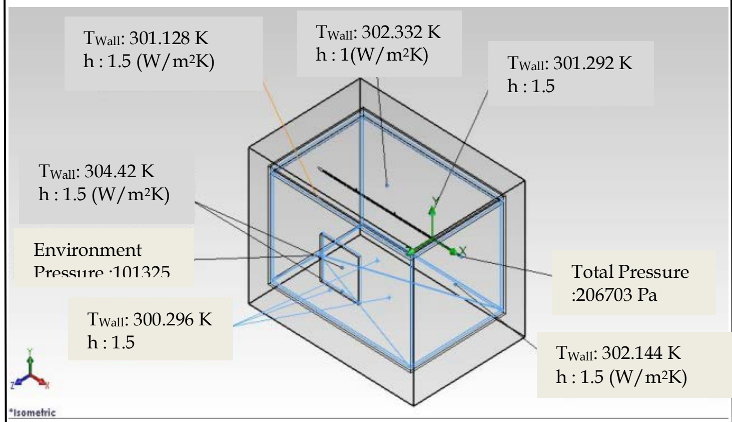


Figure 3. Boundary condition for CFD simulation in aeroponics chamber with no cooling

The number of measurement points at each box were 14, i.e, located at bottom wall, outer surface of the box (around the plant on top of box), upper wall outside the box, 20 cm from the rear wall (inside the chamber), 20 cm from front wall (inside the chamber), upper wall inside the box (around the roots), 83 cm from bottom wall (inside the chamber), 20 cm from left wall (inside the chamber), left wall inside the chamber, 20 cm from right wall (inside the chamber), right wall inside the chamber, rear wall inside the chamber, rear wall outside the box, and front wall outside the box.

4 Results and Discussion

Average maximum air temperature inside the experimental greenhouse reached 35.3 °C, average noon air temperature was 29.9 °C, average night air temperature was 26.3 °C, and relative humidity of 78%. Cooling temperature of 10 °C in the root zone gave tuber production higher than that of with no cooling as control. Treatment using 10 °C cooling resulted in a total of 579 tubers/1.5m², while the control treatment produced no tubers at all. The air temperature distribution inside the aeroponics chamber front view with 10 °C cooling is presented in Figure 4.

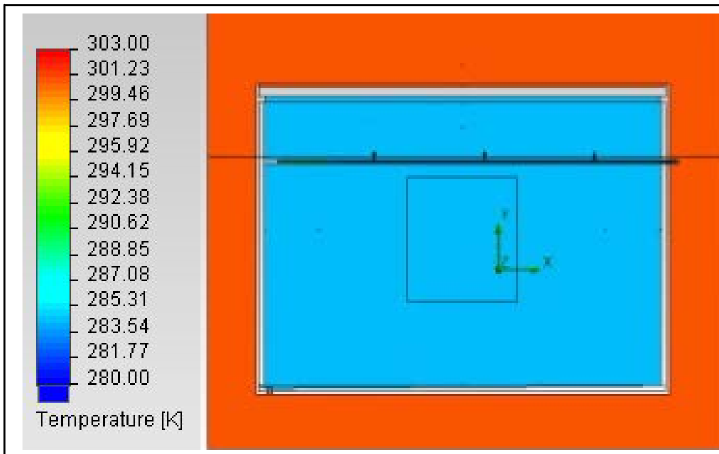


Figure 4. Distribution of air temperature inside aeroponics chamber front view with 10 °C zone cooling

ISSN 2229-5518

Blue area represents the distribution of cold air temperature inside the aeroponics chamber. Red area represents the hotter ambient air temperature outside the aeroponics chamber (Figure 5). It could be shown from the simulation results that application of root zone cooling was capable of maintaining the air temperature inside the aeroponics chamber colder and uniformly distributed around the root zone. The distribution of the average air temperature inside the aeroponics chamber was around 11.6 ºC.

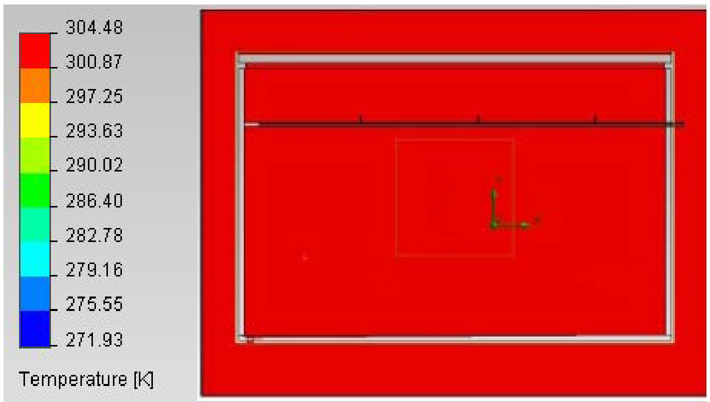
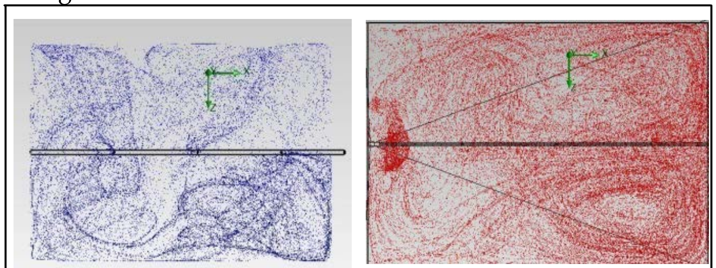


Figure 5. Distribution of air temperature inside aeroponics chamber front view with no cooling treatment

The average air temperature inside the aeroponics with no cooling treatment reached 29.5 ºC. The specific heat of the nutrition solution was higher than that of the air, so that once the nutrition was cooled its temperature would stay at lower level in long enough time [14].

Distribution of nutrition spray inside the aeroponics chamber is presented in Figure 6. The spray distribution shows that the nutrition distributes all over the chamber surface. At 10 ºC cooling, the temperature of the nutrition particle is colder (blue color), while it is hotter in the control (red color). The main point of the application of aeroponics is on the pressure produced by the pump and appropriateness of the installation design.



(a) (b)

Figure 6. Distribution of nutrition spray inside the aeroponics chamber; 10 ºC cooling (a) and control (b)

The smaller the water particles are, the larger the surface can be reached. Therefore, contact of the particles with air is also large. This enables higher O_2 binding by the water particles. The iterations done for each treatment to reach convergence are presented in Figure 7 and 9. Particles of the solution attached to the roots could stay for 15 to 20 minutes after spraying was stopped. Comparison of the average air temperature measured inside the aeroponics chamber and CFD is presented in Figures 8 and 10.

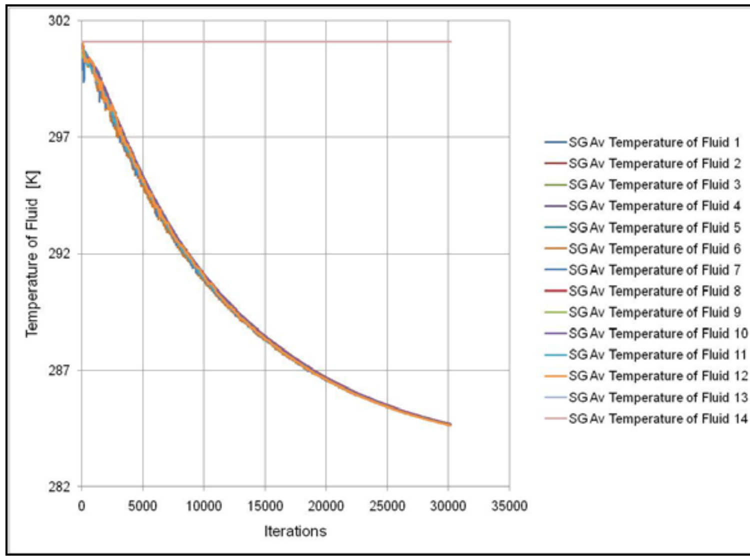


Figure 7. Iteration process in CFD simulation with 10 ºC temperature

The CFD simulation on the root zone cooling at 10 °C reaches convergence at the iteration of 30192. While that of with no cooling treatment as control reaches convergence at the iteration of 4813.

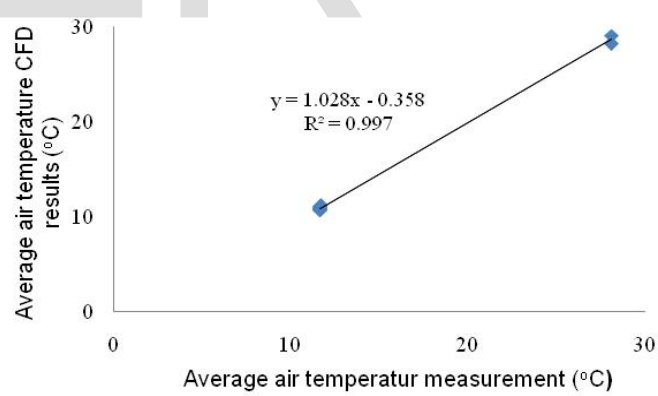


Figure 8. Correlation between air temperature measured inside the aeroponics chamber at 10 °C cooling

The correlation has R^2 value of 0.997 with coefficient of interception of 0.358 and gradient of 1.028 (at 10 °C cooling). At control temperature the R^2 value is 0.942 with interception of 11.21 gradient of 1.375. Error obtained is 6%.

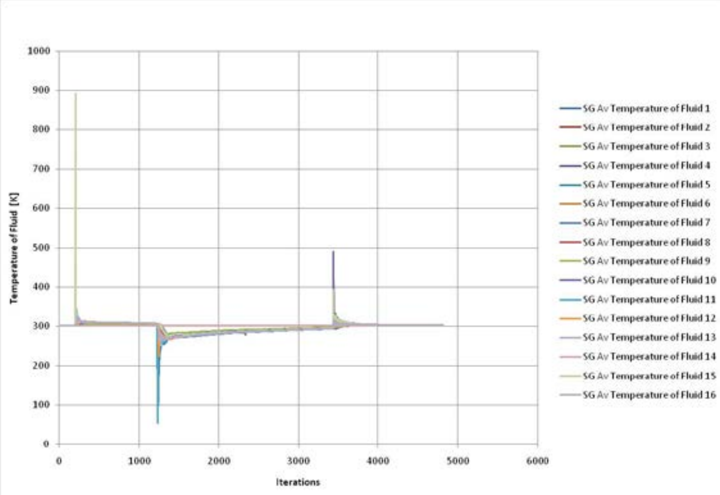


Figure 9. Iteration process in CFD simulation with no cooling treatment CFD simulation result

The supervisory system for greenhouse control has been developed and tested with cucumber crops. The results of this development and testing is the working functionalities that meet the control criteria and objective based on user preferences. This provides much greater flexibility to the user to cope with varieties of environmental constraints or conditions types of crop to be controlled in a greenhouse, hardware constraints, and type of control modes [8]. The results can be used to support the CFD simulation in aeroponics system with root zone cooling for the production of potato seed in tropical lowland.

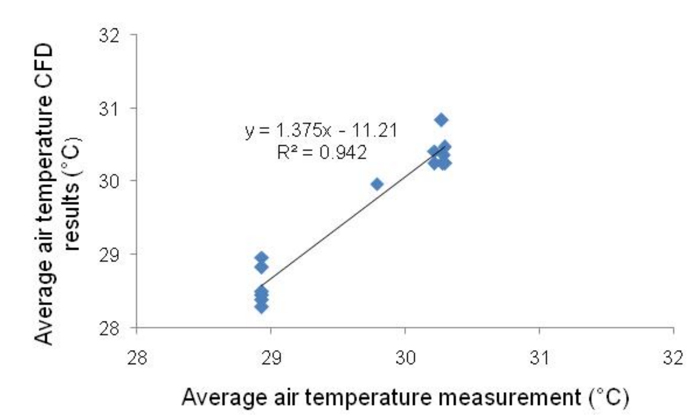


Figure 10. Correlation between air temperature measured inside the aeroponics chamber at no cooling CFD simulation result

6 Conclusion

The research results indicated that an aeroponics system with the size of 1.5 m long, 1.0 m wide and 1.0 m high, made of 12 mm plywood with 2 cm Styrofoam inside insulation was capable of maintaining the root zone temperature.

CFD was capable of predicting the average air temperature inside the aeroponics chamber accurately. The correlation had R^2 value of 0.997, coefficient of interception of 0.358 and gradient of 1.028 for root zone cooling. While the no cooling treatment had R^2 value of 0.942, coefficient of interception of 11.2 and gradient of 1.375.

References

[1] A. S. Kuntjoro, "Produksi Umbi Mini Kentang G0 Bebas Virus melaluiPerbanyakan Planlet secara Kultur Jaringan di PT. intidayaAgrolestari (Inagro) Bogor". Jawa Barat. Skripsi. Jurusan Budidaya Pertanian. Fakultas Pertanian. IPB. 62p. 2000.

[2] G. Schadach, L. Berger, I. Razilov, H. Berndt, " Computer Simulation for Fundamental Studies and Optimisation of ICP Spray Chamber". Current Research Report. ISAS (Institute of Spectrochemistry and Applied Spectroscopy). Berlin. Germany. 2000.

[3] H. Majdoubi, T. Boulard, H. Fatnassi, L. Bouirden, " Airflow and Micro Climate Patterns in a One Hectare Canary Type Greenhouse : an Experimental and CFD" . *Assisted Study. Agricultural and Forest Meteorology* 149(6-7): 1050-1062. 2009.

[4] H.K. Versteeg, W. Malalasekera, " An Introduction to Computational Fluid Dynamic, The Finite Volume Methode" . *Ltd. Essex.* 1995.

[5] H. Suhardiyanto, and T. matsuoka, " Studies on Zone Cooling System in a Greenhouse (2) : Evaluation of a System for Micro Climate Modification in a Plastic Greenhouses During Hot weather ". *Environment Control in Byology* 32 (1) : 9-16. 1992.

[6] J. He, S.K. Lee, and I.C. Dodd, "Limitation to Photosynthesis of Lettuce Grown under Tropical Condition :Allevation by Root Zone Cooling". *Journal of Experimental Botany*. 52: 359: 1323-1330. 2001.

[7] J.L. Ibarra, Z. Gonzales, A.L.D. Rio, J. C. Rubalcava, B. O. Ortiz, " Changes in Soil Temperature, Yield and Photosynthesic Response of Potato (*Solanum tuberosum* L) under Coloured Plastic Mulch". Agro Chimica 52 : 263-272. 2008.

[8] K.B. Seminar, H. Suhardiyanto, S. Hardjoamidjojo, Tamrin, "A supervisory control system for Greenhouse". Proceeding of Regional Computer Postgraduate Confrence (ReCSPC'06). Malaysia. pp 30-34. 2006.

[9] O.S. Gunawanan, D. Afrizal., "Teknologi Aeroponik, Teknologi Perbanyakan Cepat Benih Kentang." *Jurnal Ipetk Hortikultura*. 5: 16-19. 2009.

[10] S. Blackmore, "Developing the Principles of Precision Farming". Proceeding of the ICETS. China Agricultural University. Beijing. pp 11-13. 2000.

[11] S. Bougoul, T. Boulard, " Water Dynamic in Two Rockwool Slab Growing Substrates of Contrasting Densities". Sci. Horticult. 107 (4), 399-404. 2006.

[12] T. Bartanaz, M. Kacira, H. Zhu, S. Karmakar, E. tamimi, N. Katsuolas, I.B. Lee, C. Kittas, "Computational Fluid Dynamic Applications to Improve Crop Prooduction System. Computers and Electronics in Agriculture. Xxx : xxx-xxx. 2012.

[13] T. Kozai, Z. Quan, M. Hayashi, I. Wanatabe, "Cooling Load of a Greenhouse. (i) Characteristics of Cooling Load in Summer Night Time". *Journal of Agricultural Meteorology* 41(2) : 121-130. 1985.

[14] T. Matsuoka, H. Suhardiyanto, " Thermal and Flowing Aspects of Growing Petty Tomato in Cooled NFT Solution During Summer". *Environment Control in Biology* 30 (3) : 119-125. 1992.

[15] V. Otazu, " Manual on Quality Seed Potato Production Using Aeroponics International Potato Center (CIP)". Lima. Peru. 2010

[16] Y. Iwasaki, " Root Zone Aeration Improved Growth and Yield of Choir Cultured Strawberry (*Fragaria Ananassa* Duch.) During Summer". *ISHS ActaHorticuturae* 779. 2008.

[17] Z. Zhang, H. Liu, S.P. Zhu, F. Zhao, "Application of CFD in ship engineering design practice and ship hydrodynamics". J. Hydrodyn.

18, 315–322. 2006.