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A CFD Analysis of Core Temperature for Different Durian Paste Packages Layouts during Air-Blast Freezing

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ABSTRACT

Food freezing is a process of crystallising the water particles inside the food and turning it into ice. One of the rapid freezing techniques is known as air-blast freezing. It is a process that rapidly freezes products from chilled or ambient temperature to their desired temperature instantly. SOLIDWORKS Flow Simulation is utilised in this project to analyse the core temperature change for five different durian paste package layouts during the air-blast freezing. There are L1 horizontally single stacked, L2 horizontally double stacked, L3 vertically stacked, L4 fin-like stacked without gaps and L5 fin-like stacked with 3.925 mm gaps. All layouts have a fixed number of 90 durian paste packages per run to ensure consistent and accurate results. These combinations have an initial body temperature of 26°C and were simulated for 240 minutes under an air temperature of -30°C. According to the simulation results, L5 achieved the fastest freezing speed among all five layouts, with a core temperature of 26°C dropping to -20°C in 90 minutes, followed by L3 in 140 minutes, L1 in 150 minutes. Moreover, L5 gives a more evenly distributed temperature around all surfaces with a maximum core temperature after 240 minutes of freezing as it has a higher total surface area to volume ratio, which results in more surface area exposure to cool air. Therefore, L5 fin like-stacked with gaps in between has shown to have more uniform and consistent freezing and advantage in terms of freezing speed.

1. Introduction

Borneo is the third-largest island in the world, and the largest in Asia has tropical rainforests with a wide diversity of fruit tree species. Sarawak is a state within Malaysia located in Borneo with Durian planted areas of 10,714 Hectares, yield areas of 5,741 Hectares and production of 34,650 Metric Tonnes [1]. Durian is forecasted to have a growth production in Malaysia as shown in Table 1. Durian, with its popular name of the “king of fruits’’, has also been regarded as one of the High-Value Commodities (HVC) according to the Malaysian National Agrofood Policy (NAP) 2.0 (2021-2030) [2]. The document mentioned that one of the current challenges is inadequate facilities such as cold storage rooms.

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Sarawak government took the initiative to build the Collection, Processing and Packaging Centre (CPPC) with an intention to help durian farmers and agropreneurs to overcome the loss of profits from glut as well as to establish more agile and resilient value chains with high value-added activities, such as export the frozen Durian and Durian products [3]. The collected durians will be processed into durian paste and pulp, stored in a freezer for preservation, and sold to other countries such as China. This has indirectly embraced greater economic, social and spatial inclusiveness through strengthening the domestic market and producing demand-driven and export-oriented products [2].

Table 1
Forecast of Durian Production for Year 2018 – 2025 [1]

	2018	2019	2020	2021	2022	2023	2024	2025
Self-sufficient level (SSL) (%)	104.8	103.6	103.6	103.7	103.8	103.9	103.9	104.0
Planted Areas (Ha)	70,002	70,286	70,356	70,427	70,497	70,567	70,638	70,709
Harvested (Ha)	45,347	45,192	45,282	45,373	45,464	45,554	45,646	45,737
Production (t)	341,332	377,283	384,828	394,680	404,784	415,146	425,774	436,674
Productivity	7.2	8.3	8.5	8.7	8.9	9.1	9.3	9.5

Food preservation can be accomplished by various techniques such as drying, chilling, and freezing. Freezing, in food processing, is crystallizing the water particles inside the food and turning it into ice. This technique has been used for over 140 years, and the developments in freezing process have helped to overcome the perceived issues with frozen foods [4]. However, large ice crystals may form if the freezing process is long, thus causing damage to the food and affecting its quality and flavour. For example, slow freezing causes large ice crystals to grow through the cell walls of the meat [5], accelerate the oxygen penetrating it [6], lead to undesirable changes in colour and texture [7], such as browning and rancidity of meat, and increase the risk of higher drip on thawing [8]. For this reason, many refrigerated facilities have a blast freezer to minimize the product's frozen time before storing them and maintain their quality.

Air blast freezing is one of the rapid freezing techniques that can maintain the product quality by reducing the size of ice crystals forming inside the product due to a higher number of nucleation points from which ice crystals form [9]. Refrigerated air is used as the heat transfer medium during blast freezing. It is a process that rapidly freezes products from chilled or ambient temperature to their desired temperature through the convection mode of heat transfer and depends on contact between the product and the air. A blast freezer refrigeration system commonly has an evaporating temperature range between -35°C and -52°C. The required freezing temperature for each product differs from one another. For example, fish products usually need to maintain an average temperature of - 30°C [10], while beef products should keep in the range of -18° to -25°C for periods of preservation of one year or more [11]. However, each type of food, each type of fish and each type of meat requires specific conditions.

The food cooling or freezing process involves both heat and mass transfer. Foods that keep inside the refrigerator will experience the flow of energy transfer from the internal body to the outside of the surface through heat conduction and diffusion process. Then heat dissipation occurred from the food surface to the surrounding cold air through heat convection. The airflow inside the refrigeration system removes heat from the food surface and ensures even temperature distribution inside the system [12].

Thermal Properties, such as thermal conductivity, are of major interest during the conduction heat transfer. The thermal conductivity of food depends on three factors which are temperature, composition, and structure. At the same time, foods contain substances such as fat, water, carbohydrate, protein, ash and different volume fractions of air and ice for frozen foods. Carson *et al.,* [4] measured the temperature-dependent thermal conductivities of food substances and found that air has the lowest thermal conductivity, followed by fat, protein, ash, and carbohydrates, which have similar thermal conductivities. These are followed by water and ice, which have even higher thermal conductivity [13].

Forced convection is the primary mode of heat transfer in air-blast freezers, and the refrigerated air serves as the heat transfer medium. The rate of convection heat transfer is expressed by Newton's law of cooling [14]:

$$q = \lambda A(T_s - T_\infty) \tag{1}$$

where q is the heat transfer rate, λ is the surface heat transfer coefficient, T_s is the surface temperature of the food, T_∞ is the surrounding air temperature, and A is the surface area of the food through which the heat transfer occurs.

According to Sarkar & Singh [15], modelling food products during the freezing process has proven to be difficult, which agrees with the statement stated by Hamdami *et al.,* [16] and Sarkar & Singh [15]. This is because the surface heat transfer coefficient depends on the velocity of the surrounding fluid, product geometry, orientation, surface roughness, and packaging, as well as other factors. Therefore, the surface heat-transfer coefficients are determined experimentally or empirically, which expressed as Nusselt number in a function of the Reynolds number and the Prandtl number.

When airflow is fixed and cannot change the cold room equipment, an alternative solution to enhance the heat transfer rate will be changing the contact surface area with air through packaging arrangement. One of the effective ways is to mimic fin structure [17, 18]. The packages can be placed vertically with certain gap in between to enhance the cooling and freezing process. However, there was very limited understanding of the airflow and heat transfer processes for packaging with different layouts in achieving efficient cooling operation.

Hence, the aim of this project is to investigate the effects of packing dimension and arrangement on the thermal profile of durian paste during rapid freezing. A Computational Fluid Dynamics (CFD) model was developed using SolidWorks to analyse the temperature distribution and to determine the time required for the core temperature of the durian paste package to achieve the desired temperature of -20 °C with different packing dimensions and arrangements.

The preliminary results of this research will provide farmers, agropreneurs, agriculture industries and entrepreneurs with an insight into efficient or alternative ways to manage their packaging foods in cold storage and increase the supply of the goods to market. The increased effectiveness of managing packaging foods can boost the supply of products to meet the public demand and provide better quality and safer foods. The increased efficiency of managing packaging foods in cold storage will also reduce the required time to freeze the packaging foods, thus reducing the power usage and leading to energy savings [19].

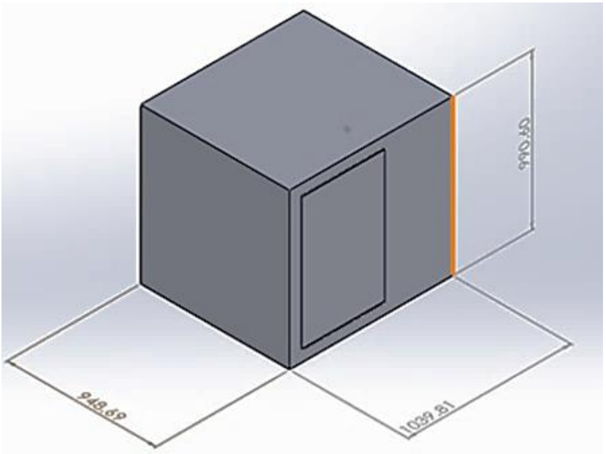
2. Methodology

2.1 Preparation of 3D Models

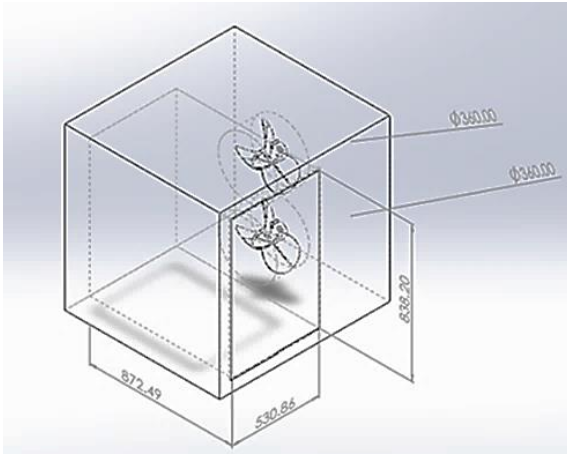
All of the 3D models in this project were prepared by using SolidWorks. The design of the air blast freezer included two evaporator fans (two refrigerated air inlets) and a rack capable of inserting ten trays at most and ten trays for storing the food models. The area of evaporator fans must be adequate to cover the cross-section area of product storage to ensure cooling air has uniform air flow and passes all the product.

For simplification, the design does not include detailed drawings of the evaporator coil, condenser coil, metering tube, compressor and expansion valve. However, the simulation has inserted parameters such as inlet velocity, ambient temperature, etc., to represent these components.

As shown in Figure 1, air blast freezer has an external dimension of 1039.81 mm (L) x 948.69 mm (W) x 990.60 mm (H) and an internal dimension of 530.86 mm (L) x 872.49 mm (W) x 838.20 mm (H). The diameter of the two refrigerated air inlets is 360 mm each.



(a)



(b)

Fig. 1. (a) External body and (b) Internal body of air blast freezer

A 3D model of the rack, as shown in Figure 2, was created. It can insert ten trays at most with a rail of 660.40 mm in length, and the gap between the two trays holder is 76.20 mm in height. The external dimension of this rack is 517.20 mm (L) x 660.40 mm (W) x 800.00 mm (H).

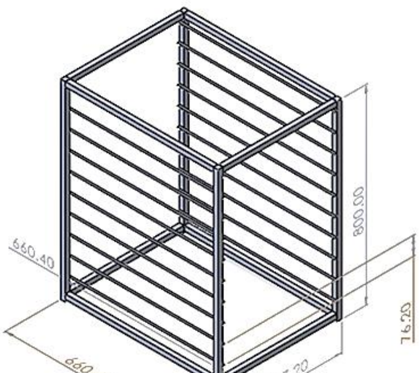
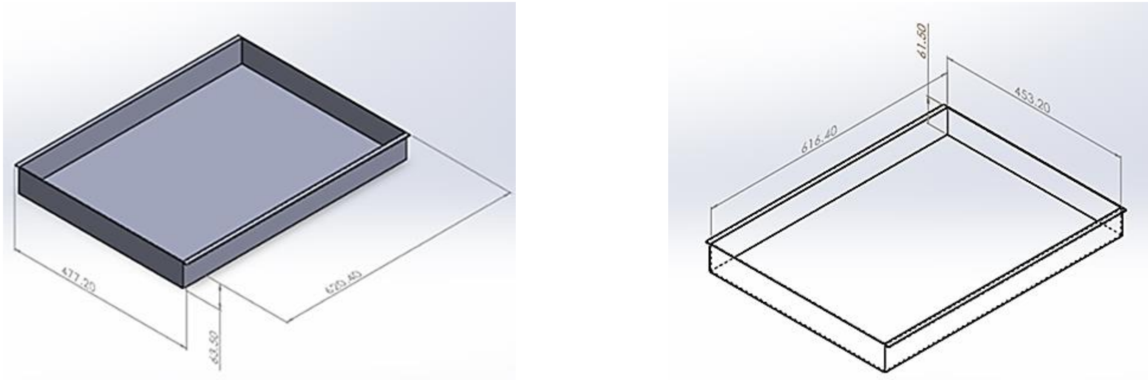


Fig. 2. Food rack of air blast freezer

The 3D models of the tray are shown in Figure 3. This tray has an external dimension of 620.40 mm (L) x 477.20 mm (W) x 63.50 mm (H) and internal dimension of 616.40 mm (L) x 453.20 mm (W) x 61.50 mm (H). A total number of ten 3D tray models had been prepared.



(a) (b)

Fig. 3. (a) External body and (b) Internal body of food tray

Figure 4 is a 3D durian paste package model, and a total number of ninety models was prepared. The durian paste package models have a dimension of 135.00 mm (L) x 195.00 mm (W) x 65.00 mm (H) each.

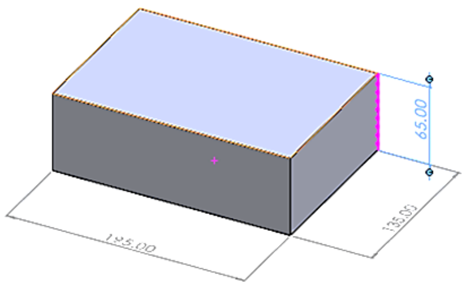


Fig. 4. Durian paste package model

2.2 Setup Different Types of Durian Paste Package Arrangements

The heat transfer for five types of durian paste package arrangements was simulated inside an air blast freezer model to study the transient temperature distribution during the freezing process and to predict the freezing time.

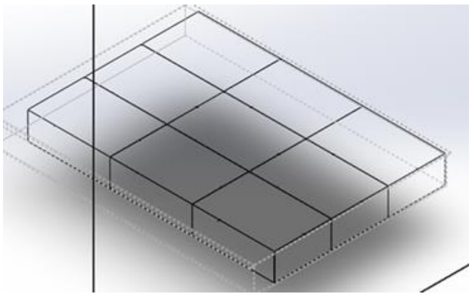
Figure 5(a) shows the L1 packaging layout of durian paste in a tray with nine durian paste packages and ten trays with a total of ninety durian paste packages inside the air blast freezer for simulation. This arrangement is a standard way of sorting due to the easiness of handling.

Figure 5(b) shows the L2 packaging layout of durian paste with eighteen durian paste packages in a tray. With five trays on a rack, give a total of ninety durian paste packages inside the air blast freezer for simulation. This arrangement has two layers of nine durian paste packages stacking each other in a tray.

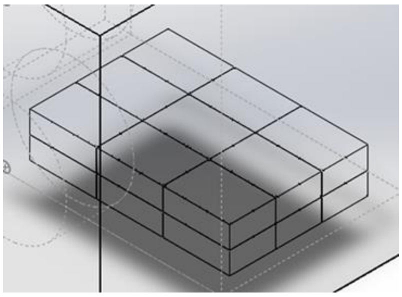
Figure 5(c) shows the L3 packaging layout of durian paste in a tray. There are eighteen durian paste packages with vertical standing arrangements and the largest surface facing the evaporator fan. The rack with five trays of this arrangement gives a total of ninety packages.

Figure 5(d) shows the L4 packaging layout of durian paste in a tray. There are eighteen durian paste packages in a tray and five trays per rack give a total quantity of ninety durian paste packages. This arrangement has eighteen durian paste packages standing vertically, with the smallest surface facing the evaporator fan.

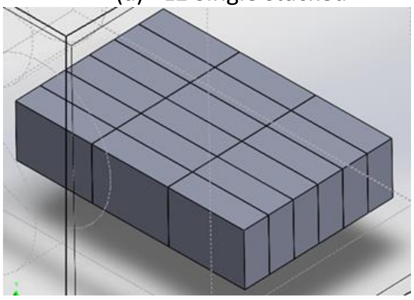
Figure 5(e) shows the L5 packaging layout and arrangement for durian paste in a tray. There are eighteen durian paste packages per tray and five trays per rack, totalling ninety packages inside the air blast freezer for simulation. This arrangement is similar to L4 but with a small gap of 3.925 mm between the two packages. The plate-fin heatsink inspires the idea of this combination.



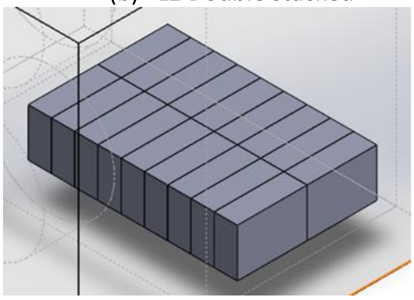
(a) L1 Single stacked



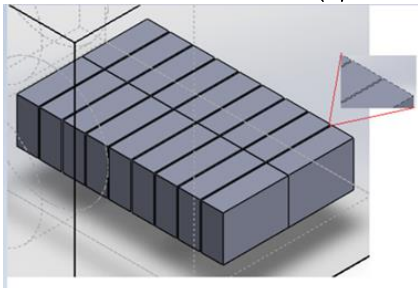
(b) L2 Double stacked



(c) L3 Vertical stacked



(d) L4 Fin-like stacked (without gaps)



(e) L5 Fin-like stacked (with gaps)

Fig. 5. Durian paste packaging layout and arrangement

Table 2 summarises the abovementioned durian paste packaging layouts and arrangements.

Table 2
Description of packaging layout and arrangement

Layout & Arrangement	Packages per tray	Trays per rack	Total packages	Descriptions
L1	9	10	90	Nine packages lie horizontally and place next to each other
L2	18	5	90	Nine packages double stacked, lie horizontally and place next to each other
L3	18	5	90	Eighteen packages stand vertically, with the largest surface facing the evaporator fan
L4	18	5	90	Eighteen packages stand vertically, with the smallest surface facing the evaporator fan
L5	18	5	90	Eighteen packages stand vertically, with the smallest surface facing the evaporator fan and a small gap of 3.925 mm between the two packages

2.3 Mathematical Model

The modelling assumed the durian paste packages are squared-shaped and placed inside a blast freezer with different layouts and arrangements listed in Table 1 and Figure 5.

Continuity, Navier-Stokes, and energy equations govern the air flow and heat transfer in the air blast freezer [20]. With the assumptions of air is Newtonian, incompressible and constant properties fluid, the governing equations for two-dimensional flow can be expressed as:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{2}$$

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial P}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{3a}$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial P}{\partial y}+\rho g_y+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \tag{3b}$$

$$\rho C_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \tag{4}$$

The heat diffusion equation for durian food package is

$$\rho C_{p,f}\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(k_f\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_f\frac{\partial T}{\partial y}\right) \tag{5}$$

At first, the air inside the freezer is calm and in a thermal equilibrium state with an initial temperature of T_0 = 26 °C. Thus,

$$For\ t=0:\quad u=v=0;\qquad T_\infty(x,y,0)=T_0;\qquad T_f(x,y,0)=T_0 \tag{6}$$

The freezer walls were assumed as adiabatic walls, according to a study conducted by Moraga *et al.,* [21]. Furthermore, the modelling had assumed zero mass transfer due to food surfaces having a thin impermeable boundary.

$$\left(\frac{\partial T}{\partial t}\right)_w=0 \tag{7}$$

The continuity condition for temperature can be achieved from the energy balance equation by applying thermal boundary conditions at the interface between fluid and solid, which is represented by Eq. (8) below:

$$k_f\left(\frac{\partial T_f}{\partial n}\right)_s=k_\infty\left(\frac{\partial T_\infty}{\partial n}\right)_s;\qquad T_{f,s}=T_{\infty,s} \tag{8}$$

where k_f is the thermal conductivity of the food, k_∞ is the thermal conductivity of air.

2.4 Parameters Setup and Simulation

After the models were ready, the simulations were carried out by SolidWorks flow simulation, based on the Finite Volume Method (FVM), where the Navier-Stokes equations are solved in a discrete form on a computational mesh.

Firstly, in the wizard section, the analysis type is set to internal analysis only. The physical features included are heat conduction in solids, time-dependent, and gravity of -9.81 m/s2 in the y-direction. The default fluid inside the air blast freezer is set as air with a temperature of -30°C, assuming the air blast freezer was normally operated for 24 hours.

Next, the material of external and internal walls was set as 302 stainless steel with polyurethane insulation material in between. The external wall temperature was set at 26°C, and the wall condition was set as an adiabatic wall with perfect insulation, which means no heat transfer from outside the wall.

Under the Solid Materials section, the rack and trays are set as 302 stainless steel. The new type of material of durian paste was defined with density of 1027.1 kg/m3, thermal conductivity of 0.42 W/m·K, specific heat of 2657.5 J/kg·K for fresh durian paste, 1659 J/kg·K for frozen durian paste, and 217100 J/kg for the latent heat of fusion.

The specific heat and the latent heat of fusion are calculated based on the water content and can be expressed by Siebel's formula as [22]:

$$C_{p,fresh} = 3.35a + 0.48 \qquad (\mathrm{kJ/kg \cdot K}) \tag{9a}$$

$$C_{p,frozen} = 1.26a + 0.48 \qquad (\mathrm{kJ/kg \cdot K}) \tag{9b}$$

$$h_{latent} = 334a \qquad (\mathrm{kJ/kg}) \tag{10}$$

These properties were calculated by taking the moisture content of the durian paste as 65% [23]. In the initial conditions section, the initial temperature of the durian paste and steel tray is set to 26°C, assuming that durian paste and steel trays were taken from room temperature to an air blast freezer.

Next, in the boundary conditions section, the two air inlet velocity is set to 12.287 m/s with a temperature of -30°C. The default pressure is set the same as atmospheric pressure.

Finally, the runtime of the simulation was set to 240 minutes of physical time and recording the data with every minute of physical time.

3. Results

The following results are generated by the SolidWorks flow simulation that was simulated for 240 minutes of physical time.

3.1 Air Velocity Distribution Inside Air Blast Freezer

Figure 6 shows the streamlines for the flowing air in the air blast freezer with different durian paste package layouts. Based on the velocity distribution shown in the figure, air velocity has a higher concentration near the air inlet, middle region, and lower region. This is because cold air has a denser density than warm air so the air will flow from the middle to the lower region. In addition, the airflow in the back row has the lowest velocity as the durian paste packages in the front row act as obstacles blocking the air passage, thus slowing down the air movement.

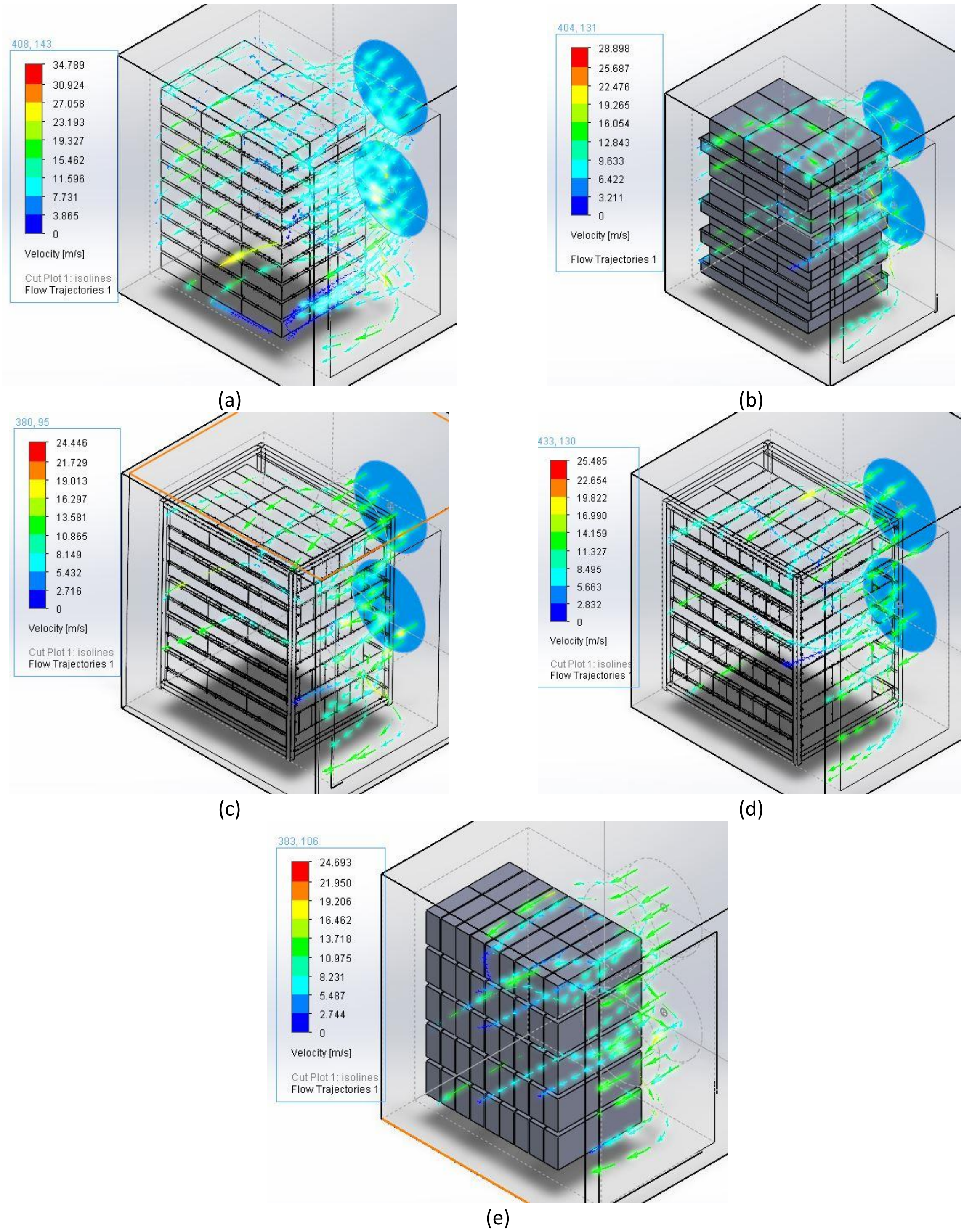


Fig. 6. Air velocity distribution in streamline format for (a) L1 single stacked (b) L2 double stacked (c) L3 vertical stacked (d) L4 fin-like stacked with no gaps (e) L5 fin-like stacked with gaps

Figure 7 shows the velocity flow field in the air blast freezer with five different durian paste package arrangements. It can be seen that the airflow through the L5 fin-like stacked durian paste packages layout still can achieve a velocity of about 13.718 m/s somewhere in the middle row and about 10.975 m/s near the end row. L1 single stacked and L4 fin-like stacked with no gap show a similar result of maximum velocity of 11.596 m/s and 11.327 m/s, respectively. It can also be clearly seen that the L2 double stacked layout will block the air passage and hence impede the convection heat transfer from the food package to the surrounding air.

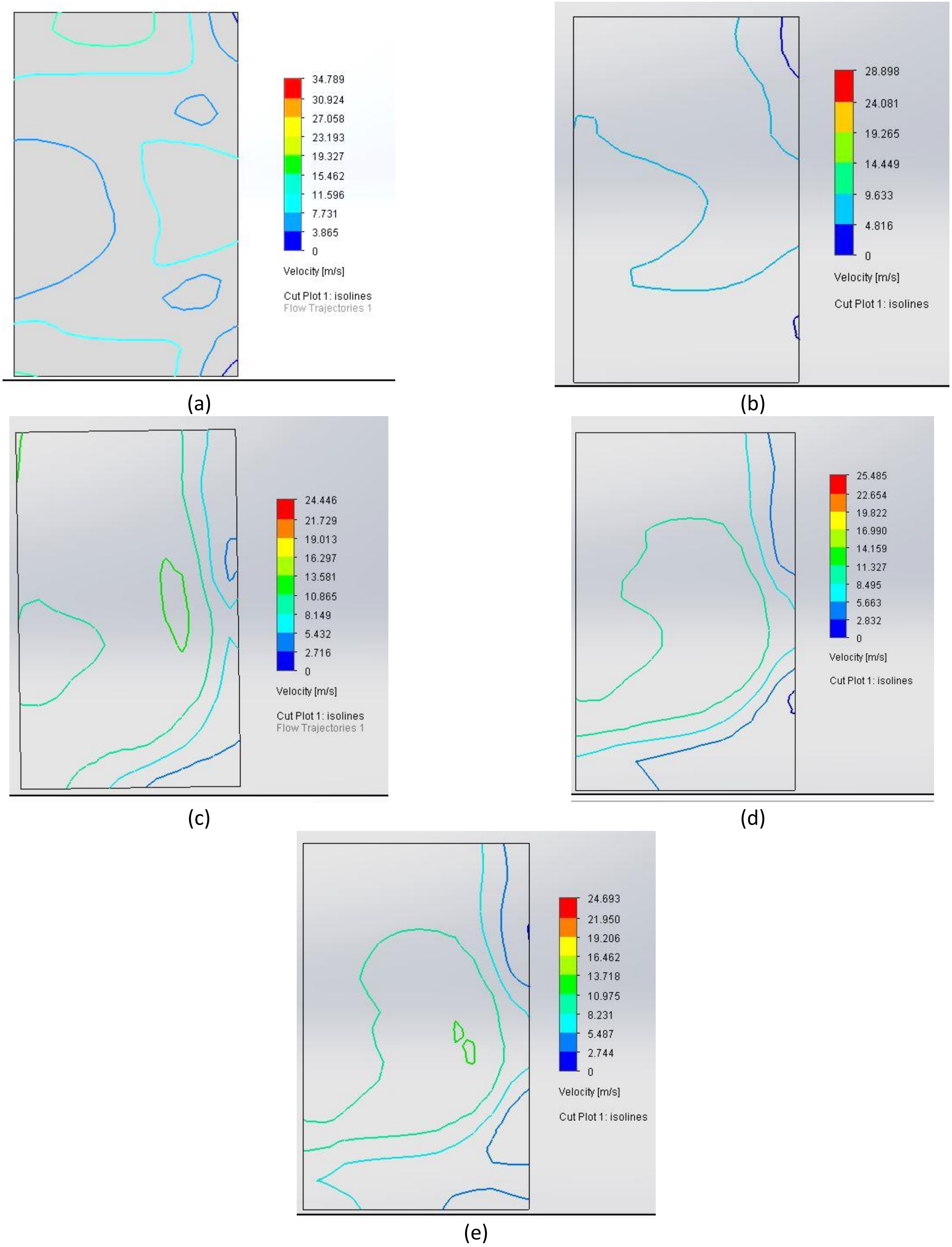


Fig. 7. Velocity flow field for (a) L1 single stacked (b) L2 double stacked (c) L3 vertical stacked (d) L4 fin-like stacked with no gaps (e) L5 fin-like stacked with gaps

3.2 Air Temperature Distribution Inside Air Blast Freezer

The initial air temperature inside the air blast freezer was set at -30°C, the same as the inlet air temperature. During the 240 minutes of operations, the air temperature has risen as it absorbs the heat from the product inlet temperature of 26°C. Nevertheless, the overall internal air temperature shows quite a uniform temperature of -30°C after 240 minutes of operations.

Figure 8 shows that the air temperature inside the air blast freezer has been maintained below -25°C. Figure 9 further indicates the location of the highest and lowest air temperature, where the overall air temperature is below -26°C, with the highest temperature of -26.62°C and the lowest temperature of -30.28°C.

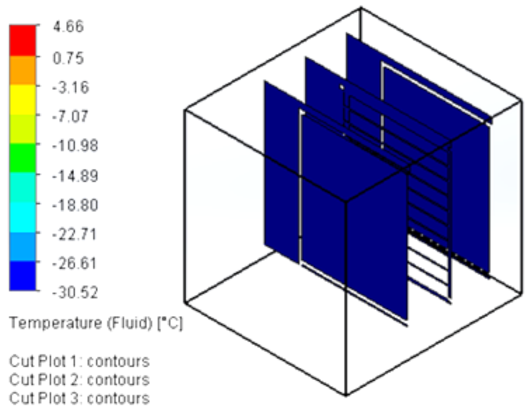


Fig. 8. Air temperature distribution in contour format

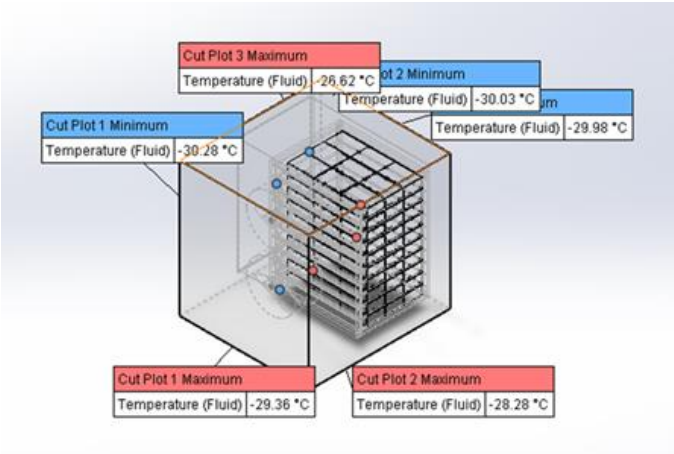


Fig. 9. Location of the highest and lowest air temperature

3.3 Temperature Distribution of Durian Paste Packages

Figure 10 shows the contour image of temperature distribution on the surface of durian paste packages with different arrangements. It can be seen that the temperature distribution for all layouts except the L3 vertical stacked layout near the air inlet was cooled down to below -20°C, which is the targeted temperature. However, after 240 minutes of the cooling period, some regions in the back row still do not cool down to the targeted temperature.

L4 fin-like stacked with no gaps in between shows similar temperature distribution as the L1 single stacked layout with a higher temperature region concentrated at the back row. However, the exposure area to refrigerated air of the L4 layout is smaller compared to the L1 layout, which is placed horizontally on the tray. Also, the L4 layout has higher conduction resistance because the thickness from the exposure surface to the core is greater compared to L1.

Even though the L2 double stacked layout has a slightly bigger gap between each tray for air to flow to the back and with most of its surface temperature lower than the L3 layout. It will have to take longer for L2 core temperature to reach the targeted temperature as double-stacked gives a thicker layer and greater conduction resistance.

Among all five durian paste package layouts, L5 fin-like stacked with gaps in between gives the best temperature distributions with quite an even temperature distributed over all surfaces, including the back row. The gaps between rows and columns make air flow easily through all durian packages, and hence more surface area is exposed to refrigerated air to enhance the convection heat transfer.

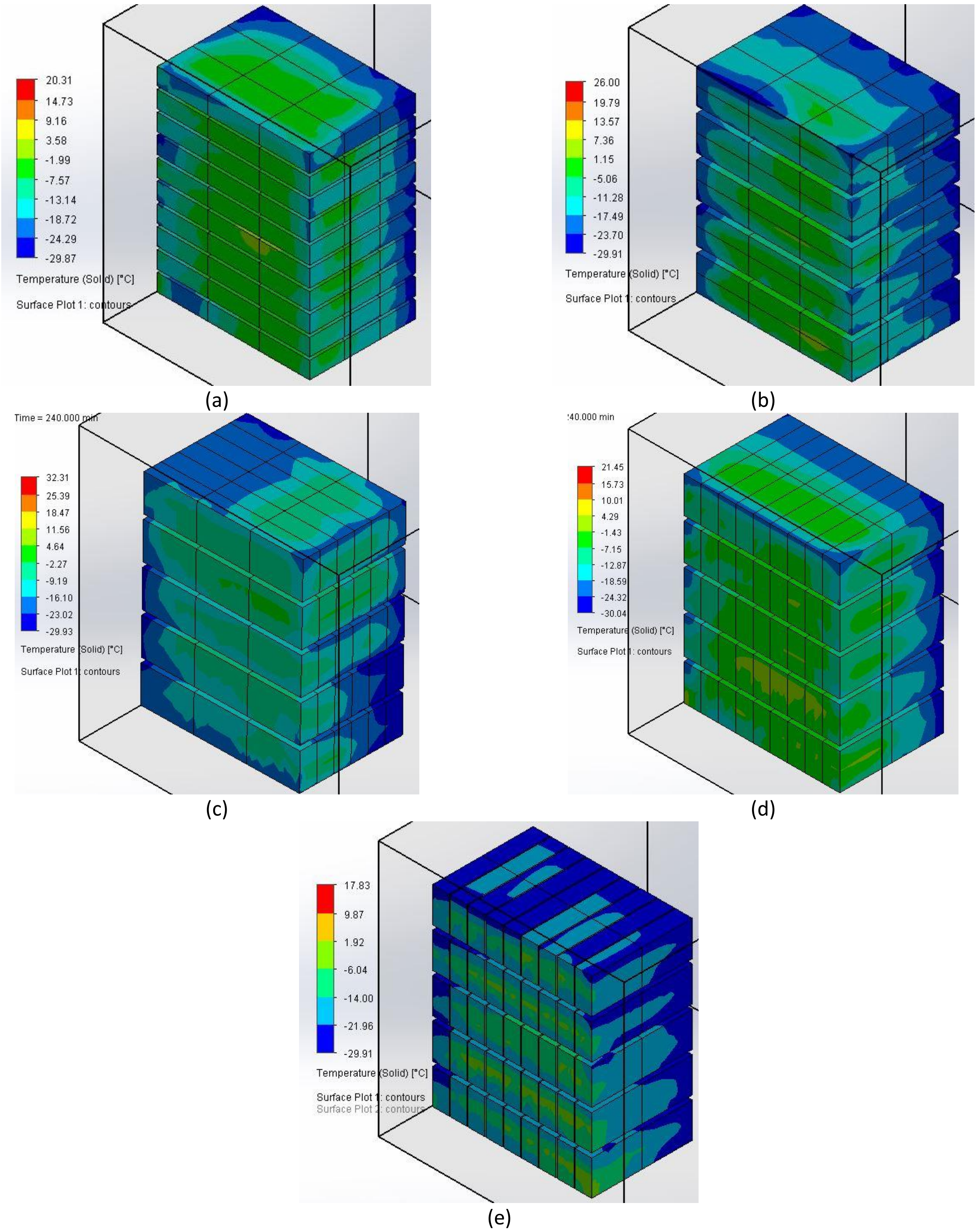


Fig. 1. Surface temperature distribution of durian paste packages in (a) L1 single stacked (b) L2 double stacked (c) L3 vertical stacked (d) L4 fin-like stacked with no gaps and (e) L5 fin-like stacked with gaps

3.4 Minimum Core Temperature of Each Layout

Durian flesh is estimated to have about 65% water content depending on the species [20, 21], and the freezing process converts most of this water into ice. Freezing requires heat removal, and Durian temperature will drop during the first cooling stage. The temperature will fall fairly rapidly to just below the freezing point of water. As more heat removal is required to turn the bulk of the water to ice, the temperature will stay constant or changes by a few degrees during the second stage of cooling, which it went through the latent heat of fusion or known as the period of "thermal arrest". When most of the water is turned to ice, the temperature begins to fall and freeze the remaining portion. A comparatively small amount of heat has to be removed during this third cooling stage.

Figure 11 shows the temperature changes at the coldest point for each Durian paste package arrangement layout during 240 minutes of freezing. The graph shows that L5 can achieve the lowest core temperature of nearly -27°C after 240 minutes of freezing, followed by L1, L3 and L2, which have almost identical temperatures in the range of 22-24°C. At the same time, L4 has the highest temperature of -17 °C among all five layouts with a significant difference and does not achieve the targeted temperature of -20°C.

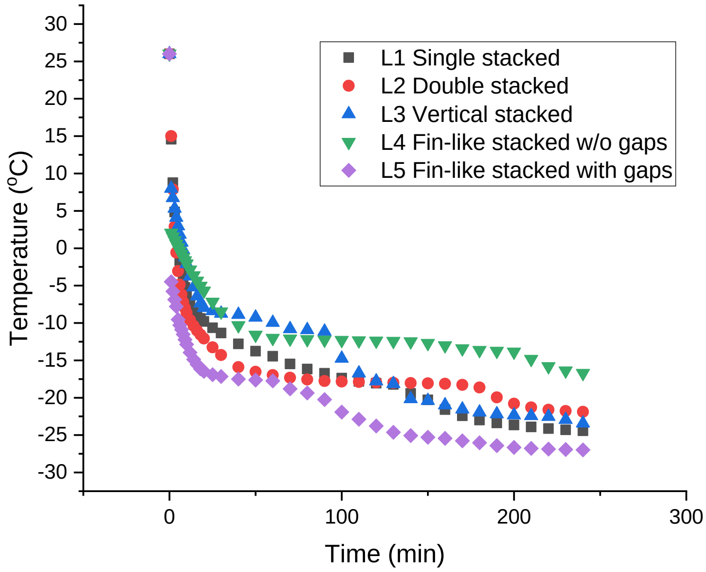


Fig. 11. Minimum core temperature of durian pastes during 240 minutes of freezing

The time each layout took to reach -20°C was also compared. For L5, it took only about 90 minutes to get -20°C. At the same time, L3 took 140 minutes, followed by L1, which took about 150 minutes, and L2 took 200 minutes, whereas L4 could not achieve the targeted temperature even after 240 minutes. These results show that L5 required the shortest duration to reach the targeted temperature of -20°C, while L4 required the most extended period to achieve the desired temperature.

The use of refrigeration for food preservation is commonly used in most countries. However, cooling and freezing methods can consume a lot of energy which uses up to 30% of electrical energy in the EU food industry [24, 25]. Hence, by changing the arrangement of the durian paste package in the air-blast freezer can help to reduce time required to freeze the product. This also demonstrated that energy savings were achievable by arranging the food product in air-blast freezer with L5 layout.

3.5 Maximum Core Temperature of Each Combination

Figure 12 below shows the highest temperature changes for each durian package arrangement layout during 240 minutes of freezing. The graph shows that L5 and L1 have almost the same maximum temperature of nearly -2.7°C and -2.4°C, respectively, after 240 minutes of freezing. L3, L4 and L2 followed it with temperatures close to 0°C. Based on the results, L5 and L1 have much more consistent and uniform freezing over all durian paste packages than others. This is because L1 and L5 have greater surface area exposure to refrigerated air and achieve a higher freezing rate.

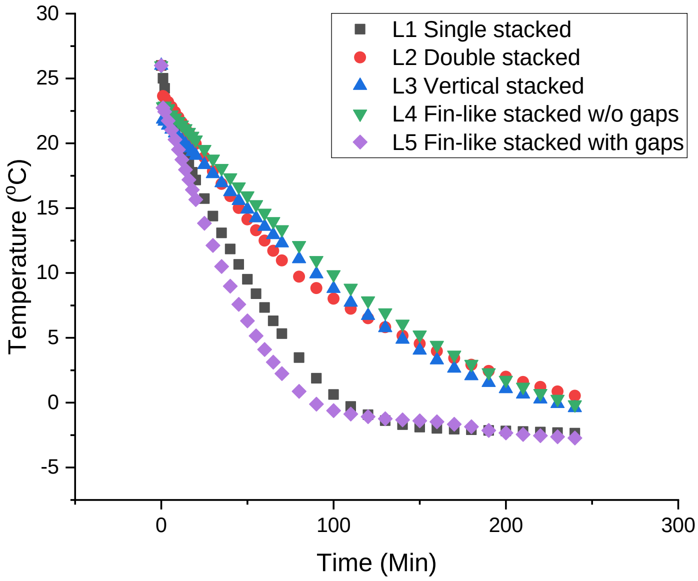


Fig. 12. Maximum core temperature of durian pulps during 240 minutes of freezing

The sample size of the current simulation is only 90 durian paste packages for each batch. Suppose the sample size grows over hundreds or thousands of durian paste packages in each batch. In that case, the total time for all the durian paste packages in the L5 layout to reach below -20°C could be significantly faster than in L1. This is because the difference in total surface area to volume ratio for both L1 and L5 layouts will continue to grow, and the quantity of durian paste packages will also increase in each batch.

From simulation results, it is well understood that the durian paste package layout significantly affects the thermal profile during rapid freezing. However, SolidWorks has a limitation in simulating the latent heat of fusion. Hence, other simulation software with the latent heat of fusion setting is recommended for food freezing simulation.

4. Conclusions

In conclusion, the Computational Fluid Dynamics (CFD) model was successfully developed using SolidWorks. The velocity distribution in the air blast freezer is much more concentrated in the region near the front row, middle and lower region. At the same time, the temperature distribution of durian pulps shows the lowest surface temperature at the front row, while highest temperature at the back row. After undergo 240 minutes of freezing process, L5 fin-like stacked arrangement gives the best results of shorter freezing time and has a more uniform temperature distribution as it has greater area expose to the surrounding cool air which obeys the Newton's law of cooling.

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