Energy management of precooling process for green cabbages

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Abstract
Cold storage is one of the most widely used and effective processes to preserve shelf-life harvested agricultural products during long periods. Research to date has not yet determined the energy management of pre-cooling methods of green cabbage. This study seeks to investigate the cooling performance of the cold storage, keeping green cabbages with good quality and to report different pre-cooling strategies. The cold storage specifications included 15 HP compressor with a voltage of 380 V, a temperature range of -50 to 50°C, and R22 refrigerant. The mass of green cabbage was examined with three values of 30, 40, and 50 kg. Moreover, the pre-cooling strategies of the green cabbages were divided into four scenarios including the parallel pattern in the front zone, staggered pattern in the front zone, parallel pattern in the back zone, and staggered pattern in the back zone. The experimental results revealed that the coefficient of performance (henceforth COP) was significantly affected by the mass of the cabbage and cooling zone of the cold storage. While the pattern in case of 30 kg cabbage precooling had a slight effect on cooling performance due to the lower density arrangement and heat extraction. The highest COP appeared at the 30 kg cabbage precooling with the strategy of staggered pattern in the front zone. The COP value was 2.61.

Keywords: Energy, Management, Precooling, Green cabbages

1. Introduction
Recent evidence suggests that cabbages provide people with a variety of essential vitamins, antioxidants, and dietary fiber, and benefit to many aspects of health [1]. Post-harvest losses and waste in the supply chain of cabbage are considerably high before the product even reaches the consumer. Industrial production is faced with the challenge of minimizing post-harvest losses. Hence, research efforts are needed to prolong the shelf-life of vegetables and subsequently reduce postharvest losses. The solution is a rapid pre-cooling process in cold storage because it can enhance keeping nutrition ingredients and freshness, improving coldness, and prevent chilling injury [2]. Generally, the capacity of the cold storage must be based on a thorough heat load calculation for each project. Refrigeration load can vary widely for stores of the same capacity depending on the design, local conditions, product mix, etc. In the practice, a safety margin of some 50 percent of the theoretical calculation has been applied [3].

Several attempts have been made to investigate the variables affecting the cooling performance. The type of cold storage greatly influenced the freezing time. For example, the immersion freezer froze the product faster than the air blast freezer operating at the same temperature due to improved surface heat
transfer [4]. An appropriate operating temperature was the main factor of cold storage with energy savings [5]. Of particular concern is the temperature of the product. To give an example, the storage temperature of fish meat and the chicken breast was approximate -30±0.5°C [6,7]. The strawberry and green bean were frozen at -27±0.5°C [8]. For the cabbage, the storage temperature was 4±0.5°C [2]. However, the lower temperature of the freezer may cause an increase in the freezing cost. Since it has been observed that most freezers are designed to operate a few degrees below the required storage temperature of the product [9]. Tian et al. [10] proposed that the freezing time was reduced as the air speed was increased by the heat pipe-assisted cooling supply. Moreover, Chauhan et al. [11] indicated that the heat transfer coefficient was changed by the velocity of each shelf. Thus, the cooling performance of each shelf was different.

Recently, in view of the increasing demand for energy and the escalating costs of energy from all sources, energy management, and energy conservation have become increasingly important in all industries and also in the food systems. Good energy management and energy conservation depend on the operation of cold stores, such as product pattern and cooling zone. Mukama et al. [12] reported the product pattern (liner-packaged stacks), and they found that the most decisive factor affecting the cooling rate and energy consumption for the forced-air precooling of pomegranate fruit inside ventilated cartons. Gruyters et al. [13] demonstrated that the apple precooling condition with the using the reusable plastic crate inside the front zone provided the best cooling rate, although the high airflow rates might cause chilling injury to the apples. Han et al. [14] found that the numerical model with computational fluid dynamics (CFD) was well suited to evaluate package performance. The aerodynamic resistance and energy consumption of a certain package design provides a more comprehensive analysis of the overall forced-air cooling process. Wu et al. [15] investigated cooling time and uniformity of the packed produce, and its resistance to airflow. They found that it could often provide key information about the overall cooling efficiency of a specific package design in full-scale experiments of forced-air precoolers for citrus fruit.

Previous studies of energy management and energy conservation have not dealt with the case of green cabbage. Besides, no research has been found that surveyed the effects of the cooling zone and product pattern on the cooling performance during precooling. This paper attempts to show the effective way for energy management and energy conservation of the green cabbage inside the cold storage.

2. Materials and Methods

2.1 Experimental Setup and Procedure

The samples of green cabbage (comprising several cultivars of Brassica oleracea) with the average size (diameter of 12.5 cm and height of 8 cm) were obtained from the cabbage farm in Songkhla, Thailand. The samples were cleaned and all extraneous materials were removed. Cold storage specifications included 15 Hp (11.18 kW) compressor with a power supply voltage of 380 V, refrigerant of R22, storage space with the dimension of 2.4 m x 3.5 m x 2m (Width x Length x Height), and stainless-steel trolley with 9 tray capacity (see Figure 1). For the cold storage feature, the cooler unit was mounted at the roof level. There were no special means of directing the air over the product and therefore it generally tended to swirl about in the empty spaces in the front zone of the room and slightly flowed between the shelves or trays.

In the experiment, the mass of green cabbage was examined with three values of 30, 40 and 50 kg. Moreover, the pre-cooling strategies of the green cabbages were divided into four scenarios including the parallel pattern in the front zone (F_PL), staggered pattern in the front zone (F_ST), parallel pattern in the back zone (B_PL), and staggered pattern in the back zone (B_ST). For the initial condition, the distance between cabbages was controlled at 5±0.5 cm (25% of product hydraulic diameter). The temperature before entering the cold storage was controlled at 28±0.5°C. The temperature differential setting was also controlled at 2°C (from -1°C to 1°C) to keep the cabbage temperature range of 4°C to 5°C. This range was the storage value [2]. Moreover, the distance between the thermal center and the outer surface of the cabbages was given by 6 cm. The finish time was the time taken to lower the
temperature of the cabbage from its initial temperature to a given temperature at its thermal center. In addition, the temperature trend of the thermal center must be hardly drooped or almost constant.

The data acquisition module consisted of a data logger (Yokogawa MV1000), Chromel-Alumel thermocouple (type K), 3 phase power meter (PM2230), and relative humidity sensor (PCE-P18-3). The temperature and humidity points were located on the experimental apparatus as depicted in Figure 2. All of the tests, measuring the same position at least 3 times and the recorded parameter points were monitored every minute. The air-cooling temperature was calculated from the average of two temperature points ($T_{17}$ to $T_{18}$). The cabbage temperatures at the upper tray were calculated from the average of eight temperature points ($T_{5}$ to $T_{8}$) and ($T_{9}$ to $T_{12}$) for the back zone. Also, the cabbage temperatures at the lower tray were determined by the average temperature points from $T_{1}$ to $T_{4}$ (front zone) and from $T_{10}$ to $T_{16}$ (back zone). Whereas, the relative humidity of the evaporator was measured from two points ($RH_{19}$ and $RH_{20}$).

![Figure 1. Cold storage](image1)

![Figure 2 Experimental apparatus](image2)

2.2 Performance analysis
The experimental test was performed to investigate the cooling performance of cold storage under different pre-cooling strategies. The efficiency of a refrigerator or heat pump is given by a parameter called the coefficient of performance (COP) [4-5]. The COP is determined by the ratio between the energy usage of the compressor ($W$) and the amount of useful cooling at the evaporator ($Q_c$). COP can be calculated from Equation (1).

$$\text{COP} = \frac{Q_c}{W}$$ (1)
The useful cooling at the evaporator was evaluated by the rate of heat transferred to the ambient air and applying the conservation of energy equation for a heating process at constant specific humidity [10], which was shown as Equation (2)

\[ Q_e = \dot{m}_w (h_{\text{in}} - h_{\text{out}}) \tag{2} \]

where \( \dot{m}_w \) is the mass flow rate of dry air and \( h_{\text{out}} \) and \( h_{\text{in}} \) are the enthalpies per unit mass of dry air at the exit and the inlet of the evaporator section, respectively.

All experiments were replicated three times and the uncertainties of parameters throughout the experiments were presented in Table 1. The result \( R \) is a given function in terms of the independent variables. \( W_R \) is the uncertainty in the result and \( w_1, w_2, ..., w_n \) are the uncertainties in the independent variables \( (x_1, x_2, ..., x_n) \). If the uncertainties in the independent variables are all given with the same odds, then the uncertainty in the result having these odds is given as Equation (3) [16].

\[ W_R = \left[ \left( \frac{\partial R}{\partial x_1} W_1 \right)^2 + \left( \frac{\partial R}{\partial x_2} W_2 \right)^2 + ... + \left( \frac{\partial R}{\partial x_n} W_n \right)^2 \right]^{1/2} \tag{3} \]

Table 1 Uncertainties of parameters throughout the experiments

| Parameters           | Uncertainty | Unit |
|----------------------|-------------|------|
| Temperature          | ±0.5        | °C   |
| Relative humidity    | ±0.1        | %    |
| Time measurement     | ±0.1        | min  |
| Air velocity         | ±0.1        | m/s  |

3. Results and discussion

3.1 Effect of the cooling zone

The cabbages inside both front and back zones were simultaneously examined to cooling performance. From Figure 3 below, we can see that the condition of parallel pattern, the temperature and relative humidity variations over the cooling time. It found that as the cabbage temperatures gradually decreased to their equilibrium temperatures which were about 4.8°C, the air temperature and relative humidity were fluctuated by the compressor operation. The results of the study indicate that the temperature difference between the upper rack and the lower rack of 30_F_PL was around 2°C. It was found to cause higher temperature than 30_B_PL approximately 1°C, as provided in figure 3(a). Table 2 above illustrates COP of 30_F_PL, which was 2.58, was almost equal to COP of 30_B_PL. Whereas, the cabbage mass of 50 kg, it showed that there is a difference of the temperature between the upper rack and lower rack the 50_F_PL and 50_B_PL were around 4°C and 2°C, respectively. As can be seen as from Figure 3(b), the front zone had a lower temperature than the back zone due to the better air ventilation in the front zone. Likewise, the front zone had higher forced convection than the back zone, and these results match those observed in earlier study [13].

Regarding the cooling performance, the COP showed the difference between 50_F_PL and 50_B_PL (11%). The results revealed that the cooling zone of the lower cabbage mass had a slight effect on the COP. However, it has been suggested that the cooling zone of the higher cabbage mass had a more effect on COP (see Section 3.3 for more details).
3.2 Effect of product pattern

Figure 4 presents average temperature variations over the cooling time for different patterns. At the front zone, the difference of average temperature between both patterns of 30 kg and 50 kg were approximately 1.5°C and 0.3°C, respectively. Both COP patterns of 30 kg showed no differences. However, it can be seen that COP of 50_F_ST (2.27) was 10% higher than the 50_F_PL (see Table 2). A possible explanation for this might be that an airflow resistance and limited obstructions in the cooling process possibly occurred in the parallel pattern. These results are likely to be related to previous work [12], turning now to the experimental evidence on the effect of the cooling load on the cooling performance.
Table 2 Performances of the cold storage

| Cooling conditions | COP  |
|--------------------|------|
| No cooling load    | 3.50 |
| 30_F_PL            | 2.58 |
| 30_B_PL            | 2.53 |
| 30_F_ST            | 2.61 |
| 30_B_ST            | 2.55 |
| 40_F_PL            | 2.38 |
| 40_B_PL            | 2.31 |
| 40_F_ST            | 2.49 |
| 40_B_ST            | 2.36 |
| 50_F_PL            | 2.13 |
| 50_B_PL            | 2.00 |
| 50_F_ST            | 2.33 |
| 50_B_ST            | 2.12 |

Figure 4. Average temperature variations over the cooling time for different patterns

3.3 Effect of cooling load
Figure 5 provided an effect of cooling loads on COP. It can be seen that the more increase of the COP’s cooling load, the steady decrease of the COP was. Interestingly, the COP was observed to have higher heat extraction inside the evaporator. While the cooling load contained 30 kg, the cooling zone and pattern had less effect on the COP. Nevertheless, for the cooling load of 50 kg, the COP was significantly changed by both cooling zones and patterns. Additionally, the maximum COP with the cooling load appeared at 30_F_ST. It can be seen from the data that the higher COP provided the faster pre-cooling time of the cabbages to approach their average or equilibrium temperature, as illustrated in Figure 4. After that, the cabbages were transferred to keep in the freezer under their storage temperature. The results indicate that the cabbage pre-cooling strategy included the product arrangement with a staggered pattern and the front zone due to more energy savings. Together, these results provided important insights into the different heat transfer enhancements of the cold storage, particularly the appropriate precooling strategy.
4. Conclusion
The aim of the present research was to examine cooling temperature profile, cooling time, and COP of the forced-air pre-cooling of the green cabbages using four different cooling strategies. The second aim of this study was to investigate the effects of product mass under different cooling strategies on the COP. This study was designed to experiment obtained cooling curves to estimate the finish time of the cabbage pre-cooling process. The evaporator fan and the compressor of the cooling unit were also used to calculate the energy usage of the pre-cooling process. The results of this investigation show that the COP was inversely proportional to the cooling load. On average values, the maximum COP occurred in the case of 30_F_ST. The pre-cooling condition of product arrangement with a staggered pattern inside the front zone can be greatly improved using the cooling performance because of the higher heat transfer rate. The findings of this research provided insights for using pre-cooling strategy in the energy management of the green cabbages.

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