Mathematical Model of Heat Transfer, Cooling Mass and Storage Time of Apples (*Malus domestica*) in Packaging

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Abstract: The cooling of fruit at high relative humidity can control respiration, moisture loss, ripening, and the action of enzymes and microorganisms that cause spoilage and decrease shelf life. A mathematical model was developed for cooling or storing packaged apples and solved with finite elements predicting one-dimensional heat and mass transfer. The model consists of two separate parts of the heat and mass transfer model, namely to predict air humidity, air condensation, and moisture content. The temperature predicted by the model for refrigeration or storage simulations is compared with the experimentally secermined temperature.Validity test and sensitivity test were used to test the validity of the mathematical model of heat transfer and mass transfer during cooling or storage of apples. Scatter plot test, residual test, and validity test to secermine the validity of the developed mathematical model. This model is successful in estimating the time-temperature profile at various locations in bulk apples packaging during the cooling process and the storage process

Keywords: apple, cooling, heat transfer, mass transfer, temperature, storage

1. Introduction

Apple (*Malus domestica*) is an agricultural commodity that has good prospects in Indonesia. Imports of apples show that the demand for this fruit is still quite high. Apple consumption data is 0.730 kg/capita/year (Directorate General of Food Crops Agriculture, 2016). The nutrients contained in apples are 156 grams (g) of water, 94.6 calories, 25.1 g of carbohydrates, 4.37 g of fiber, 18.9 g of total sugar, 10.9 mg of calcium, 9.1 mg magnesium and 20 mg phosphorus. Apples are useful because it can decrease cholesterol levels in the blood. One of them is the presence of polyphenolic compounds that function as antioxidants. The pectin component works together with the phytonutrient components in apples to control fat levels and blood sugar levels. Indonesia's apple production in 2020 was 516,531 tons (BPS, 2021), Indonesia's apple production in 1994 was 242,195 tons (BPS, 1996). The apples production in Indonesia is mostly in Malang, East Java and the rest is in the provinces of West Nusa Tenggara, Central Java and Aceh. In addition to Malang district, it turns out that in East Java province there are still several areas that also have the potential for apple crop development, including: Bondowoso district, Ponorogo district, Banyuwangi district, Kediri district, Situbondo district, and also Magetan district.

Apple provides a pretty good prospect as an export commodity. Apples are classified as seasonal fruit that can only be harvested twice a year. Storage of this fruit in fresh form can extend its usability and in certain circumstances can improve quality. Storage of fruit in a fresh state can avoid excess fruit in the market and to ensure product continuity to support regular marketing so as to increase producer profits and maintain product quality (Pantastico, 1993). According to Kader, 2002; Thomson et al., 2002, high temperatures damage fruit storage, high temperature on crops cannot be avoided, especially when harvesting is carried out on hot days such as in the tropical area. Post-harvest loss of apples in developing countries reaches 14%. Manalagi apples from Malang City are marketed in Surabaya, Jakarta, Denpasar, and other big cities in Indonesia. The main means of transportation are trucks with no cooling system. Apples in bulk form are placed into baskets or new cartons transported by truck to marketing destinations. Apples are a type of climacteric fruit, so if the temperature in the package increases, the biological activity of respiration increases (Castellanos & Herrera, 2015). Increased respiratory activity causes the emergence of respiratory heat and increased humidity inside the packaging due to water vapor produced by respiration. The increase in temperature and humidity causes fruit damage because the increase in temperature and humidity has the potential to activate spoilage microorganisms. Theoretically, apples are more durable when stored at a temperature of 10-15 ^{o}C (Kader et al., 1999; Lee & Kader, 2000).

Castellanos et al. (2015) developed a model representing physiological changes and fruit quality during storage, this model has not been able to solve the problem of heat transfer. Heat transfer and mass transfer during the transportation of apples occur in an unsteady manner (Raghava et al., 2020). Therefore, Eissa et al. (2017) andAfolabi (2014) developed an empirical model using mathematical equations to predict the relationship between time and energy balance and mass balance in fruit packaging boxes during the cooling process. The developed mathematical model makes it easier to predict the secermination of the cooling system and fruit storage during transportation to avoid physiological damage and maintain fruit quality. Research on heat transfer and mass transfer is a basic research and is rarely done because it involves solving complex differential equations. However, the complexity can be overcome with finite-difference. So that the results of the mathematical model developed from the energy balance and mass balance equations can be applied to the planning of apple cooling systems during storage and transportation as an effort to maintain product quality. Simplification of the model for solving problems in compiling mathematical equations is carried out by applying assumptions (Karim & Hawlader, 2005): (1) heat and mass transfer in one direction, (2) radiation heat transfer is ignored, (3) changes in the thermal properties of elements is uncounted in the packaging, (4) negligible shrinkage of the material, (5) negligible changes in air velocity due to temperature changes, (6) mass transfer occurs due to evaporation and condensation, (7) the walls of the packaging are impermeable to gas and water vapor, and (8) in each layer the air temperature is the same as the fruit temperature.

The apples in the package achieve energy balance and mass balance with the surrounding air through the process of heat transfer and mass transfer. The contents of the carton packaging are apples, air, water vapor which are one unit, so that the energy balance of bulk apples in the packaging can be approached using the heat and mass transfer equations due to the respiration process of apples during storage time or transportation. The purpose of this research is to develop a mathematical model of heat and mass transfer in the process of storing apples in individual and bulk forms to estimate the development of apple cooling systems during storage and transportation from the city of Malang to the cities of Jakarta, Yogyakarta and Denpasar.

2.Development of Mathematical Models of Heat and Mass Transfer

The model for estimating temperature, humidity, the amount of water evaporated, and the amount of water condensed on the surface of apples is compiled in the form of a simulation program developed from mathematical models of heat transfer and mass transfer during the cooling process and storage of bulk apples in a cardboard packaging. The mathematical model was developed from equations (1) respiration, (2) energy balance, and (3) mass balance. The mathematical model of heat transfer and mass transfer of apples stored and refrigerated in carton packaging was developed from the mathematical model of Whitney and Poterfield (1988); Lerew (1978) and Setiyo et al. (1995). A mathematical model was developed for the case of one-dimensional boundary value problems and transient conduction.

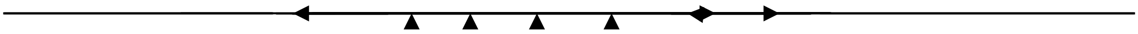

Figure.1. Energy balance and dry air mass

Inside the apple packaging, air, water vapor, and water are in one unit. The solving the energy balance and mass balance equations are carried out for each component. The incoming energy is in the form of energy from heat generation by the air, while the outgoing energy is in the form of convective heat to the air. The values of air density, the specific heat of air, material porosity, and fruit surface area are constant.

$$q_a.S.\partial X - h_p.S.(1-\varepsilon)(T-\theta) = \frac{\partial}{\partial t}(\rho_a.\varepsilon.C_a.T.S.\partial X) \qquad (1)$$

Because the value of ρ_a, C_a, ε, and S is fixed then the equation (1) becomes:

$$q_a - h_p.(1-\varepsilon)(T-\theta) = \frac{\partial T}{\partial t}(\rho_a.\varepsilon.C_a) \qquad (2)$$

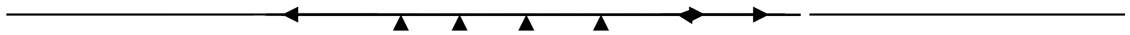

Figure.2. Energy and mass balance of water vapor

The water vapor in the packaged air that occupies the pores of the material is the result of evaporation and the transfer of water vapor due to the water vapor concentration gradient. The mass equilibrium of water vapor removed from apples and accumulated in dry air is written by the equation:

$$\rho_a.\varepsilon.C_a.D_{mv}.\frac{\partial H}{\partial X}.S\Big|_X - \rho_a.\varepsilon.C_a.D_{mv}.\frac{\partial H}{\partial X}.S\Big|_{X+\partial X} + \dot{m}_V.S.\partial X = \frac{\partial}{\partial t}(\rho a.\varepsilon.H.S.\partial X) \qquad (3)$$

Because S and ∂X the value is fixed, then both segments can be divided S.∂X, so that equation (3) becomes:

$$\rho_a.\varepsilon.\ D_{mv}\frac{\partial^2 H}{\partial X^2} + \dot{m}_v = \rho_a.\varepsilon.\ \frac{\partial H}{\partial t} \qquad (4)$$

Equation (4) can also be written:

$$\rho_a.\varepsilon.\ D_{mv}\frac{\partial^2 H}{\partial X^2} + \dot{m}_v - \rho_a.\varepsilon.\ \frac{\partial H}{\partial t} = 0 \qquad (5)$$

Because the value of ∂H/∂t is much greater form the value of $\partial^2H/(\partial X^2)$therefore, the value ∂H/∂X can be ignored, so equation (5) becomes:

$$\dot{m}_v = \rho_a.\varepsilon.\ \frac{\partial H}{\partial t} \qquad (6)$$

The energy balance of water vapor in the air in the package is formulated by a mathematical equation:

$$q_v.S.\partial X = \frac{\partial}{\partial t}(\rho_a.\varepsilon.H(C_v.T + h_{fg})S.\partial X) \qquad (7)$$

With the value of C_v and h_{fg} is fixed,then equation (7) becomes:

$$-\dot{m}_v\ (C_v.T + h_{fg}) + Q_e = \rho_a.\varepsilon.H.C_v.\frac{\partial T}{\partial t} \qquad (8)$$

The water balance containing solid material (apple) in the package is formulated in equation (9)

$$\dot{m}_p.S.\partial X = \frac{\partial}{\partial t}(\rho_p(1-\varepsilon)S.\partial X) + \frac{\partial}{\partial t}(\rho_{\ w}.\partial_w.a.S.\partial X) \qquad (9)$$

If both segments are divided by S.∂X, then equation (9) becomes equation (10)

$$\dot{m}_p = \frac{\partial}{\partial t}(\rho_p(1-\varepsilon)) + \frac{\partial}{\partial t}(\rho_{\ w}.\partial_w.a) \qquad (10)$$

Law of mass conservation

$$\dot{m}_p + \dot{m}_v = 0 \qquad (11)$$

Evaporation only occurs until the air humidity reaches saturation of water vapor, then the equations for calculating evaporation are developed by Whitney & Poterfield (1988) as follows:

$$\dot{m}_p \le \rho_a.\varepsilon.\partial H/\partial t \qquad (12)$$

$$\dot{m}_p = \begin{cases} -\dot{m}_{pv} = (1-\varepsilon).\frac{\partial \rho_p}{\partial t} = \frac{h_w.D_{wa}}{r\delta.h_D+D_{wa}}.\gamma.a.(P_s - P_v) \\ \qquad \text{Pada } H < H_{sat}, \text{ VPD} > 0 \text{ dan } \delta_w = 0 \qquad (13) \\ -\rho_a.a.\frac{\partial.\delta_w}{\partial t} \begin{cases} = \dot{m}_{pa} = -h_w.a(P_s.\Theta_s - P_v) \\ \qquad \text{Pada } H < H_{sat}, \text{ VPD} > 0 \text{ dan } \delta_w > 0 \qquad (14) \\ = -\dot{m}_c, \text{ pada } H = H_{sat} \qquad (15) \end{cases} \end{cases}$$

$$\dot{m}_p = \dot{m}_{pv} + \dot{m}_{pa} - \dot{m}_c \qquad (16)$$

Figure.3. Energy volume control

The energy balance is mathematically written in the equation:

$$-k_{ef}.(1-\varepsilon).S.\ \frac{\partial\theta}{\partial X}\Big|x\ +\ k_{ef}.(1-\varepsilon).S.\ \frac{\partial\theta}{\partial X}\Big|x+\delta x\ +\ Q_p.\rho_p.(1-\varepsilon).\delta x.S + q_p.\delta x.S = \frac{\partial}{\partial t}.(\rho_p.(1-\varepsilon).C_p.\theta.\delta x) + \frac{\partial}{\partial t}.(\rho_w.\delta_w.a.C_w.\theta.S) \qquad (17)$$

Equation (17) is simplified to equation (18)

$$k_{ef}.(1-\varepsilon).\ \frac{\partial^2\theta}{\partial X^2}\ +\ Q_p.\rho_p.(1-\varepsilon) + q_p. = \frac{\partial\theta}{\partial t}.(\rho_p.(1-\varepsilon).C_p + \rho_w.C_w.\delta_w.a) + \frac{\partial\delta_w}{\partial t}.(\rho_w.\delta_w.a.C_w.\theta) + \frac{\partial\rho_p}{\partial t}(1-\varepsilon).C_p.\theta) \qquad (18)$$

The temperature of the apples, the temperature of the air inside the package, and the temperature of the air outside the package were measured using a digital thermometer. Placement of measurement points with an interval of Δx for bulk apples. Observations were made at intervals of Δt minutes. Secermination of Δx, Δ r, and Δt is done by using the formula approach:

$$\Delta t\ \le\ \frac{\Delta r^2}{(1+Bi).2\alpha} \qquad (19)$$

$$\Delta t\ \le\ \frac{\Delta x^2}{(1+Bi).2\alpha} \qquad (20)$$

Where Bi is the Biot number and Fo is the Fourier number, the terms for the Biot number are:

$$\text{Fo}(\text{Bi} + 1) < ½ \qquad (21)$$

The empirical equation for the Seibel specific heat in foodstuffs is a function of water content. The equation is formulated in two models, namely the specific heat for food at temperatures above the freezing point and at temperatures below the freezing point. The specific heat formula is:

$$C_p = 33{,}47.M + 837\ \text{J/kg}^{o}\text{K} \qquad (22)$$

for food temperatures above freezing point.

$$C_p = 12{,}55.M + 837\ \text{J/kg}^{o}\text{K} \qquad (23)$$

for food temperatures below freezing. Bennett's (1969) research results showed that the specific heat for Red Delicious apples at a moisture content of 82.8% - 86.4%, the average was 3.676 J/kg.^{o}C.

The conductivity of food is strongly influenced by the amount of water content in the material. From the ASHRAE Fundamental (2006) data, food materials with a moisture content of 50-90% w.b and at a temperature of 2-41 ^{o}C were analyzed, the results of the analysis obtained an empirical equation of heat conductivity as a function of water content and temperature. The equation is:

$$k_p = 0{,}363749 + 0{,}250774\left(\frac{273{,}15M}{273{,}15+\theta}\right)^{1{,}8270887} \qquad (24)$$

Sweat (1974) formulated thermal conductivity as a function of water content as the research result on several fruits and vegetables with water content above 60% w.b. The thermal conductivity equation according to Sweat (1974) is:

$$K_p = 0{,}148 + 0{,}00493\ M \qquad (25)$$

The heat transfer coefficient by natural convection in a spherical shaped material is a function of (1) Nusselt number (Nu), the thermal conductivity of air(k_u), and the diameter of the material (D). Equation is written:

$$h_p = \frac{Nu.k_a}{D} \qquad (26)$$

The Nusselt number in natural convection is calculated by the following Churchill equation:

$$Nu = 2 + \frac{0{,}589.RaD^{0{,}25}}{\left(1+\left(\frac{0{,}469^{9/16}}{Pr^{9/16}}\right)\right)^{4/9}} \qquad (27)$$

Where RaD is a linear function of the Prandtl and Grasnolt numbers, which is written as an equation:

$$RaD = Gr.Pr \qquad (28)$$

The value of the Grasnolt number is approximated by the equation:

$$Gr = \frac{g.D^3.rc.\partial T}{\upsilon} \qquad (29)$$

In forced convection, the Nusselt number is a function of the Renolds number (Re) and the Prandtl number (Pr). The material is in spherical form and in the bulk conditions, the Nuseelt number is approached using the Rohsenow and Choi (1961) equation, the equation is formulated:

$$Nu = 0{,}8(Re)^{0{,}7}(Pr)^{0{,}33} \qquad (30)$$

$$Re = \frac{V_a.}{\eta}\rho_a.D \qquad (31)$$

The heat of respiration of apples from fruit and vegetable research is presented by AHSRAE (1974). The prediction results show very good results, the empirical equation of the heat of respiration of apples as a function of temperature (Θ) is formulated:

$$Q_r = 19{,}4(e)^{0{,}108.\Theta} \qquad (32)$$

3.Mathematical models for simulation

The mathematical model of heat and mass transfer during cooling and storage of apples in cartons is a case of a one-dimensional boundary value problem. The mathematical equation for estimating the temperature of apples in the packaging during the cooling and storage process is a fairly complex equation because it contains mass transfer equations ($\partial M/\partial t$), mass transfer which is a function of material temperature (Θ), air temperature (T), and humidity (H). The completion of the simulation model from the mathematical model of heat and mass transfer is carried out simultaneously, this makes the problem more complex. The solving simulation models from complex mathematical equations is easier to do numerically than analytically.

The mathematical equations of heat transfer and mass transfer are non-linear mathematical equations. Non-linear equations are easier to solve numerically than analytically. Solving the mathematical equations of conservation of mass and energy for the simulation model is used explicitly (forward) with stability, because according to (Setiyo et al., 1995) this method is accurate and the completion time is fast when using a computer compared to the Crank-Nicholson method (central). The solution of using the implicit (backward) method provides less stability and convergence constraints than the explicit method.

The humidity of the air inside the packaging changes due to the evaporation and condensation of water vapor. Because the packaging is impermeable to water vapor and gas, the humidity equation (Setiyo et al., 1995) is written:

$$H^{+} = H + \frac{\dot{m}_{pv}+\dot{m}_{pa}-\dot{m}_{c}}{\rho_a\varepsilon}.\Delta t \qquad (33)$$

$\dot{m}_{pv}$ and $\dot{m}_{pa}$ solved by equations (13) and (14), while $\dot{m}_c$ with equation

$$\dot{m}_c = \frac{\rho_a.\varepsilon(H-H_{sat})}{\Delta t} \tag{34}$$

The value of the minimum evaporation or condensation that can occur is calculated by the equation (Setiyo et al., 1995).

$$\dot{m}_{pmin} = \frac{\rho_a.\varepsilon(H-H_{sat})}{\Delta t}\,. \tag{35}$$

Water on the surface of the apple is due to the condensation of water vapor. Evaporation of condensed water occurs when the vapor pressure deviation of the air is more than zero and the air humidity is below saturation humidity. The thickness of the condensed water vapor is solved using the equation (Setiyo et al., 1995)

$$(1-\varepsilon).a.\rho_a\frac{\partial\delta_w}{\partial t} = -m_{pa} + m_c \tag{36}$$

$$\delta_w^+ = \delta_w - \frac{(m_{pa}+m_c)\Delta t}{(1-\partial\varepsilon)\rho_w.a}. \tag{37}$$

The water content of the fruit decreases due to evaporation according to Fick's law or the equation:

$$\frac{\partial M}{\partial t} = -D_{wa}.\frac{\partial^2 M}{\partial x^2} + \frac{1}{x}\frac{\partial M}{\partial x} \tag{38}$$

The energy balance of the air inside the package is a combination of energy entering through the walls of the package, the balance of dry air energy, the balance of water vapor energy, and the energy that goes out through the apple skin. The combined energy balance due to the law of conservation of energy is formulated by the equation (Setiyo et al., 1995):

$$Q_m - h_b.(1-\varepsilon).(T-\theta) - m_v\big(C_v.T + h_{fg}\big) = \rho_a.\varepsilon.(C_v.H + C_a).\frac{\partial T}{\partial t} \tag{39}$$

The solving of the air temperature inside the package by using a numerical method with the equation (Setiyo et al., 1995):

$$T^+ = T + \frac{((Q_m-h_b(1-\varepsilon)(T-\theta)-m_v(C_v.T+h_{fg}))\Delta t}{\rho_a.\varepsilon.(C_v.H+C_a)} \tag{40}$$

The temperature of apple (Setiyo et al., 1995) for 0 < x < x_s and t > 0 is:

$$\frac{\partial\theta}{\partial t} = -\alpha\left(\frac{\partial^2\theta}{\partial r^2} + \frac{2}{r}.\frac{\partial\theta}{\partial r}\right) + \frac{Q_p}{C_p} - \frac{h_{fg}}{C_p}.\frac{\partial M}{\partial t} \tag{41}$$

$$\theta^+ = \theta + (Fo - TTP)\theta_{x-\Delta x} + (1-2Fo+TTP)\theta_x + Fo.\theta_{x+\Delta x} + \frac{Q_{pr}.\Delta t}{C_p} + \frac{h_{fg}.\partial M}{C_p\ \partial t} \tag{42}$$

Material temperature (Setiyo et al., 1995) on x = 0 and t > 0 is :

$$\theta^+ = \theta + 2Fo\theta_{x+\Delta x} + (1-2Fo)\theta_{x=0} + \frac{Q_{p\,r=0}.\Delta t}{C_p} + \frac{h_{fg}\Delta t}{C_p}.\frac{\partial M}{\partial t} \tag{43}$$

The temperature of the apples on the surface of the fruit (Setiyo et al., 1995) is :

$$\theta^+ = \theta + 2Fo(\theta_{xs-\Delta x} - Bi.T) + (1-2Fo-2Bi.Fo))\theta_{xs} + \frac{h_{fg}\Delta t}{C_p}.\frac{\partial M}{\partial t} \tag{44}$$

4.Data Analysis

The data analysis was conducted to secermine the success of formulating a mathematical model in predicting temperature and mass transfer during the cooling and storage of apples in cartons. The analysis was carried out by testing the validity and sensitivity test of the mathematical model.A validity test is done by comparing the temperature of the simulation model results with the temperature data observed during cooling and storage. The analysis of variance, F distribution test, and correlation coefficient (r^2) can be seen the linearity level of the predicted temperature to the observed temperature. The F distribution test for the prediction error (residual) was carried out at a 95% confidence interval.

The sensitivity of the model is tested by examining the effect of changes in the input variable on the output variable. The size of the influence of the input variable can be used to secermine the limits of the validity of the model. The changed input variables are: cooling air temperature, initial material temperature, and initial air humidity. The external variables are the temperature of the material and the moisture content of the material (apples).

5. Results and Discussion

5.1. Preliminary research

Preliminary research on data of mass density of manalagi bulk apples which includes data p = 600 – 650 kg/m^3, ε = 0.3 – 0.456, M = 84 – 89% w.b, Da = 5.0 – 7.5 cm , as well as data for air which includes T = 24.5–28.5 ^{o}C and RH = 70.0 – 85.2% in the storage room. The data on thermic properties of water, air, apples, and cartons used for the simulation of mathematical models of heat transfer and mass transfer during the cooling and storage process of apples in cartons were calculated by using empirical equations developed by experts (ASHRAE. 2006). Data for air which includes: ρ_a = 1,17 kg/m^3, C_a = 1.005 J/kg.^{o}C, k_a= 0,02716 w/m.^{o}C and h_{fg} = 2.478.600 J/kg.The data for water or steam which includes: C_w = 4.187 J/kg.^{o}C, C_v = 1.844 J/kg.^{o}C, D_{wa} = 2,6 x 10^{-10} m^2/sec and ρ_w = 1.000 kg/m^3.The data for the carton is k_m = 0,21 W/m.^{o}C dan h_k = 2,25 W/m^2.^{o}C.

5..2. The temperature of the prediction results of the mathematical model simulation and the temperature of the observed temperature of the apples

Figure 1 and Figure 2 show the temperature of apples, including the results of observations and simulation results of mathematical models developed for the cooling process and the process of storing bulk apples in cardboard packaging. The cooling temperature for bulk apples starts at 20 ^{o}C and ends at 5 ^{o}C for apples at a depth of 30 cm from the surface of the box. The cooling process lasts for 7.5 hours. The simulation of the storage process for bulk apples was carried out for 7.5 hours with an initial temperature of 8 ^{o}Ctothe temperature on the surface of the packaging is 14,^{o}C. this storage temperature meets the optimum requirements (Chitarra & Chitarra (2005). Raghava et al. (2020), conducted a research on cooling some fruitsfor 24 hours to cool the product from 25^{o}C to 5^{o}C.In addition, Figure 4 and Figure 5 also show the difference in temperature from the simulation results of the mathematical model as well as the observations of the apples studied. The temperature difference between the simulation results of the mathematical model and the observed temperature for bulk apples in the cooling and storage processes is -0,5 – 0,5^{o}C with the average of 0,23 ± 0,017^{o}C.

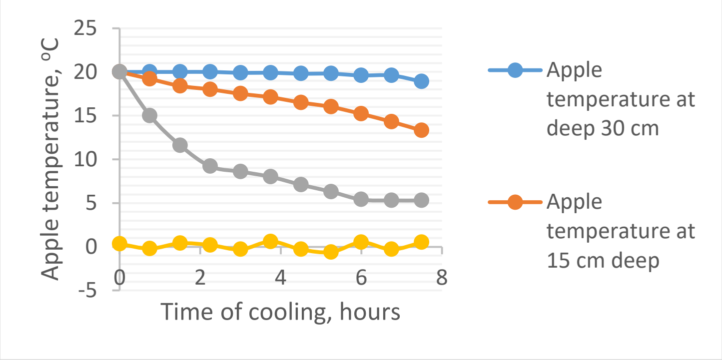

Figure.4. Temperature simulation results of a mathematical model for the cooling process of bulk apples

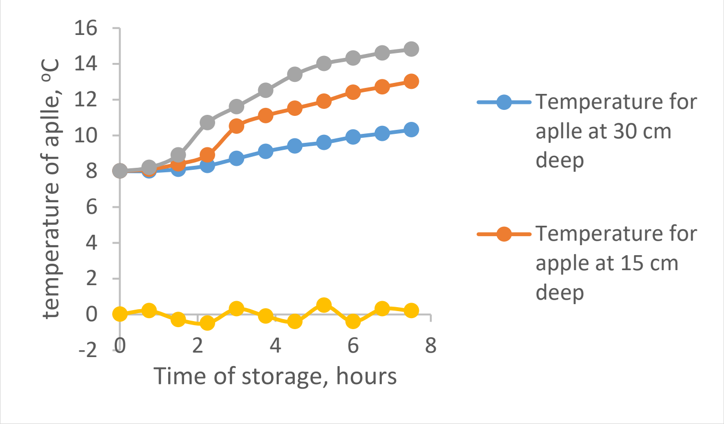

Figure.5. Temperature simulation results of a mathematical model for the storage process of bulk apples

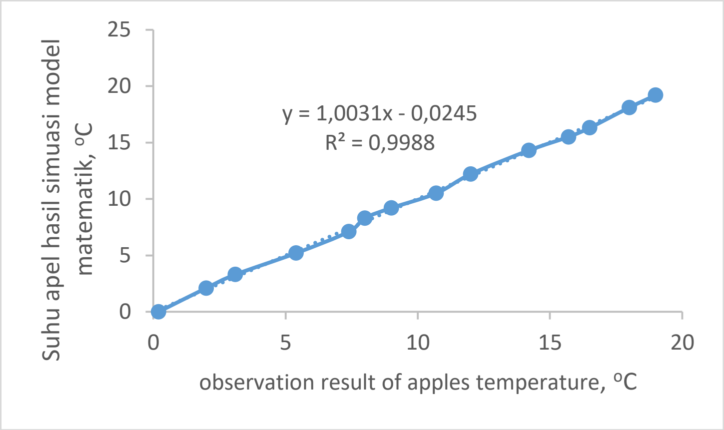

Figure.6. Scatter plot of the temperature of the mathematical model simulation with the observed temperature of bulk apples in the cooling process

The temperature difference value from the simulation model and the observation result is evenly distributed, so from the residual plot test results, it is concluded that the difference value is independent of cooling and storage time and independent of the depth of the observation point. The results of the scatter plot of the temperature of bulk apples are the results of a mathematical model simulation with the observed temperature in the cooling process and the storage process.The relationship is a linear relationship with a gradient of 1.003 and 1.0005, the values of r^2 are 0.98 and 0.99, and the line passes through the centre point (0.0). The condition of the temperature relationship between the simulation results of the mathematical model and the observed temperature proves that

The mathematical model of heat transfer and mass transfer of apples during cooling and storage is valid. In addition to the above, the temperature difference between the simulation results of the mathematical model and the temperature measurement results is independent of the measurement time (t) and the depth of the temperature measurement point (L for the distance in bulk apples). The percentage of temperature prediction errors from the simulation results of the mathematical model developed is between 3.2 – 6.5%. The prediction error value is still below 10% (or a confidence interval of 0.05), therefore the mathematical model is valid.

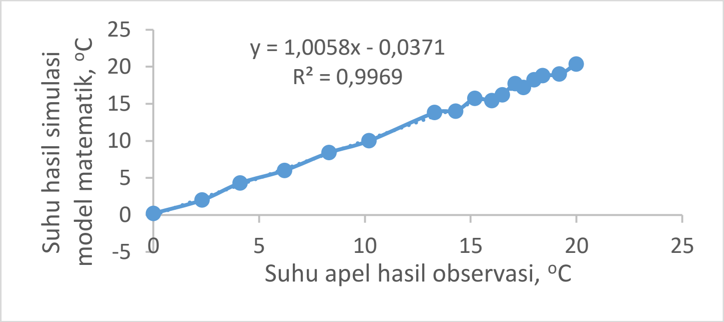

Figure.7. Scatter plot of temperature simulation results of mathematical models with observed temperatures on bulk apples in the storage process

5.3.Energy balance in bulk apples storage

The heat of respiration (Q_r) is approximated by an empirical equation which is a function of fruit temperature (Θ), this equation is written $Q_r = 19{,}4\ e^{0{,}108\Theta}$.The heat of respiration of apples at 5 - 22°C the results of the mathematical model simulation and observation results are as shown in Figure 5. The heat of respiration at that temperature is between 21.23 – 28.32 watts. The process of storing apples as a biological material causes the process of respiration still occurring. In the process of aerobic or anaerobic respiration, apples produce heat, this amount of heat should not be ignored in the storage process because the heat produced causes changes in the temperature in the room and the temperature of the fruit itself. The heat increases the temperature of the fruit which is stored for 7.5 hours from the model simulation results and the average observation is 68.2% or 15.87 watts. The heat to increase the temperature as shown in Figure 5 ranges from 10.05 – 18.20 watts. This value is close to the research results of Meneghett et al. (2013). The amount of heat lost to the environment in a mathematical model using the equation $Q_t = \rho_p.C_p.V.\Delta\Theta$ (Incropera & DeWitt, 1990).

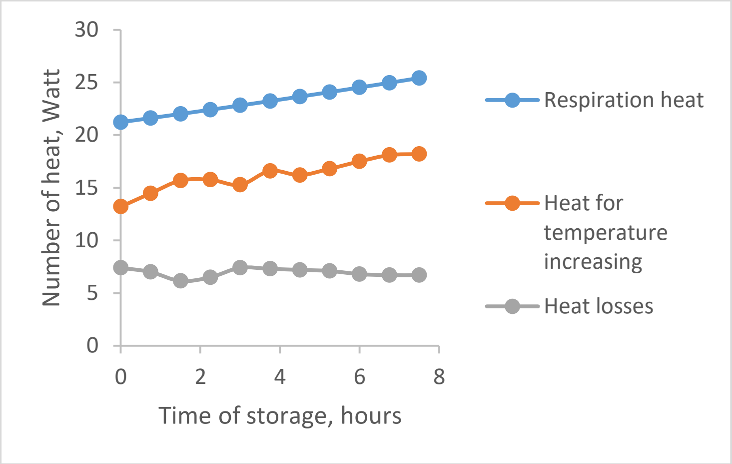

Figure.8. Respiration heat, increases in temperature and heat lost to the environment during storage of bulk apples in carton packaging

The impact of temperature changes is the evaporation and changes in air humidity in the cooling and storage boxes. The heat of respiration is only about 0.17 watts or 0.73% on average to evaporate water from apples to the environment. The heat of evaporation of water vapor on the fruit surface is approximated by the equation $Q_e = m_p(C_v.T + h_{fg})$ (Incropera & DeWitt, 1990), the heat value for the evaporation process varies between 0.12 – 0.21 watts. Based on the energy balance mathematical model simulation, 31.2% of the heat of respiration is lost to the environment. The amount of heat from the bulk apple storage packaging box that is lost to the environment is 6.7–11.2 watts or an average of 7.25 watts for storing apples for 7.5 hours from a temperature of 8 – 14 ^{o}C and the average ambient temperature 26,2^{o}C. The difference between the simulation model of respiration heat, the heat lost to the environment and heat to raise to the temperature with the observed results of -0.4 – 0.3 watts, the value of the difference is independent of the time of observation. Based on this, the mathematical model of energy in storing apples in cardboard packaging is valid in estimating the heat of respiration, heat of evaporation, heat to increase fruit temperature and heat lost to the environment (Ertekin & Yaldiz, 2004; Waewsak et al., 2006)

5.4.Mass balance on cooling and storage of bulk apples

During the cooling process, condensation occurs on the surface of the apples when the relative humidity in the cooling room has reached 100% or the air is saturated with water vapor. The prediction results from the mathematical model simulation developed by the thickness of the condensed water vapor covering the surface of the apple fruit is $1.3 \times 10^{-7} – 2.2 \times 10^{-7}$ m. This happens when the relative humidity at the beginning of the cooling process is 70% and the initial temperature of the air inside the package is 24 ^{o}C, and the cooling air temperature is 2^{o}C. However, during the process of storing bulk apples, the evaporation process from the apples and condensation on the surface of the fruit did not occur. The amount of water evaporated from apples from this study caused fruit loss of 1.64 – 1.71%, which is in accordance with the research of Brown et al. (2007). The process of evaporation from water condensed on the surface to the surrounding air continues to occur, due to the difference in vapor pressure between the two points or the water vapor pressure deficit is greater than zero. For the evaporation from the fruit into the surrounding air occurs when there is a difference in water vapor pressure between the two, and there is no condensation of water vapor on the surface of the fruit. Air humidity in the packaging process of storage and cooling of bulk apples changes due to the process of evaporation and condensation of water vapor. The prediction results from the mathematical model simulation developed, the prediction of air humidity in bulk apples at the end of the cooling process is 0.0052 kg of water vapor per kg of air with an average fruit temperature of 5^{o}C. The results of the prediction of air humidity in the end of the storage process are 0.015 – 0.020 kg of water vapor per kg of air.

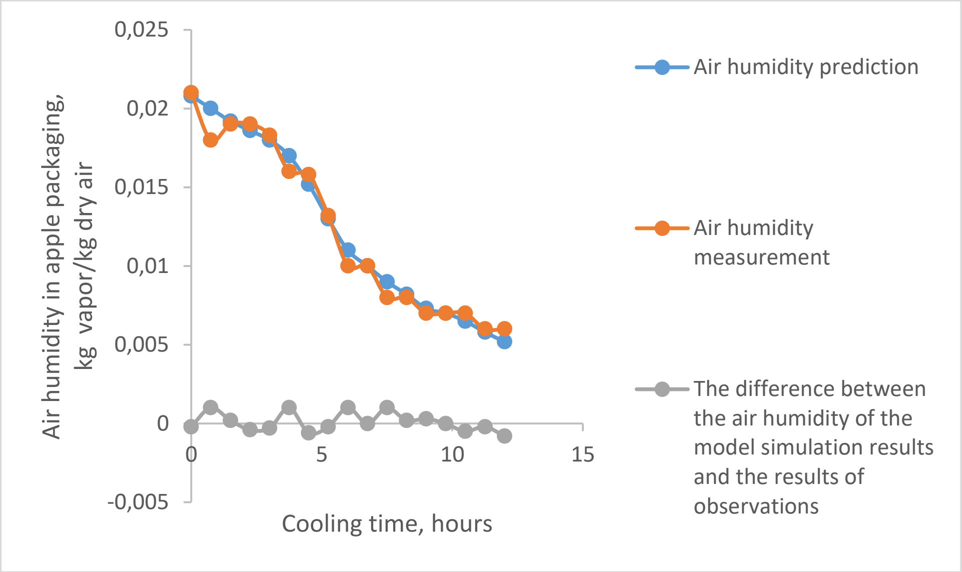

Figure.9. Air humidity in a cardboard packaging for apple cooling process

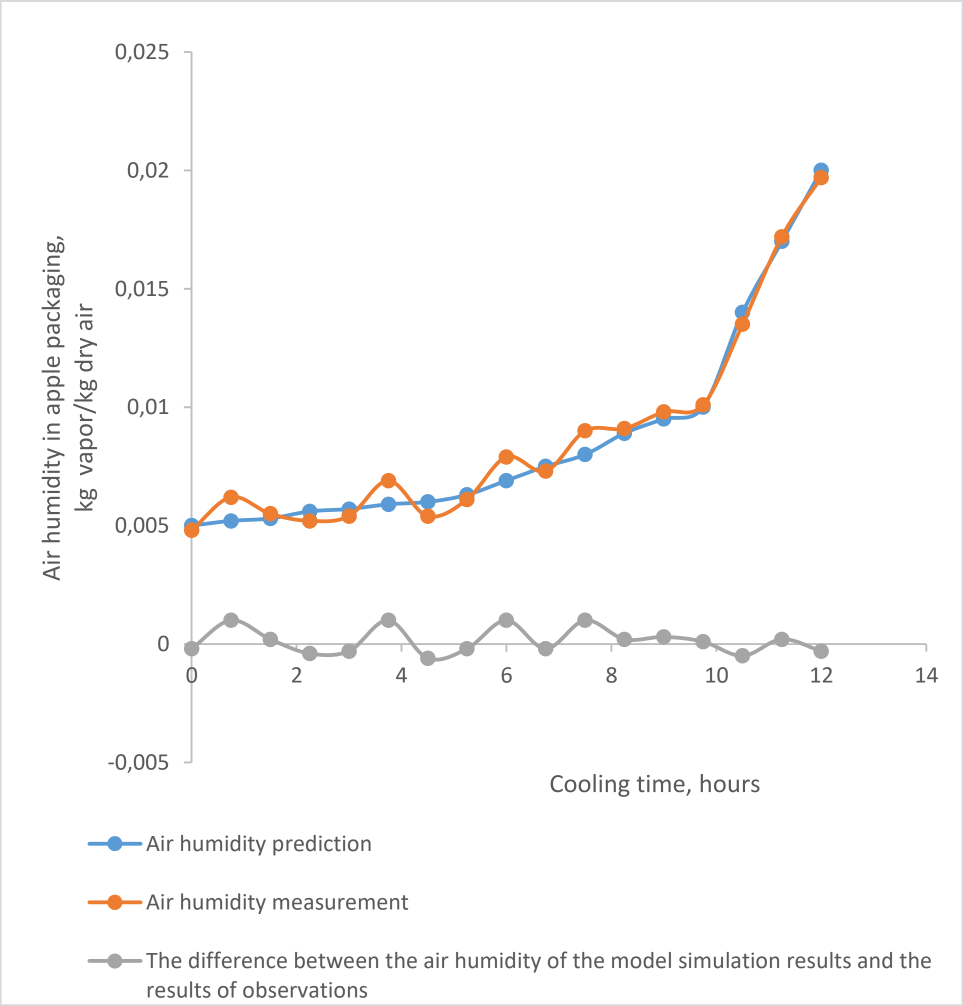

Figure.10. Air humidity in a cardboard packaging for apple storage proses

The results of laboratory experiments at the beginning of measuring the temperature of bulk fruit, air humidity at a temperature of 25.5 ^{o}C is 0.0201 – 0.0208 kg of water vapor per kg of dry air or equivalent to a relative humidity of 85 – 87%. The results of the measurement of air humidity at the end of the experiment for an air temperature of 25.6 °C of 0.0201 – 0.0208 kg of water vapor per kg of dry air. Based on the difference in air humidity from the simulation results of the mathematical model with the measurement results (Figure 6) with an average difference value of 8.82 x10^{-5} kg of water / kg of dry air for the cooling process of apples in the package, while for the apple storage process in packaging (Figure.7) with an average difference of 13.5 x 10^{-5} kg of water/kg of dry air. The results of this study are close to the results of similar studies on cooling Ana apples (Eissa et al., 2017). Based on the difference in air humidity values from the mathematical model simulation with the measurement results and the distribution of the difference in values, the mathematical model to predict the mass balance in the cooling and storage process of bulk apples developed is quite valid. The value of the difference in air humidity between the two is -0.0006 – 0.001 kg of water vapor/kg of dry air.

5.5.The Application of the simulation of the mathematical model of heat transfer and mass transfer of apples during the cooling process and the storage process in carton boxes

Based on the results of the validity test and the sensitivity test of the mathematical model, the results of the mathematical model of heat transfer and mass transfer of bulk apples during the cooling and storage process are valid and have sensitivity to changes in fruit diameter, pile thickness, environmental temperature, environmental humidity and moisture content of the material. The validity and sensitivity of this mathematical model can be used as a reference for the use of mathematical models in the transportation process of apples from Malang to other cities, especially to design the fruit cooling system. In the apple transportation model, the lower cooling temperature limit is 2 °C or the chilling injury point of the fruit and the upper limit for the storage temperature is 15 °C. At temperatures below 2 °C the fruit is damaged, and above 15 °C there is an increase in the speed of the fruit respiration process and causes the fruit to ripen physiologically. The simulation of the cooling model for apples in bulk is illustrated in Figure 11.

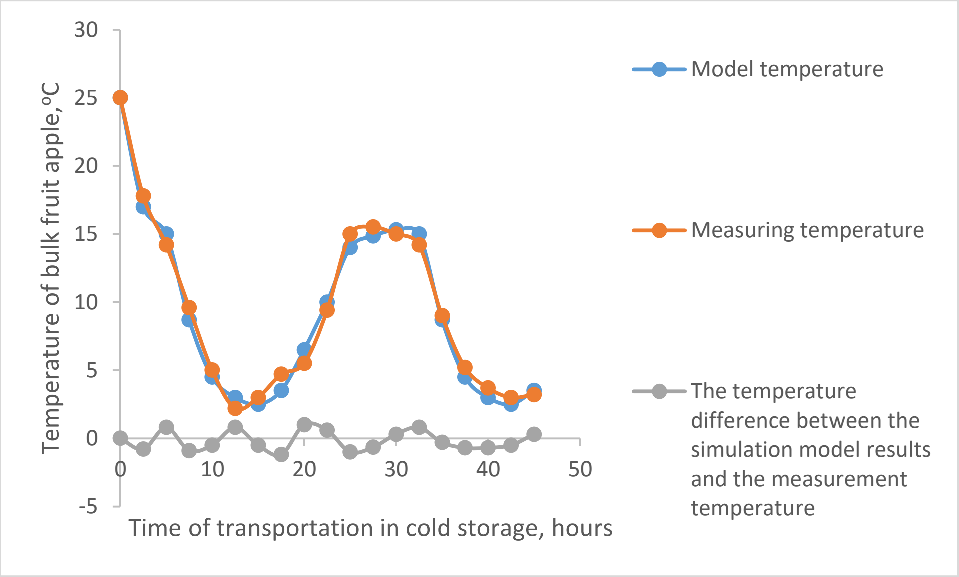

Figure.11. Simulation of cooling and storage temperatures of bulk apples during the transportation process

Figure 11 shows the cooling process for decreasing the temperature to reach 2 °C is 10-12 hours, and the process of increasing the temperature to reach 15 °C apples can be stored for 12-15 hours. Therefore, in transportation for marketing apples, cooling stations are needed in cities that require a travel time of more than 12 hours or make boxes equipped with cooling systems. This is done so that the apples marketed do not experience damage which results in lowering the quality and selling value**.** The results of the study for the delivery of apples from the city of Malang to the city of Yogyakarta with a distance of 383 km or a travel time of 8 hours does not require a cooling system, but if the apples will be sent to Jakarta with a distance of 882 km or 19 hours of travel, a cooling system is needed. For the delivery of apples from Malang to Denpasar requires a travel time of more than 12 hours due to problems at the Ketapang-Gilimanuk crossing, a cooling system during fruit transportation is required. The amount of electrical power to cool bulk apples from 25 °C to 5 °C is 0.032 kWh per kg of apples. The application of the mathematical model for the delivery of apples to marketing places is able to reduce product loss, reduce transportation costs, and optimize the product transportation system. This is also done by Ambaw et al. (2021).

6.Conclusion

Mathematical models of heat transfer and mass transfer for the cooling process and the process of storing bulk apples are very valid to be used to predict temperature and are used to estimate the development of apple cooling systems in the marketing process to other cities. The model for solving the air temperature in the package using a numerical method with the equation:

$$\boldsymbol{T^{+} = T + \frac{((Q_m - h_b(1-\varepsilon)(T-\theta) - m_v(C_v.T + h_{fg}))\Delta t}{\rho_a.\varepsilon.(C_v.H + C_a)}}$$

Apple fruit temperature for $0 < x < x_s$ dan $t > 0$ is :

$$\theta^{+} = \theta + (Fo - TTP)\theta_{x-\Delta x} + (1 - 2Fo + TTP)\theta_x + Fo.\theta_{x+\Delta x} + \frac{Q_{pr}.\Delta t}{C_p} + \frac{h_{fg}.\partial M}{C_p\ \partial t}$$

Material temperature on $r = 0$ and $t > 0$ is :

$$\theta^{+} = \theta + 2Fo\theta_{x+\Delta x} + (1 - 2Fo)\theta_{x=0} + \frac{Q_{p\,r=0}.\Delta t}{C_p} + \frac{h_{fg}\Delta t}{C_p}\frac{\partial M}{\partial t}$$

The temperature of the apples on the surface of the fruit is:

$$\theta^{+} = \theta + 2Fo(\theta_{rx-\Delta x} - Bi.T) + (1 - 2Fo - 2Bi.Fo))\theta_{rs} + \frac{h_{fg}\Delta t}{C_p}\frac{\partial M}{\partial t}$$

The temperature difference between the simulation results of the mathematical model and the observed temperature is between -0.6 - 0.4^{o}C or 3-4.5%, with satisfactory model validity test results.

7.Suggestions

The development of the apples cooling system for the marketing process needs to be done if the transportation of fruit delivery for marketing does not exceed 12 hours.

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