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Analysis of refrigeration load in potato cold storage under practical operating conditions

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Abstract

The poor performance of commercial potato cold storage units could be attributed mainly to inconsistency in operating parameters (loading rate, cool-down time, actual storage capacity, etc.). The refrigeration system, designed on the basis of common refrigeration load calculation practice, seems to be unable to cope up with these variable operating conditions which resulted in uncontrolled storage air conditions during the loading period. Therefore, attempts have been made in the present work to estimate the refrigeration load under the practical loading conditions corresponding to the prescribed cooling rates. In this study, the combinations of two loading patterns with two cooling rates, were considered to predict the refrigeration load of the potato cold storage unit having the storage capacity 18600 metric ton. The effect of operating parameters on total refrigeration load was presented during the transient cooling period. For prevalent irregular loading rates, the estimated transient total refrigeration load during the cool-down period was found to be uneven (as compared to smooth trend with constant conditions of loading and cooling) and strictly followed the trend of loading pattern. The peak refrigeration load value was about 20% higher for actual irregular loading pattern in comparison to constant loading rate as considered in common cooling load calculation practice.

Keywords: Transient refrigeration load, Potato cold storage, Loading pattern, Cooling rate

Introduction

The foundation for planning and running any kind of cold storage is based on a precise assessment of the refrigeration loads under the prevailing practical conditions. In the older potato cold storage units, the design and selection of refrigeration system is based on the common refrigeration load calculation practice wherein a constant daily drop in product temperature under the fixed product loading rate had been considered. The potato cold storage units set up before the year 2010 used to follow this approach for design and selection of refrigeration system components. Subsequently, the refrigeration load has been estimated as per criteria prescribed in National Horticulture Board (NHB) standards NHB – CS – type 01 -2010 (Anonymous, 2010) [1]. In NHB standards, a constant daily loading rate (4 – 5%) and temperature drop of 10 °C in the first day and thereafter 1°C per day is prescribed. However, these conditions of loading and cooling rates are being rarely followed by commercial potato cold storages. The prevalent practical loading pattern is quite uneven and hence the cooling rates also varied widely from the suggested one. The daily loading rate of potatoes in cold storage directly correlates with the arrival of the goods, which also fluctuates widely throughout the loading period. Because of this erratic loading pattern, energy demand fluctuates sharply, storage air temperature is uncontrolled, and cooling rates are unequal (Chourasia *et al.* 2004a) [6].

Many methods are available in the literature for calculation of refrigeration load for various types of refrigerated facilities. The different aspects of cooling load estimation of a potato cold storage and presented the ideas about possible efficiency improvements in existing cold storages (Islam *et al.*, 2013) [7]. Using energy simulation, the refrigeration load assessed in cold storage facilities and used phase change materials to build energy-efficient plant operations (Joybari *et al.*, 2015) [8]. Sari and Pratami (2018) [12] analysed the overall cooling load by using the concept of cooling load temperature difference (CLTD). Using a CFD tool, Tasiya, and Gajdhar (2021) [14] concentrated on the temperature distribution of fresh fruit and vegetable cold rooms and computed heat load calculations. Therefore, the refrigeration load

in potato cold storage by 16.4% while maintaining ideal storage conditions of 4 -7°C and 85 - 90% relative humidity (Sáenz-Baños *et al.*, 2022) [11].

Concentrating on the relevant work for the Indian potato cold storage system, the entire refrigeration demand in potato cold storage during a brief cooling period was explicitly (Chourasia *et al.*, 2004b) [4]. estimated the effects of loading patterns and cooling rates on moisture loss and refrigeration load requirements using the CFD technique (Chourasia and Goswami, 2008) [5]. Paranjpey (2014) [9] presented the refrigeration load calculation for potato cold storage as per NHB standards – CS – type 01 -2010. Chaudhary and Sharma (2015) [3] presented a thermal system design of a potato cold storage based on common cooling load calculation practice. However, none of these cited refrigeration load calculation approaches considered the conditions of variable daily loading rates that prevailing in Indian potato cold storage industry. Therefore, attempts have been made in the present study to estimate the actual refrigeration load under the prevalent operating conditions. The transient refrigeration load was estimated based on actual loading patterns collected from the potato cold storages during the loading season and compared with that of calculated as per criteria prescribed in NHB standards as well as common calculation practice.

2. Materials and Methods

This chapter outlines the theoretical framework and methodology used to study the effect of various practical operating parameters on the transient refrigeration loads in the cold storage. For this purpose, a commercial potato cold storage unit of 18600 metric ton was selected to collect relevant data on operational, design and constructional features to use as input parameters for calculation of the refrigeration load.

2.1 Theory

The relevant formulae that incorporate variable loading and cooling rates, along with their associated attributes to calculate the transient refrigeration load for a potato cold storage facility are described below.

2.1.1. Structural heat leakage load

The heat transferred through the cold storage structure is calculated using the following relationship (Prasad, 2003) [10].

$$Q_s = \sum_{x=1}^6 (q_x) = U_x A_x (\Delta T_x + T_{s,x}) \quad (1)$$

where Q_s (kW) is total structure heat leakage load; q_x (kW) is heat leakage through the x^{th} surface (walls, ceiling and floor) of the cold storage; U_x ($W \times m^{-2} \times K^{-1}$) and A_x (m^2) are the overall heat transfer coefficient and exposed surface area of the x^{th} surface, respectively; ΔT_x ($^{\circ}C$) is temperature difference across the x^{th} heat transfer surface; $T_{s,x}$ ($^{\circ}C$) is temperature increment for solar radiation exposure of the x^{th} surface.

2.1.2. Product load

The product is made up of sensible heat, which lowers the product's temperature from its starting point to its final storage temperature, and heat of respiration, which uses less heat to evaporate the product's moisture. Chourasia *et al.* (2004a) [4] evaluated the product load on a specific day (t).

$$Q_{p,t} = m_p \left(\frac{C_p \Delta T_p}{86400} + q_{res,t} - \frac{m_l (h_{eva,t})}{86400} \right) \quad (2)$$

where Q_p is product load (kW); m_p is mass of the product loaded on a particular day (kg); C_p is specific heat of product (kJ /kg $^{\circ}C$); ΔT_p is temperature of the product ($^{\circ}C$); $(q_{res})_t$ is metabolic heat of respiration (kW); m_l is rate of moisture loss from the product (kg / kg day); $(h_{eva})_t$ the latent heat of vaporization (kJ).

2.1.3. Infiltration load

The infiltration heat load was calculated from (Stoecker, 1998) [13].

$$Q_{inf} = C_{inf} A_d \sqrt{H} \left(\frac{\rho_i - \rho_o}{\rho_i} \right)^{\frac{1}{2}} \left(\frac{2}{1 + \left(\frac{\rho_i}{\rho_o} \right)^{\frac{1}{3}}} \right)^{\frac{3}{2}} \left(\frac{\rho_o + \rho_i}{2} \right) (H_o - H_i) \frac{t}{24} \quad (3)$$

where Q_{inf} is infiltration load (kW); C_{inf} is infiltration coefficient ($\sqrt{m \times s^{-1}}$); A_d is surface area of the door (m^2); H is height of door (m); ρ_i is density of inside air ($kg \times m^{-3}$); ρ_o is density of outside air ($kg \times m^{-3}$); H_o is enthalpy of corridor air ($kJ \times kg^{-1}$ dry air); H_i is enthalpy of inside air ($kJ \times kg^{-1}$ dry air); t is door opening time (hour).

2.1.4. Ventilation load

The calculation of ventilation load can be done by using following equation Prasad (2003) [10].

$$Q_v = \frac{nV\rho_o}{86400} (H_o - H_i) \quad (4)$$

where Q_v is ventilation load (kW); n is number of air exchange in a day; V is volume of cold storage (m^3).

2.1.5. Load due to human

The calculation of load due to human can be estimated (Stoecker, 1998) [13].

$$Q_h = n_p h_G \frac{t_w}{24} \quad (5)$$

where Q_h is load due to human being (kW); n_p is number of persons; h_G is heat generated per person (kW); t_w is working time in a day (hour).

2.1.6. Load due to electrical appliances

The load caused by electrical appliances, which includes lights, fans, and other electrical devices occurred only during the loading time in a day. Nonetheless, because the fans run constantly, the heat is released throughout the day. Using the relationship below, the cooling load from lights, fans was computed (ASHRAE, 1989) [2].

$$Q_e = \left(I A_f \frac{t_w}{24} \right) + (F_n r_n W_F) \quad (6)$$

where, Q_e is load due to electrical appliances (kW); I is required light intensity ($W \times m^{-2}$); A_f is floor area (m^2); F_n is number of fans in a row, r_n is number of rows; W_F is fan wattage.

The total refrigeration load ($Q_{T,t}$ in kW) due to all components on a particular day (t) can be computed from the summation of all the individual components as given by equation 1 to 6. The total refrigeration load,

$$Q_{T,t} = Q_s + Q_{p,t} + Q_{inf} + Q_v + Q_h + Q_e \quad (7)$$

2.2. Methodology

2.2.1. Data collection

A commercial potato cold storage unit was visited in Hooghly district of West-Bengal state to collect the relevant inputs for calculation of the transient refrigeration load using the equations 1 to 7. All the necessary data like structural details, daily loading rate, prevalent temperature and relative humidity of air, details of electric appliances (like, number of fans, lights, etc and their wattage) were collected from cold storage for the calculation of refrigeration load under the prevalent operating conditions. A summary of the collected data from the cold storage unit are presented in table 1.

2.2.2. Estimation of transient refrigeration load under the variable loading and cooling rates

The actual loading pattern is quite irregular in nature which causes the drift in refrigeration demand from the estimated one (Chourasia *et al.*, 2004b) [6]. Therefore, daily loading rate data were collected from a cold storage to estimate the total refrigeration load during transient cooling under the various combinations of loading patterns and cooling rates as given in table 2.

3. Results and Discussion

3.1. Loading pattern of cold storage unit

3.1.1. Total loading in the cold storage

Structural details and other relevant design parameters of cold storage unit selected to analyse the actual refrigeration load under the prevalent operating conditions are shown in table 1. The actually stored capacity for the cold storage unit was found to be different from the designed capacity as can be seen in table 1.

The actual daily product loading rate in cold storage unit is presented in fig 1. It can be observed that the loading pattern is quite irregular and daily loading rate varied abruptly from the constant loading rate. Also, the loading duration was found to vary from 26 to 31 days in comparison to prescribed period of 20 to 25 days (Paranjpey, 2014) [9]. This, irregular loading pattern is one of the main causes behind the fluctuations in storage air temperature and poor performance of the cold storage in term of product quality.

3.1.2. Cumulative loading in the cold storage

The cumulative percentage quantity of product loaded with storage period is shown in fig 2. During the loading period of 31 days, three distinct phases (initial, middle and last) of loading durations were observed. In the initial phase of 5

days loading, the loading rates increased slowly and speed up during the middle phase between the 5-20 days of time span. In the last phase (20-31 days), the loading rate was again found to decrease.

3.2. Total transient refrigeration load in cold storage for different cooling and loading patterns

Total transient refrigeration load is presented in fig 3 for different combinations of loading and cooling patterns (actual loading rate and cooling rate as per NHB norms; actual loading rate and constant cooling rate; constant loading rate and cooling rate as per NHB norms; constant loading rate and constant cooling rate) as listed in table 2. In general, the transient refrigeration load increased with time and attained a peak value and thereafter decreased to a constant value called steady state refrigeration load.

The estimated total refrigeration load under the observed daily actual loading rate and cooling rate as per NHB standards is shown in fig 3a. The estimated daily transient refrigeration load was quite uneven for the cold storage unit. Also, the refrigeration load has shown a tendency to increase with time up to middle of storage period and then declining to a steady value.

The estimated total refrigeration load with time under the actual loading rate and constant cooling rate (2°C per day) is shown in fig 3b. The trends of overall temporal variation in total refrigeration load and time of occurrence of peak load values for the cold storage were almost same as that of cooling rate as per the NHB standards. Also, the peak refrigeration load was almost same for both the cooling rates. This indicates the dominance of loading pattern, in comparison to cooling rates, on the refrigeration load.

The transient total refrigeration load with time under the constant loading rate (4% of actual loading capacity) and cooling rate as per NHB is shown in fig 3c. The refrigeration load increased slowly, and peak refrigeration load was observed at the end of loading for the cold storage unit. Thereafter, the load decreased sharply in next 8 days before attaining the constant value (steady state load). Also, the peak refrigeration load value was 18% less in comparison to actual loading rate for the storage unit.

The variation in transient total refrigeration load for constant loading rate and under constant cooling rate is shown fig 3d wherein three distinct phases can be observed. In the initial phase, the refrigeration was found to increase sharply for first 9 days of the loading period, thereafter, increased slowly and attained the peak load value on last day of loading similar to constant loading and NHB cooling pattern. Thereafter, from 25th day, it decreased sharply to a stable value of steady state refrigeration load.

Table 1: Structural details and other relevant design parameters of cold storage unit

Cold Storage Chamber	Design capacity (MT)	Actual product loaded (MT)	Structural details				Orientation (Cold storage door facing direction)
			Length (m)	Height (m)	Width (m)	Thickness of thermocol insulation (m)	
1	5000	16871	32.92	16.46	30.18	Floor - 0.076; Walls - 0.1016; Ceiling - 0.127	South
2	5000		32.92	16.46	30.18		
3	8600		41.55	17.37	35.59		

Table 2: Independent as well as dependent parameters of refrigeration load

Dependent parameters	Independent parameters	
	Loading patterns	Cooling rates
Total transient refrigeration load	Actual loading patterns collected from cold storage units	As per NHB (10 °C reduction in first day and thereafter 1 °C per day drop up to storage temperature)
	Constant loading rate @ 4% of total capacity per day as prescribed by NHB	Constant cooling rate @ 2 °C per day used conventionally in refrigeration load calculation

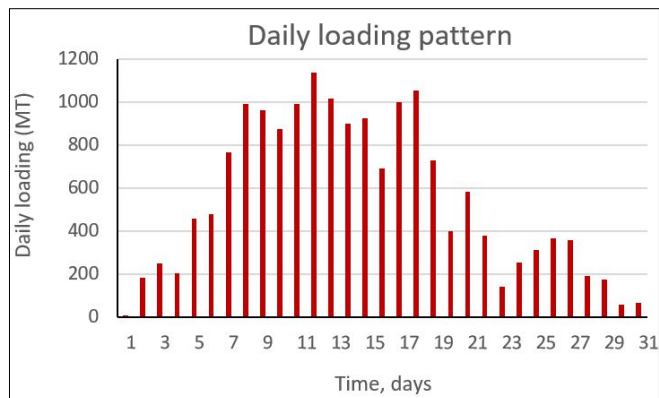


Fig 1: Loading pattern of the cold storage unit

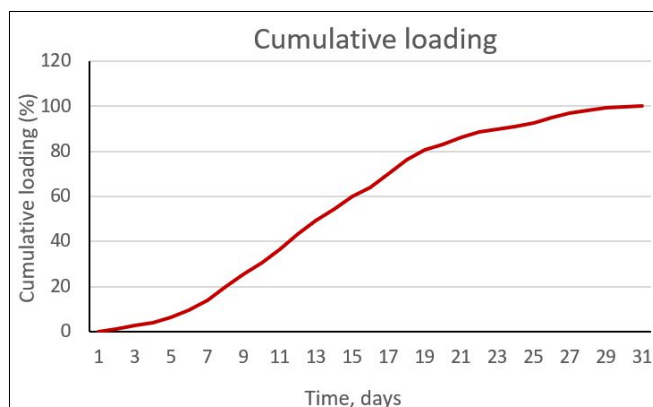
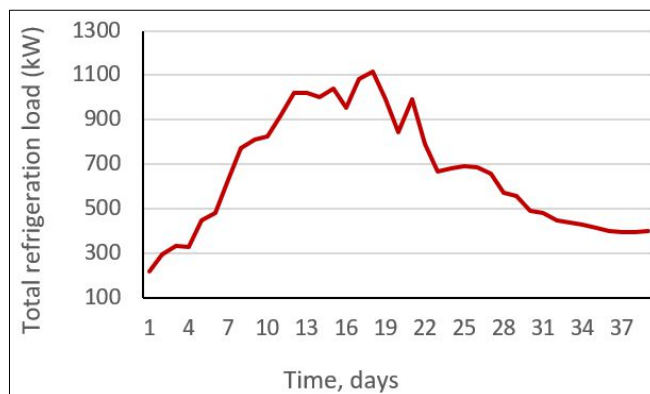
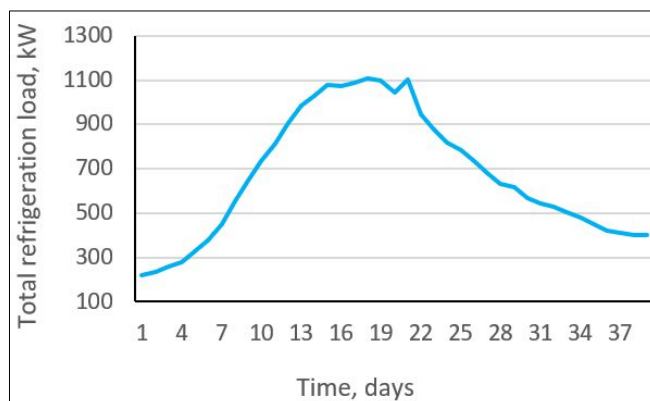


Fig 2: Cumulative loading pattern in selected cold storage unit



A



B

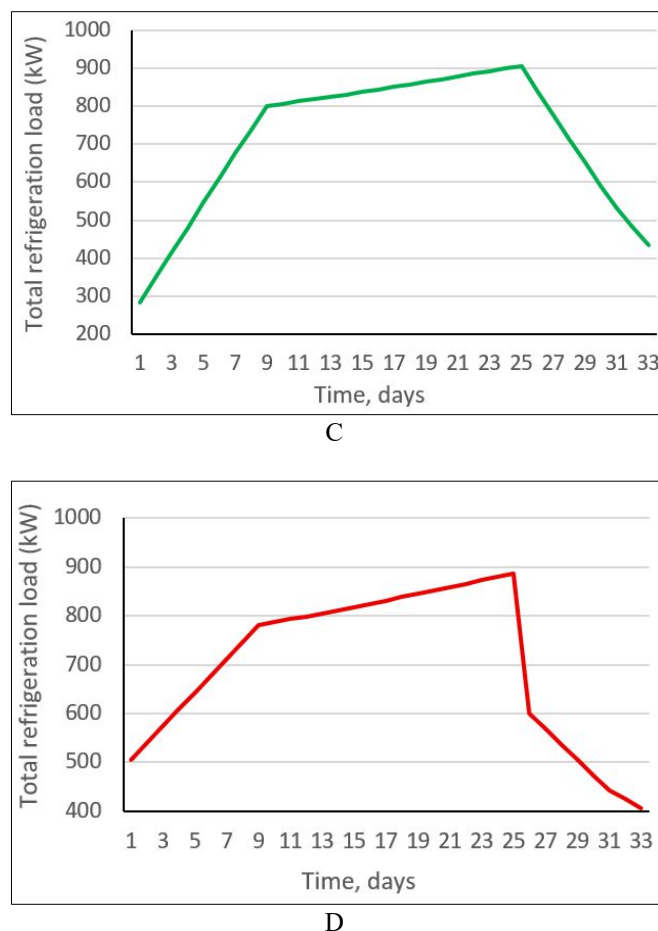


Fig 3: Variation of total transient refrigeration load (a) Actual loading rate and as per NHB cooling rate (b) Actual loading rate and constant cooling rate (c) Constant loading rate and as per NHB cooling rate (d) Constant loading rate and constant cooling rate

4. Conclusions

A wide temporal variation in transient refrigeration load was observed for different combinations of loading patterns and cooling rates. The observed loading patterns in the cold storage unit was specific and quite irregular in nature, in which, the daily loading rate varied abruptly from the constant loading rate. Also, the loading duration was found to vary from 26 to 31 days in comparison to prescribed period of 20 to 25 days and the loading of product completed in a maximum of three distinct phases.

Following the trend of loading pattern, the estimated daily transient refrigeration load was also quite uneven for the cold storage unit. This indicated the dominance of loading pattern, in comparison to cooling rates, on the refrigeration load. The refrigeration load has shown a tendency to increase with time up to middle of storage period and then declining to a steady value. For this cold storage unit, the peak refrigeration load value was about 20% higher for actual loading rate in comparison to constant loading rate.

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