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Half-cooling time of cabbage stored in a refrigerated room

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Abstract: Cabbage heads stored in containers in a high-capacity cooling room were evaluated by the half-cooling times. The temperature of the heads and the surrounding air in their immediate vicinity was measured by a puncture thermometer. The shortest half-cooling times were measured in the immediate vicinity of the evaporator; in contrast, very long half-cooling times were measured in a container on the opposite side of the cooling room. The measured values were longer by one order of magnitude. When cabbage heads are inside the container furthest from the evaporator, without being covered by a layer of stacked containers, then the heat transfer passes directly into the ambient air, thus, the half-cooling times in this container were not the longest. The head cabbage cooling, evaluated by the half-cooling time (in hours) and the end of cooling time (in hours), in the chambers to a storage temperature (0 °C) are directly proportional. The heads in a container 14 m from the evaporator, in the bottom position, but not covered by other containers had a half-cooling time of 194.7 hours, with a total time of 973.5 h, because the air circulating around the container, permanently cooled down the stored heads. The total calculated cooling time will be extended 5.0 times. For the heads in the same position, but 7 m from the evaporator, the heat dissipation at the bottom position was so slow that the half-cooling time was 225 hours, and the total time was 1 125 hours (46.88 days), which was the longest cooling time for the cabbage heads.

Kewords: head cabbage; refrigeration; distance of container from evaporator

Cabbage produce is usually cooled to its long-term storage temperature in special facilities designed to rapidly remove produce heat (Fricke 2006). Cabbage should be cooled as soon as possible after harvest to preserve its quality and reduce wilting. If cabbage is harvested under cool conditions, it can be placed in storage and cooled without pre-cooling (Sargent et al. 1988; Thompson et al. 1998; Beaudry 2000; Geeson, Browne 2018).

Room cooling is accomplished by placing warm produce in a refrigerated room. The heat load must be removed quickly, no matter which cooling technique is used. Cooling times are at least 24 h and can be much longer if the produce is not packaged correctly. Field heat can cause the rapid deterioration of some horticultural crops, and it is, thus, desirable to remove this heat as quickly as possible after harvesting. For head cabbage, there is no time limit between cooling and harvest. The rate of cooling the produce depends on many factors, including the rate of the heat transfer, the difference in the temperature between the produce and the cooling medium, the thermal properties of the produce and the packaging and stacking arrangements (Thompson 1996). The aim of this project was to assess the half-cooling time of the temperature of head cabbage and the ambient air in the containers stored in a highcapacity cooling room. Using these criteria, the cooling of the heads placed in the containers on the top, in the middle and at the bottom of the stacks were measured. Further, the values of the half-cooling time were obtained for the containers that were well defined by their distance from the evaporator.

https://doi.org/10.17221/136/2018-HORTSCI

MATERIAL AND METHODS

The cabbages were harvested when the heads were firm and heavy, and the size was appropriate for the market. The squeakiness of the leaves when rubbed together can be considered a sign of freshness. The outer leaves were trimmed so that they would not interfere with air circulation between the heads but continued to provide some protection against the physical damage and water loss. The cabbage was harvested by hand and inspected, sorted and graded in the field. Heads with yellow leaves or mechanically damaged leaves were not be stored. The filled containers were loaded onto a trailer for transport to the storage warehouse. The produce was simply loaded into a cold room, and cold air was circulated around the stored containers. The total heat load from the product, its surroundings, the air infiltration from the containers, and the heat production from the respiration of the harvested cabbage was converted in the evaporator. After the cooling phase, the temperature in the storage room was maintained at 0°C with 94–98% relative humidity. The refrigerated storage temperatures minimized the respiration, thus, decreasing the heat production. A space between containers of 10–15 cm was sufficient to allow cold air to circulate around the individual containers. Produce in vented containers will cool much faster than produce packed in un-vented containers. If the produce is loaded into the room so tightly that cooling cannot take place at all, the refrigeration never attains the recommended levels. The cold air velocity in the space between the containers was measured at 0.31–0.42 m/s by a PL135HAN hand Thermo-Anemometer.

Calculation of the half-cooling time. The measurement of this parameter always took place in a container with the preloaded heads in three layers (on top, in the middle and at the bottom). The head temperature was measured with a precision of 0.1 °C by a puncture thermometer at one-third of the diameter of the head from the surface. The measurement was carried out after cooling the container to a final temperature of 0 °C. The air temperature was also measured in the space between the heads on the same layer. The distribution of the containers in the cooling room is shown in Tables 1 and 2 and Figure 1.

Table 2. The half-cooling time for the bottom container at the end of cooling chamber No. 3. No containers were stacked above this one

Position of measurement in container	Position 1 × 14 m	
	$\tau_{1/2}$ of head in container (h)	$\tau_{1/2}$ of air in container (h)
– on the top	89.3	60.7
– in the middle	178.3	130.9
– at the bottom	194.7	147.1
Mean	154.1	112.9
Standard deviation	56.7	45.9

Warehouse in Mlekojedy has 4 cooling chambers. You can compare parameters of each cooling chamber in Table 3.

Formula for the half-cooling time:

$$\tau_{1/2} = \frac{\ln 2}{a} \qquad a = \frac{\ln t_0 - \ln t_1}{days}$$

where: $\tau_{½}$ – half-cooling time (h); t_0 – initial product temperature (°C); t_1 – final product temperature (°C); days – number of days from the initial product temperature to the final product temperature.

Calculation the evaporator cooling capacity. The cooling capacity of the evaporator – Equation (5) is calculated from the mass of the air circulating (kg/s) in the evaporator – Equation (4) and the differences between the enthalpy of the incom-

Table 1. The half-cooling time for the different positions of the containers with heads near the evaporator and in the middle of cooling chamber No. 3

Position of measurement in container	Position 4 × 1 m		Position 1 × 7 m	
	$\tau_{1/2}$ of head in container (h)	$\tau_{1/2}$ of air in container (h)	$\tau_{1/2}$ of head in container (h)	$\tau_{1/2}$ of air in container (h)
– on the top	22.6	6.7	183.0	150.4
– in the middle	31.2	11.5	198.0	160.5
– at the bottom	37.8	21.5	225.0	178.3
Mean	30.5	13.2	202.0	163.1
Standard deviation	7.6	7.6	21.3	14.1

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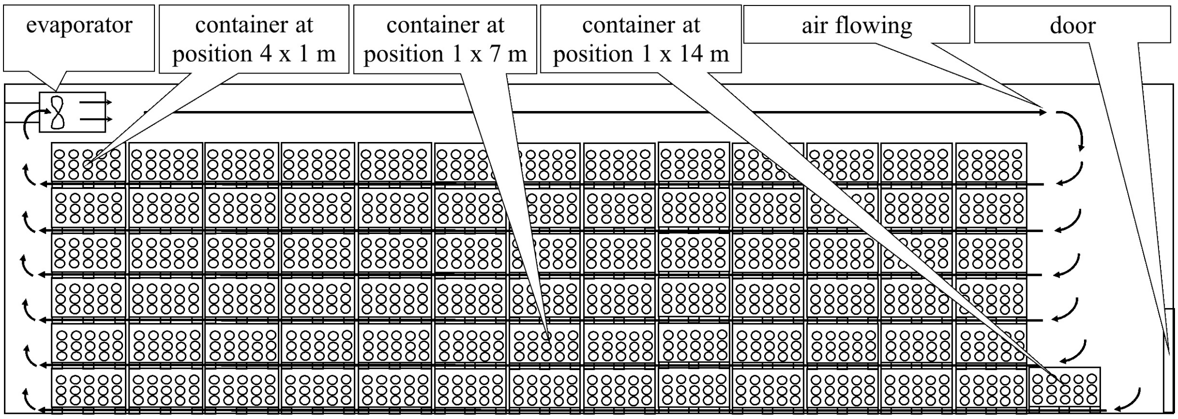

Figure 1. The air flow in cooling chamber No. 3

ing air – Equation (1) (kJ/kg) and outgoing air Equation (2) (kJ/kg). The resulting enthalpy is the sum of the thermal capacity of the dry air in Equation (1) (kJ/kg) and the humid air in Equation (2) (kJ/kg). The calculation of the enthalpy for the dry and humid air was performed separately.

Calculation the enthalpy of the incoming air:

$$i_E = c_p \times t_E + x_E (2\,501 + c_p' \times t_E) \quad \text{(kJ/kg)} \tag{1}$$

Calculation the enthalpy of the outgoing air:

$$i_A = c_p \times t_A + x_A \times (2\,501 + c_p' \times t_A) \quad \text{(kJ/kg)} \tag{2}$$

The rate of the air volume coming into the evaporator:

$$\dot{V} = s \times \omega \quad (\text{m}^3/\text{s}) \tag{3}$$

The mass of the air coming into the evaporator:

$$\dot{m} = \dot{V} \times \rho \quad \text{(kg/s)} \tag{4}$$

The cooling capacity of the evaporator:

$$\dot{Q}v = \dot{m} \times (i_E - i_A) \quad \text{(kW)} \tag{5}$$

where: i_E – enthalpy of the incoming air; i_A – enthalpy

Table 3. The power of the evaporators in the cooling chambers for storing cabbage

		Designation of cooling chamber			
		No. 1	No. 2	No. 3	No. 4
Cooling power of the evaporator	kW	67.1	11.3	8.7	25.5
Velocity of air flowing from the evaporator	m/s	17	3	5	6
Temperature of inlet air	°C	6	4.5	9	6
Enthalpy of inlet air	kJ/kg	19.8	17	26.1	19.9
Temperature of exhaust air	°C	5	2.4	8	5
Enthalpy of exhaust air	kJ/kg	18.6	13.8	24.8	18.6
Chamber area	m^2	144	84	168	267
Chamber volume	m^3	806	470	941	1 494
Number of containers in cooling chamber	No.	702	360	810	1 242
Weight of heads in cooling chamber	t	210.6	108	243	372.6
Height of cooling chamber	m	5.6	5.6	5.6	5.6
Cooling power per tonne of heads	kW/t	0.32	0.1	0.04	0.07
Cooling power per container with heads	kW/container	0.1	0.03	0.01	0.02
Refrigeration capacity per 1000 m^3	kW/1 000 m^3	83.3	24.3	9.2	17.1
Hours needed to cool air in chambers	h	20.8	63.7	186.2	97.4

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of the outgoing air; c_p – specific heat of the dry air (constant 1.005); t_E – temperature of the incoming air (°C); x_E – specific humidity of the saturated air (g/g); $c_p{'}$ – specific humidity of the water vapour (constant 1.84); t_A – temperature of the outgoing air (°C); x_A – outgoing air humidity; $\dot{V}$ – rate of the air volume coming into the evaporator (m^3/s); s – evaporator discharge port area (m^2); ω – air velocity (m/s); $\dot{m}$ – mass of the air coming into the evaporator (kg/s); ρ – density of the saturated air coming from the evaporator (kg/m^3); $\dot{Q}v$ – cooling capacity of the evaporator (kW).

Refrigeration capacity. By using room cooling, produce can be cooled and subsequently stored in the same place, without re-handling and with no special facilities needed for cooling operations. Warm products placed in a refrigerated storage unit cool quite quickly if they have direct exposure to the cold air. Packed produce can be cooled in about 24 h if packed in vented containers. The vents are aligned between the boxes when the boxes are palletised, and the pallets are spaced 10–15 cm apart (Guillou 1960). The floor area of the refrigerated store unit is calculated for the maximum amount of cabbage heads stored in plastic containers with the ventilation spaces on the bottom and sides. The containers were longitudinally situated to the air flow coming out of the refrigerator units, and were stacked in six containers to a row, with the storage height is usually about 4.2 m. Adequate airflow was needed to distribute the refrigerated air throughout the storage rooms in order to maintain uniform air temperatures. The cold storage rooms were designed to have an air flow capacity of 0.3 m^3/min/t of stored product (Thompson et al. 1998). In the case of the cabbage heads being stored in the individual storage rooms; this requirement was abundantly fulfilled. According to this author, the desired temperature will be reached within a few days to about 1 week after filling the storage room. The actual airflow can then be reduced to about 20–40% of the design capacity and still maintain adequate temperature uniformity. This can be done by the intermittent operation of the fans, or by keeping the fans constantly on, but reducing their speed with an electronic speed control system. Slow air speeds reduce the moisture loss from the product (Kroca, Hellickson 1993). The airflow was distributed uniformly throughout the cold room in order to minimise the temperature variability. The products loaded in the containers were cooled by the airflow which was distributed according to the following pattern: air flows from the evaporator on the top to the opposite wall and then comes back through the containers to be sucked in by the evaporator. The determination of the refrigeration capacity of the cool room was based on estimating the heat input into the cold storage from the uncooled product, the product respiration, the heat conduction through the walls, floors, and roof, the air infiltration through the doors, lights, motors, equipment, and the personnel (Wennberg et al. 2002; Suojala 2003; Taniwaki et al. 2009). Cold room designers make estimates based on the aforementioned thermal sources and then add 20–30% extra capacity as a safety factor. The fundamental rule for refrigerated produce storage is that 10–14 kW of refrigeration capacity is required per 1 000 m^3 of storage volume. The equipment of this cooling system included refrigerated shipping docks requiring 14–25 kW per 1 000 m^3. A vapour recompression method called mechanical refrigeration was used in the equipment for this cold storage. The temperature difference between the inflow and outflow from the refrigerator should be at least 5 °C, ensuring a high RH (relative humidity). A uniform temperature was maintained by having an adequate refrigeration capacity, a uniform air distribution, minimising the temperature difference between the evaporator coil and the air temperature, and a precise temperature control system. A high RH of 85–95% was needed to reduce the product moisture loss.

Estimation of the half-cooling time. The empirical cooling time estimation used a fractional unaccomplished temperature difference. All the cooling processes exhibit a similar behaviour. After an initial lag, the temperature at the food's thermal centre decreases exponentially. A common concept used to characterise the cooling process is the half-cooling time, which is the time required to reduce the temperature difference between the commodity and the cooling medium by half (Becker, Fricke 2004). The half-cooling time is independent of the initial temperature and remains constant throughout the cooling period, as long as the cooling medium temperature remains constant. Therefore, once the half-cooling time has been determined for a given commodity, the cooling time can be predicted regardless of the commodity's initial temperature or the cooling medium temperature.

Statistical analysis. The measured values contained in Tables 1 and 2 are the results of the average of the three measured values. These values were

https://doi.org/10.17221/136/2018-HORTSCI

used in the more complex calculations of the enthalpy value and evaporator cooling performance.

RESULTS AND DISCUSSION

Half-cooling time for the cabbage heads and the ambient air located within a large-capacity cooling chamber. A satisfactory air movement in very large rooms is usually obtained by mounting fans in one wall near the ceiling, with air returns in the same wall near the floor. The parameters of cooling chamber No. 3 are in Table 4. You can see the air flow measurement in cooling chamber No. 3 without containers in Table 5. Containers should be stacked with their sides exposed, with air channels parallel to the direction of the air movement. The half-cooling time depends on the position of the container inside the cooling chambers, indicated by the height from the bottom and the distance from the evaporator (Table 1). The distance of two containers were measured, the first of which was just in front of the evaporator, at a height of 4 m and a distance of 1 m from the evaporator. The second container was 7 m from the evaporator, but 1 m from the floor. For these containers, both the half-cooling time of the cabbage heads and the half-cooling time of the ambient air in the immediate vicinity were measured concurrently. In each container, three layers were measured for the heads, but also for the ambient air. In Table 1, the temperatures of the cabbage heads are described as on the top, in the middle and at the bottom. The half-cooling time shown in this table has a completely different value for the measurements in the head and the air environments. We can equally distinguish the half-cooling time on the surface, at the centre and at the bottom of the container. The heat transfer between the air and the head has a positive value in favour of the rapid air cooling, rather than chilling the head (Holt, Schoorl 1983). Perhaps most obviously, the value of the half-cooling is derived from the distance between the evaporator and the location within the cooling chamber. The distance of the container from the evaporator is decisive for the complete cooling; conversely, placing a container in a stacked column is of less importance. The difference in the distance from the source of the cold slows the half-cooling time of the product by one order of magnitude (from 22.6 h on the top, for the container 4 × 1 m away, to 225 h the bottom, for the container 1 × 7 m away (Table l)). It is also evident that the outermost container determines the final cooling time of the cooling chamber. The value results from the fact that the flow rate of the distributed air slows down with the distance from the evaporating fan (Table 5).

Table 4. The parameters of chamber No. 3

Width	11.2 m
Length	15 m
Height	5.6 m
Volume	940.8 m^3
Means rate of air in front of the evaporator	5 m/s
Maximal rate of air in front of the evaporator	10.19 m/s
Rate of air behind the evaporator	0.88 m/s

Table 5. The air flow in cooling chamber No. 3 without containers

Height from floor (m)	Distance from evaporator (means ± standard deviation)		
	1 m	7.5 m	15 m
5.5	3.72 ± 0.27	2.56 ± 0.87	1.68 ± 0.33
4.5	3.73 ± 0.33	1.17 ± 0.91	0.7 ± 0.20
3	0.20 ± 0.05	0.21 ± 0.09	0.32 ± 0.22
2	0.33 ± 0.15	0.49 ± 0.06	0.18 ± 0.09
1	0.45 ± 0.16	0.72 ± 0.12	0.65 ± 0.16

Storage of the cabbage heads in a container without stacked layers. Table 2 shows the half-cooling times measured under the same conditions and layers in each row, each having one or more stacked layers. Although these containers were on the farthest side (14 m from the evaporator), they lacked any cover layers of containers placed above them. The upper layer of the cabbage heads was chilled with a half-cooling time of 183.0 h when the container was at a height of 1 m and a distance of 7 m from the evaporator (Table l). Conversely, in the container at the end of the cooling room, the half-cooling time of the heads was 89.3 h (Table 2). When the cabbage heads were inside the container (in the top position), in the most distant container from the evaporator, the direct heat dissipation was lost to the free space. When the heads of cabbage were in the farthest container from the evaporator, in the middle position or at the bottom position, the heat dissipation lost to the free space was slower. In this case, the cooling of the cabbage head slowed down, and the corresponding half-cooling time increased to 178.3 hours (in the middle position) and to 194.7 hours (at the bottom) (Table 2).

https://doi.org/10.17221/136/2018-HORTSCI

Cooling performance and air movement in the cooling chambers. For cabbage heads, room cooling is a relatively low cost, but very slow, method of pre-cooling. (Kitinoja, Thompson 2010). Reducing the temperature of the fresh produce after harvest greatly reduces the respiration rate, extends the shelf-life, and protects the produce quality, while reducing volume losses by decreasing the rates of water loss and decay. Produce is simply loaded into a cold room, and cold air is circulated around the containers. Typical cooling times for room cooling are 10–20 h with low energy efficiency. According to Thompson et al. (1998), refrigerated produce storage will require 10–14 kW of refrigeration capacity per 1 000 m^3 of storage volume, and refrigerated shipping docks require 14–25 kW per 1 000 m^3. These conditions were met by cooling chambers 1, 2 and 4 (Table 3).

Time required for the heat removal into the evaporator. The heat from the stored cabbage was sucked into the evaporator at the values given in Table 3. Each chamber had an air velocity in the range of 5–17 m/s, which was measured by an anemometer from the evaporator surface profile. The heat removed is a multiple of the specific heat of the cabbage head (4 kJ/kg/°C) and the temperature difference between the onset and end of the cooling time (6 °C), when the cabbage head attains the same temperature with the environment as the cooling air. Thus, the sums of the heat output (kJ) obtained are evaluated in relation to the cooling capacity of each chamber (in kW) and to the time (in hours) required to cool the air recirculated from the evaporator to the volume of the chamber. The number of hours needed to cool each chamber is shown in Table 3. The longest cooling time was calculated for chamber No. 3 (186.2 hours), because 243 t of cabbage heads were stored there and its cooling capacity (8.7 kW) was the lowest of the four assessed chambers.

Compliance of the calculation of the cooling air and half-cooling time in one chamber. From Table 3, it can be seen that it took over 186.2 hours air cooling to reach a final value of 0 °C in chamber No. 3, because a total of 5.83 GJ of heat was withdrawn from the heads of the cabbage (243 t), which was transferred by circulating the air to the evaporator with a cooling capacity of 8.7 kW. The half-cooling time was measured concurrently. In general, the total time needed for cooling the heads is five times longer than the measured and calculated half-cooling time of the heads.

When the heads were situated in the top position with a corresponding half-cooling time of 22.6 h (Table 1), the total time required was 113 hours. The half-cooling time of the air in the spaces between the heads in the same position was 6.7 h, so that the total cooling time of the air was 33.5 hours.

For the heads in the middle position, with a half-cooling time of 31.2 h (Table 1), a total time of 156 h was needed. The half-cooling time of the ambient air in the same position was 11.5 h, with 57.5 h of total air-cooling time required.

The heads in the bottom position in the container at the same height as the air flowing from the evaporator, but only 1 m away from it, had a half cooling time of 37.8 h, and a total cooling time of 189 hours. The half-cooling time of the ambient air in this position was 21 h its total cooling time was 107.5 hours. At this point, all the heat from the heads was turned into the circulating air and the heads had the same temperature as the circulating air.

The heads on the opposite side of chamber No. 3 were located at a distance of 14 m from the evaporator and were in the top position, with a half-cooling time of 89.3 h (Table 2) and a total time of 446.5 hours. The half-cooling time of the ambient air in this position was 60.7 h, with 303.5 h of total cooling time.

Half-cooling time in the container without a covering layer. The head in the top position, with no covering container and 14 m distance from the evaporator (Table 2), has a shorter half-cooling time than that in the container in the same position at 7 m distance (Table 1), which had other containers with heads stacked above it. The positions of the assessed containers can be seen in Figure 1. The head in the container on the bottom, but without any covering containers had a half-cooling time of 194.7 h (Table 2) with a total time of 973.5 h, when the air was circulated along the container, permanently cooling down the stored heads. The calculated cooling down time was extended 5.0 times.

The half-cooling time for the containers situated on the opposite side of the chamber. If the heads were in the same position, but 7 m from the evaporator, in the bottom position, the heat dissipation was so slow that the total time calculated from the half-cooling time (225 h) was 1 125 h (46.9 days), which was the longest cooling time for a head of cabbage.

Reasons for the knowledge about the half-cooling time for head cabbage storage. The si-

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multaneous measurement of the half-cooling times of the air among the heads and of a solid material, such as a head of cabbage, allowed one to obtain technologically similar results, in which the values for the air were always slightly lower (shorter half cooling time) in compare with measurement half cooling time inside of heads. The half-cooling time yields clear results for the heads of cabbage situated in the different parts of the cooling chamber. The shortest half cooling time have heads which are close to evaporator. If distance of heads from the evaporator is longer, the half cooling time increases. The free heat loss from the container not blocked by the top layer in the stack was also reflected in the short half-cooling time. The head of cabbage situated on the opposite side to the evaporator provides proof of the final cooling of the whole chamber. The result must be formulated as the final cooling time for a head of cabbage already inserted in the containers.

CONCLUSION

Information was obtained about the cooling in containers by evaluating the half-cooling time to express the cooling of a head of cabbage and the ambient air immediately in contact with the cooled heads. The heads of cabbage placed just in front of the evaporator yielded a very low value. By contrast, the value was extended by up to one order of magnitude in the containers placed on the opposite wall of the cooling room. The half-cooling times in Tables 1 and 2 show a completely different value for the measurements in both the head and air environments, and equally distinguishable half-cooling times on the surface, in the centre and at the bottom of the container. The heat transfer between the air and the heads has positive values in favour of rapid air cooling. The air between the heads was always cooled faster by the ambient air than the heads of cabbage were cooled. This is summarised by the half-cooling times of the heads of cabbage and the air in Tables 1 and 2.

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