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Research Paper

Simulation of in-line versus staggered arrays of vented pallet boxes for assessing cooling performance of orange in cool storage

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HIGHLIGHTS

- CFD simulations of heat and mass transfer in Fruit cold storages were developed.
- Cooling performance of inline vs. staggered arrangements of pallet boxes evaluated.
- Staggered array caused 28–38% reduction in ¾ cooling time compared to inline.
- Staggered array increased 18–53% surface heat transfer coeff. at the boxes wall.
- Staggered array didn't make improvement in temperature homogeneity and weight loss.

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ABSTRACT

The cooling performance of fruits and vegetables including transient heat removal, temperature homogeneity and moisture loss inside the cool storages is affected by pallet boxes arrangement. In this paper, the effect of two different types of vented pallet boxes arrangement including in-line and staggered on cooling performance were compared while longitudinal gaps between the pallet boxes and cooling airflow varied at three commonly applied levels. Validated computational fluid dynamics (CFD) models of airflow, heat and mass transfer were applied as an alternative for the experiments. Results showed that staggered array increased the surface heat transfer coefficient at the pallet boxes wall from 18% to 53%, which caused 28% to 38% reduction in ¾ cooling time compared to in-line. The most effectiveness of staggered array on heat transfer coefficient occurred for 0.25 m longitudinal gap between the pallet boxes. Staggered array did not improve temperature homogeneity and moisture loss. Results also showed that, an increment of longitudinal gaps from 0.1 to 0.25 m caused 10% reduction in ¾ cooling time. Increasing more than 0.25 m, did not showed reasonable improvement in cooling performance.

1. Introduction

Fruit freshness depends on heat and moisture transfer rate during the cooling inside the cool storages. Orange can be directly cooled for several months in cool storage without precooling process. Inside a full loaded large cool storages, where cooling airflow is recycled through the pallet boxes and heat exchanger, based on the position of the fruit packages and the cooling airflow intensity, it would take more than several days for the fruits to reach to the recommended set point temperature. Higher temperature causes fruits increasing respiration and transpiration, which leads to more moisture and freshness loss. Lower than critical temperature, is also harmfully causes chilling injury and physiological disorders. Beside this, the temperature difference of the products can cause condensation of water vapor on the product surfaces and increasing the risk of microorganism infections. The cooling performance of fruits and vegetables is evaluated based on the cooling rate, homogeneity of product temperature and moisture loss [11,12]. Most of the heat exchanger and blower units are designed to obtain 2.8 m^3/min cooling airflow per ton of products [29]. For a long-term storage, the product will reach to the set point temperature within one week after the facility is filled, then airflow circulation capacity can be reduced to 20–40% of the design capacity, still maintaining adequate temperature uniformity. This can be manipulated by intermittent operation of blowers or by keeping the blowers constantly on, but reducing their speed with an electronic speed control system. The power and position of heat exchanger and blower unit as well as the arrangement of products pallet

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boxes, can affect airflow pattern inside the storages. In large industrial cool storages, the columns of pallet boxes usually arranged in-line. Staggered array of pallet boxes can also be applied. Longitudinal and transverse gaps among in-line and staggered arrays can generate different arrangement of pallet boxes inside the storage. The airflow pattern inside the environment of storage can affect turbulence intensity and surface heat transfer coefficient on the surface of pallet boxes. Consequently, conductive heat transfer between fruits and the walls of pallet box would be affected. Beside this, airflow can infiltrate inside vented pallet boxes among porous stack of the fruits and make more intensive heat and moisture removal.

In this paper, the cooling performance of different types of pallet box arrangement subjected to different cooling airflow rate supplied by the heat exchanger and blower unit were compared. Since numerous experiments with an enough repeat were needed to proceed this study, validated Computational Fluid Dynamics (CFD) models of air flow and heat and mass transfer were applied which is usually an economic and reliable alternative to physical experiments [36]. Many authors have shown numerical modeling to be a promising and reliable tool for prediction of airflow, heat and moisture transfer in refrigeration systems [31,34]. Among different numerical methods, the applicability of CFD as a reliable numerical method was approved in cooling systems comparing to the experiments [28,37,38,13,22,24,4,5,19,18,17]. In recent years, CFD was applied to improve the cooling process. Moureh et al. [23] reported improvement in ventilation rate of slotted packages in a refrigerated cargo using air ducts inside enclosure. Han et al. [15] used CFD model to optimize fruit packages shape. Ferrua and Singh [11] investigated different design parameters effecting cooling rate and homogeneity for strawberries during pre-cooling. Ho et al. [16] studied the effect of fan airflow and its location in cooling process inside a cool storage. Delele et al. [7] optimized the relative humidity, cooling time, sprayed water droplets and commodity weight loss using multi scale modeling of different operational conditions of humidification system.

The CFD model applied in this study was previously validated against experiments and reported to be capable for predicting air velocity, product temperature, and weight loss with reasonable accuracy and was reliable enough for numerical studies on larger domain in order to optimize cooling process[27].

2. Materials and methods

2.1. The model geometries and boundary conditions

Orange (*Citrus sinensis* cv. Valencia) packed inside the pallet boxes were modeled as a porous medium with a source of heat, because it was considered to generate heat through respiration and loss of moisture due to the vapor pressure deficit as well. Several studies reported porous medium model to be confident enough for applying in large geometries such cool storage environment [33,27,17].

In large industrial cool storages, the columns of pallet boxes usually arranged in-line. Staggered array of pallet boxes can also be applied as can be seen in Fig. 1. If the cooler units considered being capable to provide sufficient airflow, the air would flow

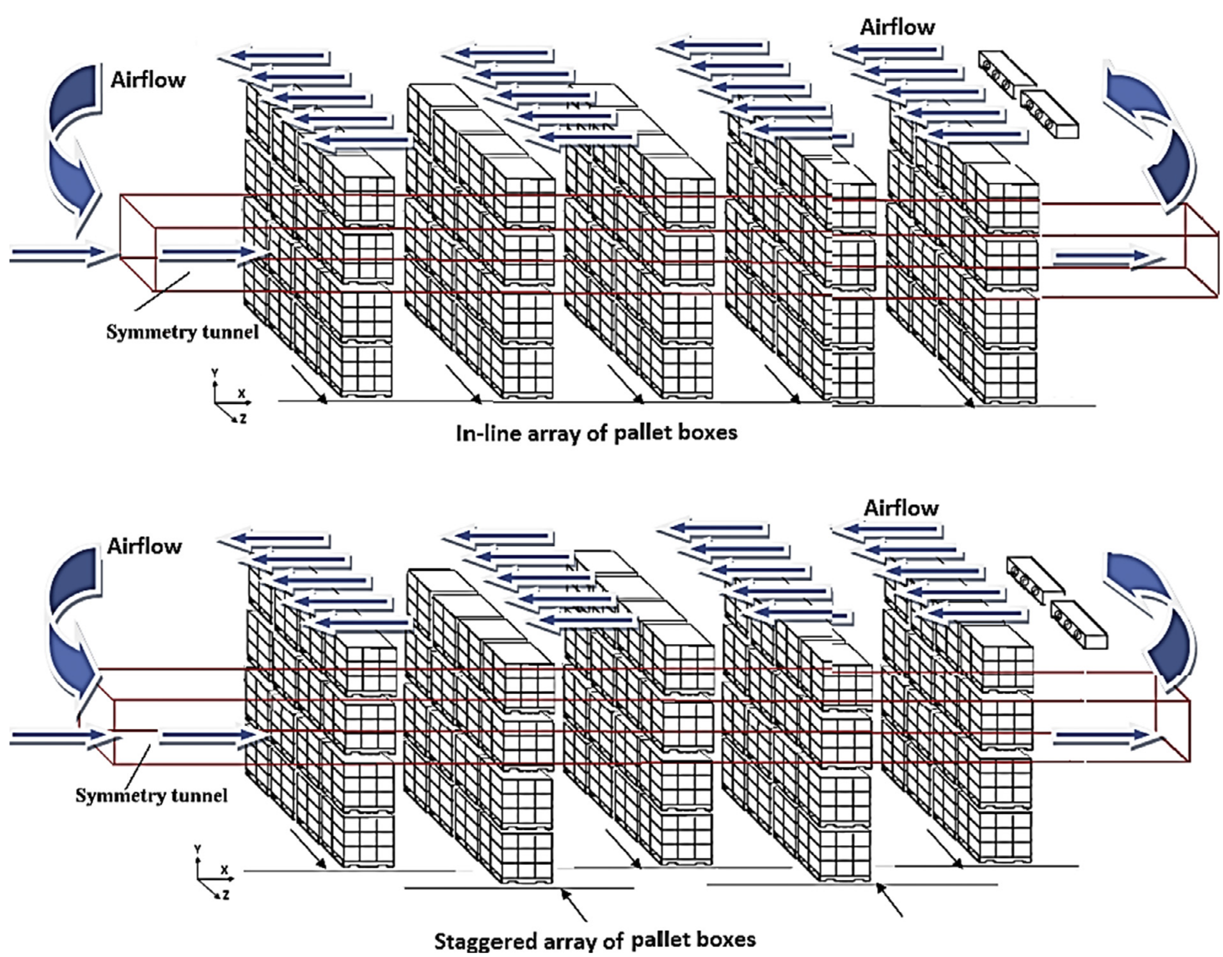

Fig. 1. In-line array (top) and staggered array (down) of columns of stacked pallet boxes in a cool storage.