Experimental and numerical investigation of cooling performance of a cold storage in a pharmaceutical industry

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Abstract. This paper describes the study of cooling performance of cold storage in a pharmaceutical industry. It was intended to investigate the temperature distribution inside the storage that is an important performance factor in pharmaceutical industry cold storage. Cold storage that used is a ceiling type with the liquid bottle loading. Temperature distribution and the storage cooling performance were studied using experimental measurement and numerical simulation. Some variation of bottle arrangement and rack arrangement have been observed to show the impact of distribution temperature and cooling performance of cold storage. Surface temperatures of the bottles were measured with different bottles and rack arrangement. The temperature of cold storage was set to 5°C. In numerical simulation, a transient three dimensional Computational Fluid Dynamic (CFD) model was developed to investigate the cooling performance and temperature distribution inside bottle. At this stage, the results showed that rack arrangement that parallel with the cold room fan and V shape bottle layout has given a good cooling performance (it takes 1480 minutes to reach a stable temperature at the setpoint) and an optimum temperature distribution (with temperature difference of 0.58°C). For the measurement of the distribution of temperature in the bottle, the mean deviation value between the simulation and the experiment on the measurement of 2 coordinate points (X = 0,1 m, Y = 0,3 m, Z = 0 m and X = -0,1 m, Y = 0,3 m, Z = 0 m) were 5,5 % and 7,6 %.

1. Introduction
In a pharmaceutical industry, especially in a biotechnology industry, product quality begins from raw materials until final products. Monitoring for each step process should be done includes storage processing. Those were done to guarantee that the product still in a good quality.

A cold storage was used to store the product that need cold temperature to guarantee its quality. To achieve the desired temperature, a refrigeration system is employed. Using refrigeration system, high energy consumption of the cold storage could happen. Therefore the cold storage should be designed as efficiently as possible with considering of its performance. Most cold storage are designed by experiences which may cause increasing operating cost. Moreover, a uniform airflow field can also improve the refrigeration quality of the products in the cold storage.

Some studies to improve performance of cold storage have been done both experimentally and by numerical simulation. Several studies modeling of temperature distribution in cold storages have demonstrated the effectiveness of various methods (Nahor et al. 2005; Konishi et al. 2009, Tanaka et al.
2011, Akdemir et al. 2013, Mahdi et al. 2014). Rajan et al. (2015) investigated performance of cold storage for the different stacking arrangements experimentally. The temperature is the only parameter at which the performance of cold storage depends on.

The objective of this study is to investigate the effect of loading arrangements of vaccine bottles to the cooling performance of cold storage by experiment. It also investigates temperature distribution and cooling rate inside the bottle both experimentally and by numerical simulation.

2. Research Methodology
This research was conducted using two kinds method, by experimental and by numerical simulation using Ansys Fluent.

2.1 Experimental Setup
Thermocouple sensors were used to measure air temperature distribution and the cooling rate of the cold storage

2.1.1 Operation description. Cold storage that used is a ceiling type with dimension 290 cm (L) x 260 cm (W) x 250 cm (H). The refrigeration system works with a vapor compression mechanism with R22 refrigerant. The schematic diagram of the cold storage is shown in figure 1.

![Figure 1. Schematic of Cold Storage](image)

The cold storage was designed for 2 – 8 °C store temperature with set point temperature 5 °C. The cold storage is used to store 24 liquid vaccine bottles with 20 litres volume each bottle. These bottles were arranged in 2 racks and cooled to achieve 5 °C. Distribution temperature measurement was done with thermocouple sensors that put at the outside bottle surface.

2.1.2 Bottle & Rack Arrangement In this research, some variation of bottle and rack arrangements were observed to see optimum condition of the cold storage that can be achieved. Bottle and rack arrangements were designed with considering of cold air flowing through the bottles and personnel accessibility.
a. Arrangement I
In this arrangement, the rack was arranged parallel with fan evaporator and 4 bottles were arranged straightly in each step of the rack. The schematic of arrangement is shown in figure 2.

![Figure 2. Arrangement of Bottle and Rack I](image)

b. Arrangement II
In this arrangement, the rack was arranged parallel with fan evaporator and 4 bottles were arranged with V shape layout in each step of the rack. The schematic of arrangement is shown in figure 3.

![Figure 3. Arrangement of Bottle and Rack II](image)

c. Arrangement III
In this arrangement, the rack was arranged parallel with the door and 4 bottles were arranged straightly in each step of the rack. The schematic of arrangement is shown in figure 4.
d. Arrangement IV
In this arrangement, the rack was arranged parallel with the door and 4 bottles were arranged with V shape layout in each step of the rack. The schematic of arrangement is shown in figure 5.

2.2 Numerical Simulation Method
In numerical method, simulation of cooling process inside the bottle was carried out. This research is started by drawing geometry of bottle that shown in figure 6. The bottle is drawn according to its original dimension (280 mm in diameter and 520 mm in height). The material of bottle is high density polypropylene (hdpp) and the material of liquid is water. Inside the bottle, it is assumed that heat conduction is the only mode of heat transfer. The equation for the conservation of energy for the bottle with constant properties at transient state can be written as
\[
\frac{\partial (\rho \cdot c_p \cdot T)}{\partial t} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + q_{gen} \tag{1}
\]
Because it was assumed that no heat generation inside the bottle, the equation become
\[
\frac{\partial (\rho \cdot c_p \cdot T)}{\partial t} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) \tag{2}
\]
The variables \( \rho \) and \( C_p \) are fluid density and fluid specific heat.

The boundary conditions on temperature can be written as

On wall of bottle: \(-k \frac{\partial T}{\partial n} = h(T - T_{\text{ext}})\)

The variable \( k \) is thermal conductivity of bottle with liquid and the variable \( h \) is heat transfer coefficient of fluid. External temperature was set constant at 5 °C and heat transfer coefficient, \( h = 15 \text{ W m}^{-2}\text{ K}^{-1} \).

3. Result and Discussion

It was intended to see the effect of bottles and rack arrangements on the performance of cold storage. In this section, the average product temperature distribution and cooling rate for various bottles and rack arrangements has been presented. The graphs of average surface bottle temperature distribution inside the cold storage for four different arrangements are plotted as follows.

a. Arrangement I

The average temperature distribution, maximum temperature and minimum temperature of cold storage are plotted as following:

![Figure 6. Geometry of Bottle](image)

![Figure 7. Average temperature distribution in arrangement I](image)
b. Arrangement II
The average temperature distribution, maximum temperature and minimum temperature of cold storage are plotted as following:

![Figure 8. Average temperature distribution in arrangement II](image)


c. Arrangement III
The average temperature distribution, maximum temperature and minimum temperature of cold storage are plotted as following:

![Figure 9. Average temperature distribution in arrangement III](image)
d. Arrangement IV

The average temperature distribution, maximum temperature and minimum temperature of cold storage are plotted as following:

![Graph showing temperature distribution](image)

**Figure 10.** Average temperature distribution in arrangement IV

The performance of cold storage with different arrangement can be summarized as shown in table 1.

| Table 1. Cooling performance of cold storage in different loading arrangement |
|-----------------------------------------------|-----------------|-----------------|
| Temperature Difference, in ºC                 | Cooling time to the stable setpoint temperature, in minutes |
| Arrangement I                                 | 0.79             | 1510             |
| Arrangement II                                | 0.58             | 1480             |
| Arrangement III                               | 0.93             | 1596             |
| Arrangement IV                                | 0.84             | 1500             |

Based on experimental result, arrangement II has the best cooling performance. It has more uniform distribution temperature than the other arrangements. It also has less cooling time than the others. Cold air can easily flow through the outer surface of each bottle in this arrangement.

The graphs of distribution temperature around coordinate X = 0 which resulted by numerical simulation method are shown in the following figures.
Figure 11. Distribution temperature inside the bottle at $t = 3000$ second

Figure 12. Distribution temperature inside the bottle at $t = 30000$ second

Figure 13. Distribution temperature inside the bottle at $t = 60000$ second

Figure 14. Distribution temperature inside the bottle at $t = 90000$ second

Figure 11 shows cooling process of bottle in the early time. The top of bottle was cooled faster than the other part of bottle. Figure 12-13 show profile of temperature distribution inside the bottle during cooling process time. It shows that cooling process begin from the bottle wall. The liquid temperature
that close to wall of bottle is colder than the liquid temperature in the center of bottle. Figure 14 shows that temperature around the bottle close to the temperature of environment (5 °C).

Comparison result between simulation and experimental method is shown in figure 15.

**Figure 15.** Comparison result between simulation method and experimental method.

Figure 15 (a) and 15 (b) show comparison result between simulation and experimental methods inside the bottle. The average difference temperature is about 0.45 °C and 0.64 °C. It results average error about 5.5 % and 7.6 %. In the experiment, temperature is not constant at 5 °C so it can contribute error between simulation and experiment.
4. Conclusion

Based on result of experimental and numerical simulation, it can be concluded that:

- Loading arrangement of the bottles influences cooling performance of the cold storage.
- Numerical simulation can be used to predict heat transfer and to assess cooling performance in the cold storage.
- The model has an error about 5.5% - 7.6%

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