Agri. & Biosys. Eng. Vol. 3(2):65-72(2002)

Prediction of Air Movement and Temperature Distribution at Different Store Methods Using 3-D CFD Simulation in Forced-Air Cooling Facility

G. M. Yang, H. K. Koh

Abstract: Temperature is the most influential environment parameter which affects the quality change of agricultural products in cold storage. Therefore, it is essential to keep the uniform temperature distribution in the storage room. This study was performed to analyze the air movement and temperature distribution in the forced recirculating cold storage facility and to simulate optimum storage method of green groceries using 3-D CFD(three dimensional computational fluid dynamics) computer simulation which applied the standard $k-\varepsilon$ turbulence model and FVM(finite volume method). The simulation was validated by the experimental results for onion storage and the simulation model was used to simulate the temperature and velocity distribution in the storage room with reference to the change of storage method such as location of storage, no stores, bulk storage, and pallet storage. In case of no stores, internal airflow was circulated without stagnation and consequently air movement and temperature distribution were uniform. In case of bulk storage, air movement was stagnated so much and temperature distribution of onion was not uniform. Furthermore, the inner temperature of onion roses more than the initial temperature of storage. In case of pallet storage, air movement and temperature distribution of onion were so uniform that the danger of quality change was decreased.
Keywords: Cold Storage Facility, Cold Storage, CFD, Storage Method, FVM

Introduction

Vegetable and fruits maintain metabolism, and general physiology functions and cellular tissue are transformed under cold storage. Quality change of postharvest is largely affected by respiration and transpiration. Cold storage facility manages quality factors under the optimum environment condition. Environment factors that influence quality change of vegetable and fruits are temperature, moisture, atmosphere, wind velocity, light, and pressure difference, etc.

Nielsen(1978) analyzed flow characteristics constituted small ventilating opening. Maximum velocity in the inverse flow influenced by cross sectional view not by the shape of an inflow. Timmons(1979) analyzed air movement in the space ventilated using fluid dynamics theory which was Ψ-ω turbulent model and Navier-Stokes equation. Kang(1996) showed similarity between standard $k-\varepsilon$ model and Low-Raynolds -number $k-\varepsilon$ model by Rousseau(1995) about air movement of cold storage facility. Cho(1997) studied about 2-D air movement and heat flow for cold storage facility using $k-\varepsilon$ turbulent model. Kim (1997) suggested a guide to calculate air cooling load for designing cold storage facility which was suitable for weather condition and environment in the country.

The objective of the study was to examine unsuitable air conditioning and inadequacy design of foreced-air cooling and also to research about optimum storage method using 3-D CFD simulation.

The authors are **Gil Mo Yang**. Ph.D. and **Hak Kyun Koh**, Professor, School of Bioresources and Material Engineering, Seoul National University, Suwon, Korea.
Corresponding author: Gil Mo Yang, Research Associate, School of Bioresources and Material Engineering, Seoul National University, Suwon, Korea. E-mail: gmyang@snu.ac.kr

Materials and Methods

1. Simulation

CFD-ACE+ 6.4 commercial package was used for complicated shape and their mathematical models was as follow.

(1) Governing Equations

① Continuous equation

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

ρ : density, u_i : velocity

② Momentum equation

$$\frac{\partial}{\partial x_i}(\rho\ u_i\ u_j) = \frac{\partial \tau_{ij}}{\partial x_i} + \rho f_i + \frac{\partial(\overline{\rho\ \dot{u_i}\ \dot{u_j}})}{\partial x_i} \tag{2}$$

f_i : external force like electromagnetic force or gravity

τ_{ij} : stress tensor

③ Energy equation

$$(\rho\ u_i\ h)\frac{\partial T}{\partial x_i} = \frac{\partial}{\partial x_i}(K\frac{\partial T}{\partial x_i}) + H \tag{3}$$

h: enthalpy, T: temperature,

K: heat transfer coefficient, H: inside heat

(2) Standard $k-\varepsilon$ turbulence model

The $k-\varepsilon$ model is a two equation model that employs partial differential equations to govern the transport of the turbulent kinetic energy, k , and its dissipation rate, ε. Several versions of the $k-\varepsilon$ model are in use today. The standard $k-\varepsilon$ model employed in this study was based on Launder and Spalding(1974).

The square root of k was taken to be the velocity scale, while the length scale was modeled as

$$l = \frac{C_\mu^{3/4} k^{3/2}}{\varepsilon} \tag{4}$$

The expression for eddy viscosity was

$$\nu_t = \frac{C_\mu k^2}{\varepsilon} \tag{5}$$

Flow from fan is assumed as one way turbulence flow. k and ε were calculated by the boundary condition.

$$k = \frac{3}{2}(I\ u_\tau^2) \tag{6}$$

I : turbulence intensity

u_τ : velocity

$$\varepsilon = \frac{C_\mu^{3/4} k^{3/2}}{K \cdot L} \tag{7}$$

C_μ : closure coefficient

K : diffusion coefficient

L : the mixing length of turbulence

The modeled equations for k and ε are

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho u_j k) = \rho P - \rho\varepsilon + \frac{\partial}{\partial x_j}[(\mu + \frac{\mu_t}{\sigma_k})\frac{\partial k}{\partial x_j}] \tag{8}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_j}(\rho u_j \varepsilon) = C_{\varepsilon_1}\frac{\rho P \varepsilon}{k} - C_{\varepsilon_2}\frac{\rho\varepsilon^2}{k} + \frac{\partial}{\partial x_j}[(\mu + \frac{\mu_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_j}] \tag{9}$$

with the production P defined as

$$P = \nu_t(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\frac{\partial u_m}{\partial x_m}\delta_{ij})\frac{\partial u_i}{\partial x_j} - \frac{2}{3}k\frac{\partial u_m}{\partial x_m} \tag{10}$$

The five constants used by Launder and Spalding (1974) in the model are:

$C_\mu = 0.09$, $C_{\varepsilon 1} = 1.44$, $C_{\varepsilon 2} = 1.92$,

$\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$

The standard $k-\varepsilon$ model is a high Reynolds model and is not intended to be used in the near-wall regions where viscous effects dominate the effects of turbulence. "Wall functions" was used in cells adjacent to walls.

In the standard wall function approach employed, the wall shear stress was obtained by assuming the velocity profile between the wall and the first grid point away from the wall obeys the following "law of the wall":

$$u^+ = y^+ \text{ for } y^+ < 11.5, \qquad u^+ = \frac{1}{x}\ln(Ey^+) \text{ for } y^+ > 11.5 \tag{11}$$

The wall shear stress was calculated iteratively from the known values of y and u in the first cell. The constants appearing in equation (11) were experimentally determined to be $E = 9.0$ and $x = 0.4$. Because the semi-empirical relations for k and ε in the first cell assumed a logarithmic velocity profile, the turbulence wall functions were strictly valid only if the center of the cell nearest the wall was inside the logarithmic boundary layer ($y^{+} > 30$).

Interpretation of turbulence phenomenon was calculated by standard $k-\varepsilon$ turbulence model which was stand on the basis of FVM.

3-D simulation was carried out, changing storage method and location of onion.

2. Mesh generation

Mesh generation is the process for searching the solution in moving area what you want. Mesh was composed to be 1:1 mapping not twisted and continuous for the differential value of coordinates diversion smoothly. The area that gave rise to the incline of moving function, around the fan and wall, was crowded by lattices to prevent errors or diffusion. A lot of skewness between lattices was avoided because this amplified truncation error. Used mesh was as belows, Fig. 1, Fig. 2, Fig. 3 and Fig. 4. Number of cells were 122,590 in case of no stores and 148,994 in case of pallet storage.

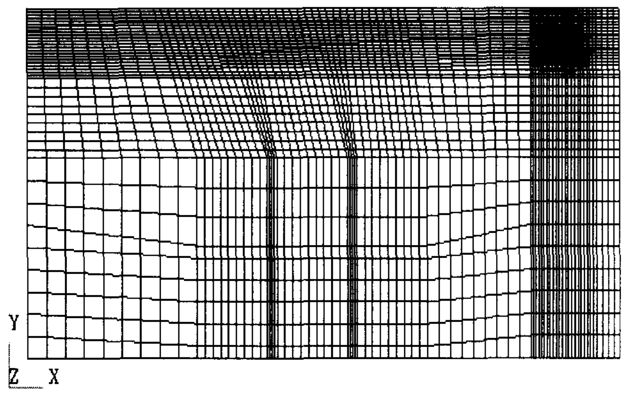


Fig. 1 Front view of mesh generation for the pallet storage facility.

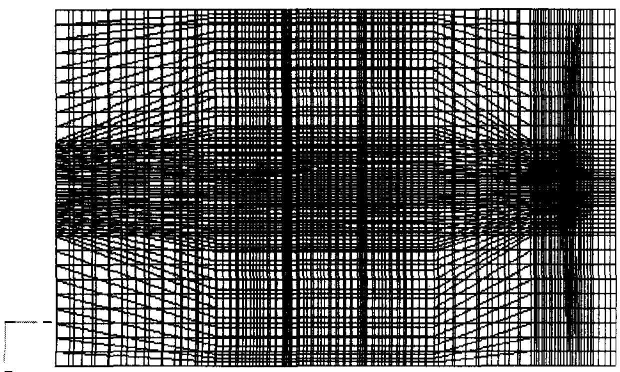


Fig. 2 Top view of mesh generation for the pallet storage facility.

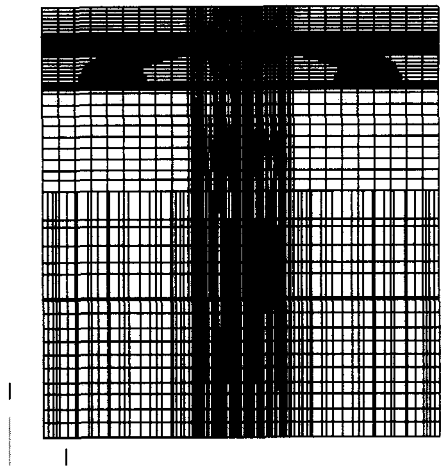


Fig. 3 Side view of mesh generation for the pallet storage facility.

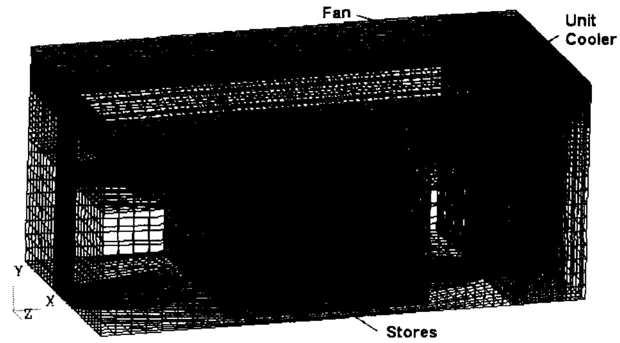


Fig. 4 Full view of mesh generation for the pallet storage facility.

3. Boundary condition

Initial condition for simulation doesn't have influence on the last calculated value directly but process which is proceeded to get that value. Especially, in case of pressure, kinetic energy of turbulence(k), and the dissipation of turbulence(ε), establishment of rational initial value is very important. In this study, initial condition and boundary condition are established by experimental value.

Heat generation based on fan operation, incoming heat through wall, and respiratory heat are considered as inside heat source. It was assumed that the part of enclosed fan was solid and only heat transfer is generated on that.

Average temperature of stored onion was 2.2℃. ASHRAE Handbook(1998) was used for referring physical property of onion. Table 1 indicates boundary conditions.

Table 1 Boundary conditions

Inlet (rear of a fan)	Velocity	7.59 *m/s*
	Temperature	-1.5 ℃ (271.65 *K*)
Outlet (rear of a capillary)	Velocity	2.52 *m/s*
	Temperature	2 ℃ (275.15 *K*)
Physical properties of fan	Density	7,830 kg/m^3
	Specific heat	0.11 *kcal/kg-K*
	Heat transfer	73 *W/mK*
Physical properties of fan	RPM	1,135
	Blade angle	25°
	Generated heat	144 *kcal/h*
Incoming heat through wall		2.342 *W/m²*
Physical properties of onion	Respiratory heat	6.22 *W/m²*
	Density	493 *kg/m³*
	Specific heat	0.9 *kcal/kg-K*

The initial speed of a current was calculated as measuring 4 points of the fore part of the fan and the average value of wind velocity was 7.59 m/s. Turbulence intensity was 0.02. The mixing length of turbulence, L, was 0.46m.

Inlet condition was 7.59 m/s which was measured value. Calculated k was 0.034565 and ε was 0.0057387 calculated using $k-\varepsilon$ turbulence model.

4. Materials

Onion that was harvested on early July of 2000 in Muan, Jeonnam in Korea and 2,000 kg was used for storage experiment. Onion and outside temperature was 23℃ and 31℃ and room temperature was 12℃ at first and then decreased 11℃, 10℃, 9℃ ··· 0℃ for 10 days so that the onion had uniform temperature before the experiment. Room and onion temperature was measured when room temperature was 0 ℃.

5. Experimental equipment

Fig. 5 shows a schematic representation of overall experimental equipment. 18 temperature sensors and 2 velocity sensors were set up in the cold storage facility. Each sensor was connected to 4 of 8 input channel and 1 output channel. Those are also connected to computer through RS-232 cables. Plate sensor was established to measure heat flux on the wall and heat transfer from inside room was cut off using isolated tape.

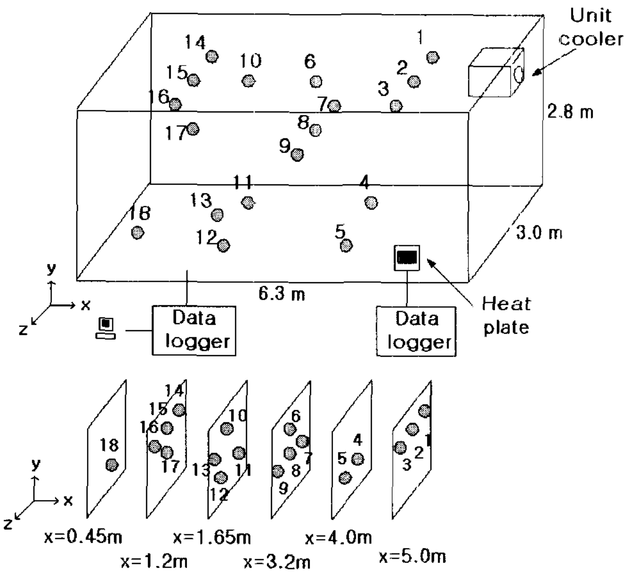


Fig. 5 Schematic representation of overall experimental equipments.

6. Experimental methods

In case of no stores, temperature sensors were established on each section. Target temperature was 4℃ and 0℃ and temperature distribution was measured until normal state was achieved. Measured and simulated temperatures were compared, and the air movement in cold storage facility was analyzed by using the simulated results.

No stores, bulk storage and pallet storage were experimented to prove similarity between measured and predicted values simulated by CFD.

In case of bulk storage, stored onion was adjoined to the floor. The contact area with cold air was 12.85m^2.

In case of pallet storage, there was the passage of air movement among onion. Those intervals were 0.1m from floor, 0.75m from walls, 0.24m among onion and 0.13m between the upper onion and the under onion. The contact area with cold air was 45.44m^2. The contact area of pallet storage was about 3.5 times as compared with bulk storage.

Results and Discussion

1. Similarity between measured and predicted values

Fig. 6(a) shows measured and predicted temperatures for no stores. The predicted temperature using the CFD model was in good agreement with the measured. The 6th point in a clod storage room was the lowest temperature due to the characteristic of cooling air movement from unit cooler. The average difference between the two was 0.17℃.

Fig. 6(b) shows measured and predicted temperatures for bulk storage method. the average difference between those values was bigger than those of no-storage and pallet-storage methods. The contact area of onions in bulk storage with cooling air was smaller and the respiration heat of onions was more irregular than pallet storage. The average difference between two values was 0.45℃.

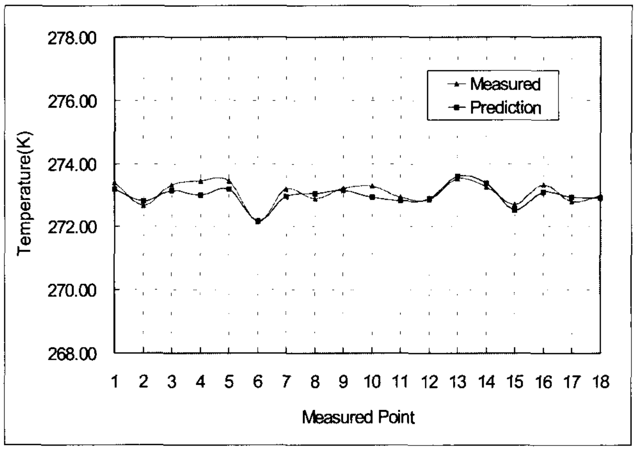
Fig. 6(c) shows measured and predicted values of temperature for pallet storage. the contact area of onions with cooling air was larger than that of bulk storage where the average difference was as small as 0.28℃.

2. Simulation of air movement and temperature distribution

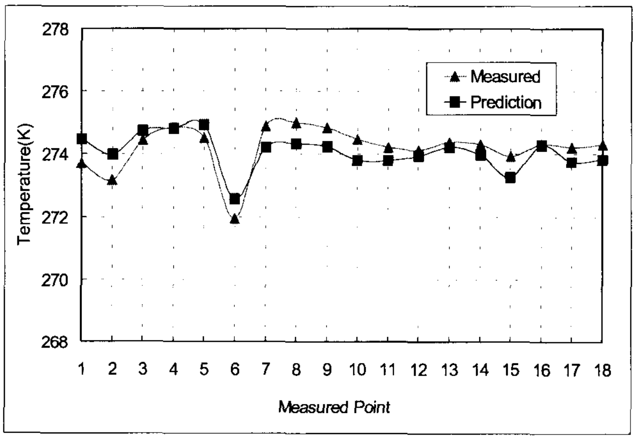
CFD models were developed to simulate the air movement and to predict temperature distribution in a cold storage facility.

Three different types of arrangement were considered for bulk storage of onions; onions at center, left side, and right side of the cold storage facility, where unit cooler was located on the right side.

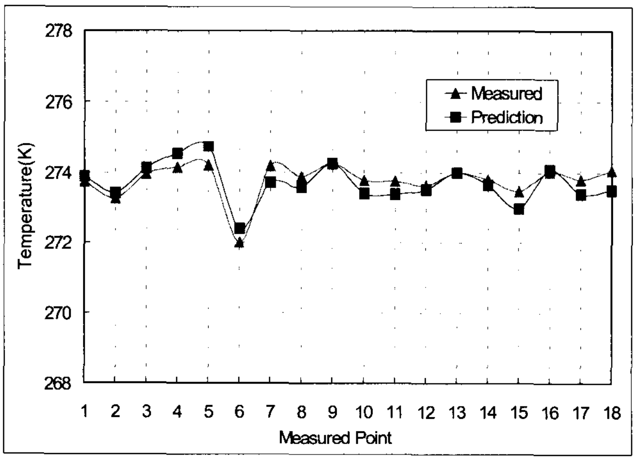
Dimension of bulk of onion was 2.35×1.37×1.26m. Fig. 7(a) shows velocity distribution of cold air and temperature distribution of bulk storage of onions. Strong eddy was generated in the left side of onion and cold air flowed backward in the right side of onion as shown in Fig. 7(a). An excessive temperature deviation was generated between up and down side of onion as shown in Fig. 7(b). Temperature on the left side of onion was 0.5℃, the inside of onion was 3.61 ℃ and the right side of onion was 1.25℃ on the average when target temperature was 0℃.



(a) No stores

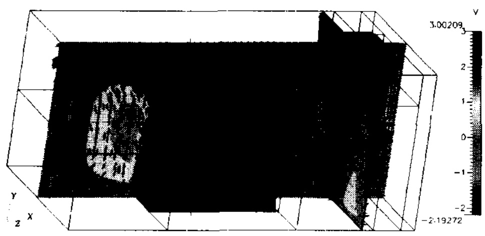


(b) Bulk storage

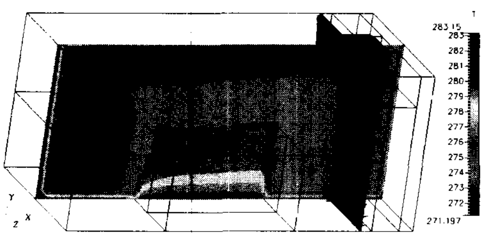


(c) Pallet storage

Fig. 6 Comparison between measured and predicted temperatures in a cold storage facility.



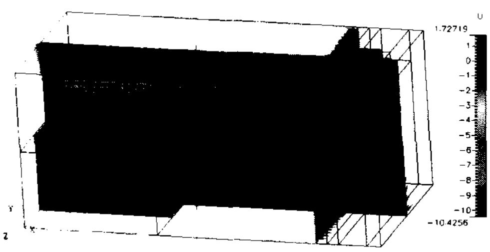
(a) Velocity distribution



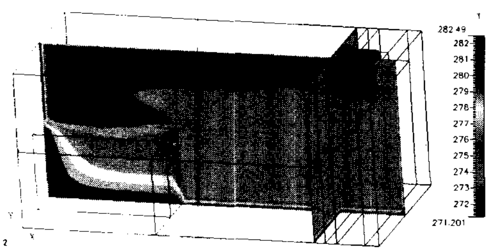
(b) Temperature distribution

Fig. 7 Velocity and temperature distribution for bulk storage at the center in cold storage facility.

Fig. 8 illustrates the velocity distribution of cold air and temperature distribution of bulk storage on the left side of room. Influent heat through of cold storage facility exerted a bad effect upon onion as shown in Fig. 8(a). For that reasons, temperature distribution of inside of bulk storage of onion was not uniformed as shown in Fig. 8(b). The mean temperatures of onions inside and the right side of the bulk storage were 4.85 ℃ and 0.75, respectively.



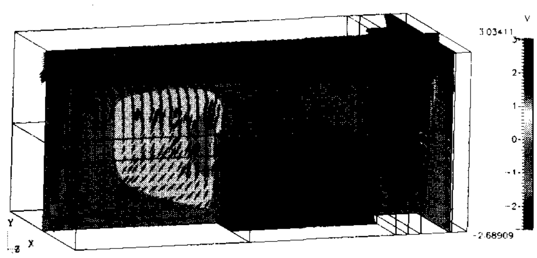
(a) Velocity distribution



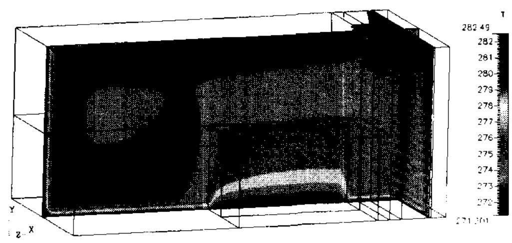
(b) Temperature distribution

Fig. 8 Velocity and temperature distribution for bulk storage at the left side in cold storage facility.

Fig. 9 shows the velocity distribution of cold air and temperature distribution of the bulk storage on the side of unit cooler. Cold air induced a large eddy in the presence of onion and, in the opposite side, turbulence flow was generated on the opposite side.



(a) Velocity distribution



(b) Temperature distribution

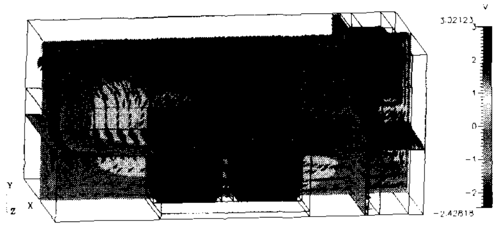
Fig. 9 Velocity and temperature distribution of bulk storage on the right side in cold storage facility.

Fig. 10 illustrates the velocity distribution of cold air and temperature distribution of pellet storage of onions. Contact area of onion with cold air was 45.44m^2. That was increased 71.1% than that of bulk storage.

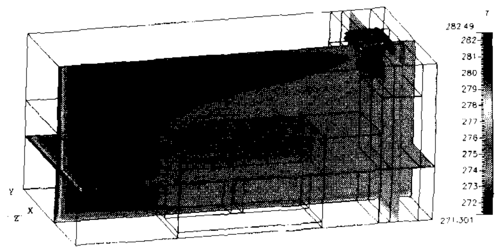
Cold air flowed among onion well as shown in Fig. 10(a). Onion maintained an uniform and low temperature distribution. When a room temperature was set to 0℃, the left side of onion was 0.18℃, inside of onion was 1.71℃ and the right side of onion was 0.82℃ as shown in Fig. 10(b). Fig. 10(c) and (d) show temperature distribution of the left side and the right side of onion. Although cold air flowed between onion well, onion was apt to suffer damage due to cold air as shown in Fig. 10(c). Since the left side of onion contacted with cold air directly. On the other hand, the right side of onion showed an uniform temperature distribution. This was caused by irrational velocity and unreasonable design of cold storage facility.

To solve this problem, onion needs to be arranged at the side of room in the state of pallet storage as shown in Fig. 11. This solution could prevent cold-weather damage by avoiding direct contact of onions with cold air from unit cooler.

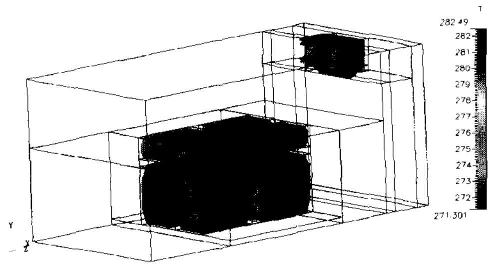
However, if onion is stored as Fig. 11, this is uneconomic method for large quantity of onion and could be minimized when onion was stored having 10 cm interval and 800 to 1,135 fan rpm as shown in Fig. 12. But temperature of the right side of onion was little higher than that on the left side of onion. The reason was considered as unreasonable design of cold storage facility. The more research about the development of new model for cold storage facility should be continued to solve this problem.



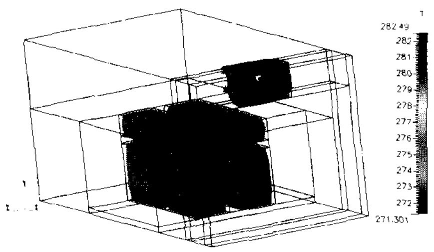
(a) Velocity distribution



(b) Temperature distribution

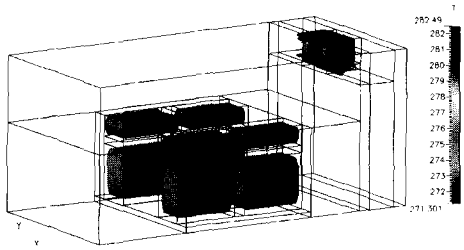


(c) Left side view for temperature distribution of onion

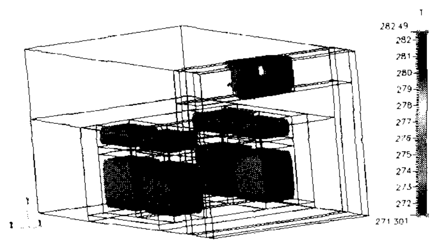


(d) Right side view for temperature distribution of onion

Fig. 10 Velocity and temperature distribution of pallet storage of onions.

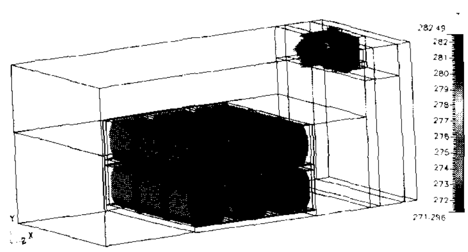


(a) Left side view for temperature distribution of onion

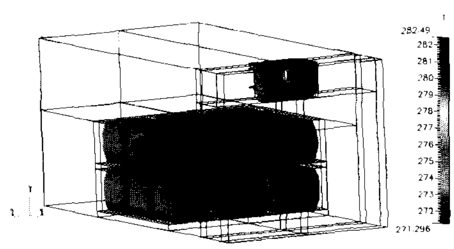


(b) Right side view for temperature distribution of onion

Fig. 11. Temperature distribution of onion when it is stored at the side of room.



(a) Left side view for temperature distribution of stores



(b) Right side view for temperature distribution of stores

Fig. 12 Temperature distribution of stores when air velocity is decreased to 800 RPM (5.7m/s).

Conclusions

3-D CFD simulation for cold storage facility was accompanied. Optimum storage method of vegetable was suggested. Air movement and temperature distribution between onion was analyzed. It was also simulated how cold air gave an effect of temperature distribution and air movement in onions. Pallet storage was more useful than bulk storage. It was recognized that study about optimum design of cold storage facility is necessary.

Acknowledgments

We thank the members of SNU prosys(agricultural process system) laboratory for supplying an effort. This study was conduced by the research fund supported by Korea Research Foundation(KRF).

References

American Society of Heating. Refrigerating & A/C Engineers. 1998. ASHRAE Handbook.

Baird, C. D., and J. J. Graffney. 1986. Numerical procedure for calculating heat transfer in bulk loads of fruits or vegetables. Transaction of the ASHRAE. 82(II):525-540.

Califano, A. N., and N. E. Zaritzky. 1993. A numerical method for simulating heat transfer in hetero- geneous and irregularly shaped foodstuffs, Journal of Food Process Engineering 16:159-171.

Cho, B. K. 1997. Study on the temperature distribution & air flow in cold storage room using $k-\varepsilon$ turbulence model. Seoul National University Agricultural Machinery Eng. Master's Thesis.

Gommori, M., H. Kogure, and T. Hara. 1986. Reduction of thermal energy loss in cyclic operation of refrigeration cycle. Trans. of the JAR. Vol 3. No. 2:37-44.

Husain, A., C. S. Chen, and J. T. Clayton. 1973. Simultaneous heat and mass diffusion in biological materials. Journal of Agricultural Engineering Research 18:343-354.

Kang, S. W. 1996. Development of a poisson model to predict recirculating flows in clod storage rooms. Ph.D. dissertation. Cornell University, Ithaca, New York.

Kim, G. S., K. S. Lee, J. H. Yun, and I. C. Song. 1997. Study on the method of calculating air cooling load for cold storage facility. HAVAC. Summer Conference : 372-377.

Launder, B. E., and D. B. Spalding. 1974. The Numerical Computation of Turbulence Flows. Computer Methods in Applied Mechanics and Engineering 3:269-289.

Nielsen, P. V., A. Restivo, and J. H. Whitelaw. 1978. The velocity characteristics of ventilated room. Trans. ASME. J. Fluids Engrg. 100:291-298.

Rousseau, A. N. 1995. A computational fluid dynamics study of incomplete air mixing in a model slot-ventilate enclosure. Ph. D. dissertation. Cornell University. Ithaca, New York.

Timmons, M. B. 1979. Experimental and numerical study of air movement in slot-ventilated enclosures. Unpublished Ph.D. dissertation, Cornell University. Ithaca, New York.