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A MULTIDISCIPLINARY APPROACH OF COLD CHAIN TRANSPORTATION

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Abstract: Perishables requested by consumers all over the world are transported intensively and request no interruption of the cold chain. In this context, cold chain logistics, quality and safety of the products together with convenient comprehensive cost of cold chain transportation are under the attention of all actors involved in the process. Refrigeration is the technology with a key role in this activity. It is a technology with high energy consumption and rises environmental problems. In this paper cold chain transportation is approached multidisciplinary, so that this manuscript can be used as a guidance for different specialists. Are provided fundamentals of vapour compression refrigeration systems and formulae for costs affecting the total cost of this activity. It is taken into discussion multimodal transport, being considered costs reflecting on shore and on board transport of perishables.

Key words: Cold chain, cost, perishables, refrigeration.

1. INTRODUCTION

Rise of life standards all over the world results in consumer demand on quality and safe perishable purchase. This has a high impact on cold chain industry.

Cold chain logistics deal with providing perishables located in different places with minimal transportation duration and costs.

Cold chain logistics is impacted by globalization and important losses, resulting the importance of ensuring the sustainability of this activity [1]; it involves producers, suppliers, transporters and distributors.

In this complex interaction refrigeration plays a key role.

It is required securing specific low temperature and continuous transport under required conditions for perishable items.

Typically, refrigerated transportation uses vapour compression refrigeration systems in order to ensure the requested low temperatures found in quality and safety of the transported product.

The importance of refrigerated transport in cold chain is seen in Figure 1, which shows the elements of this concept.

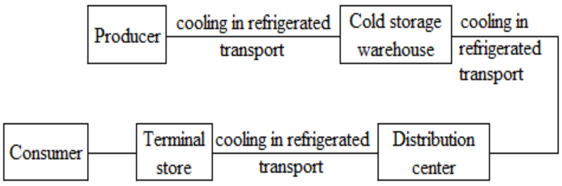

Figure 1 Schematic representation of cold chain

This paper gives information on the technology used in cold chain transportation, more specifically on vapour compression refrigeration system and calculation aspects regarding the total cost of this activity.

2. REFRIGERATION TECHNOLOGY USED IN COLD CHAIN

Vapour compression refrigeration systems involves the following main components: mechanical piston compressor, condenser, throttling valve and evaporator.

In the compressor, the refrigerant is compressed from low pressure to higher pressure, while being in superheated vapour state.

In the condenser, the refrigerant is turned into liquid, at constant pressure, while it releases heat to a cooling media.

Then, the refrigerant is throttled and loses from its pressure value.

In the evaporator, the refrigerant evaporates by absorbing latent heat of evaporation.

The vaporization process closes the working cycle.

It is important to notice that the heat transferred to the refrigerant in this heat exchanger represents the refrigerating effect.

In order to estimate the efficiency of the refrigeration cycle it is defined the Coefficient of Performance (COP), given by the rate between the refrigerating effect and the work consumed at the compressor.

The energetic cycle analysis is provided below [2], [3]. The ideal cycle comprised by compression (1–2), cooling (2–2’), condensation (2’–3), throttling (3–4) and evaporation (1–4) is given in Figure 2.

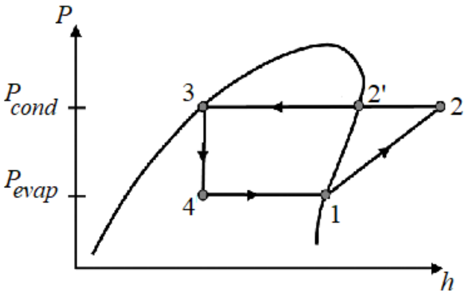

Figure 2 Ideal vapour compression refrigeration cycle in pressure – enthalpy diagram

The refrigeration effect:

$$q_{evap} = h_1 - h_4 \tag{1}$$

The work input to the compressor:

$$l_c = h_1 - h_2 \tag{2}$$

The heat evacuated in the condenser:

$$q_{cond} = h_2 - h_3 \tag{3}$$

The Coefficient of Performance:

$$COP = \frac{h_1 - h_4}{h_1 - h_2} \tag{4}$$

where:
h – specific enthalpy, kJ/kg.

Sustainable refrigeration technology should meet demands related to environmental issues (such as depletion of ozone layer and global warming) and energy consumption [4].

3. ESTABLISHMENT OF COMPREHENSIVE COST OF COLD CHAIN LOGISTICS

Nowadays, perishables quality and safety have social effects and cost implications; are of great importance on schedule delivery, customer satisfaction, waste decrease, information, transportation infrastructure, management, planning or environmental aspects [5].

The establishment of comprehensive cost of cold chain logistics takes into consideration

- port charge,
- shipping fee,
- refrigeration cost,
- green and carbon emission costs,
- penalty cost,
- split compensation and
- damage costs [6], [7], [8].

The comprehensive cost “C_c” is given by the sum between port charge cost (C_{PC}), shipping cost (C_{SH}), vehicle cost (C_v), refrigeration cost (C_{Ref}), fuel consumption cost (C_{FC}), carbon emission cost (C_{CO_2}), fuel cost of the refrigerator ship (C_{FR}), penalty cost (C_p), split compensation cost (C_{SP}) and damage cost (C_D).

These costs result from expenses caused by cargo operation at the port, maintenance, salaries, materials, operations, cooling, fuel, damage to the environment, change in the initial schedule, split of customer demand, freshness attenuation.

The formula is given as:

$$\begin{aligned} C_C &= C_{PC} + C_{SH} + C_v + C_{Ref} + C_{FC} + \\ &+ C_{CO_2} + C_P + C_{SP} + C_D \end{aligned} \tag{5}$$

The components of this total cost are found in the following.

$$C_{PC} = \sum_{i=1}^{n} a_i \tag{6}$$

where:
a_i – port charge in port “i”.

$$C_{SH} = f_k \left(\sum_{k=1}^{K} \sum_{i,j=0}^{n} x_{ij}^k t_{ij}^k + \sum_{k=1}^{K} \sum_{j=1}^{n} y_j^k \left(w_j^k + T_j \right) \right) \tag{7}$$

where:
f_k – shipping fee unit time of refrigerating vessel k,
x_{ij}^k – variable considering if ship “k” route is between two ports j and i,
y_j^k – variable considering if ship “k” route is in service of port j,
k – number of ships at the disposal of considered distribution centre,
t_{ij}^k – voyage time between ports i and j,
w_j^k – waiting time of vessel “k” in port j,
n – number of ports.

$$C_v = \sum_{v=1}^{V} f_v \tag{8}$$

where:
f_v – cost of v-th delivery vehicle,
V – number of delivery vehicles.

$$C_{Ref} = H_c \cdot t_{cos} \tag{9}$$

where:

H_c – hourly cost of cooling during transportation,

t_{cos} – time need to reach consumer.

$$C_{FC} = \sum_{i \in M \bigcup N} \sum_{j \in M \bigcup N} \sum_{k \in K} \sum_{t \in T} v_{ij} t_{ijk} f_t \lambda_f z_{ijt}^k \tag{10}$$

where:

M – distribution centre collection (m∈M),

N – supplier and seller demand not set (n∈N),

λ_f, f_t – fuel consumption rate distribution vehicles,

$$z_{ijt}^k = \begin{cases} 1 \\ 0 \end{cases}$$

it is a decision variable showing that value 1 is when vehicle k is moving in time t on road i, j, and value is 0 in otherwise,

v_{ij} – average speed of the vehicle,

t_{ijk} – time spend by vehicle k on road i, j.

$$CO_2 = (CO_2 + CO_C) \cdot (n_c d_i \, l_c S_C) \tag{11}$$

where:

CO_2 – carbon footprint of the vehicle,

CO_C – carbon emission resulted from cooling system during transportation for each distance covered,

n_c – number of cycles in recovery view,

d_i – distance covered by the vehicle,

l_c – load capacity of the vehicle,

S_C – social cost of the carbon.

$$\begin{aligned} C_{FR} = & \sum_{k=1}^{K} \sum_{i,j=0}^{n} x_{ij}^k UP_{HHO} \frac{g_e \left(\Delta_{ij}^k\right)^{2/3} \left(v_{ij}^k\right)^2 d_{ij}}{10^6 C} + \\ & + \sum_{i=1}^{K} \sum_{j=1}^{n} y_j^k UP_{MDO} \, \varphi \left(u_j^k + s_j\right) \end{aligned} \tag{12}$$

where:

UP_{HHO} – unit price of heavy fuel oil,

g_e – heavy fuel oil consumption rate of the main engine,

Δ_{ij}^k – displacement of the ship between i and j,

v_{ij}^k – speed of ship travelling from i to j,

d_{ij} – distance between ports i and j,

C – admiralty coefficient,

UP_{MDO} – unit price of marine diesel oil,

φ – diesel marine oil consumption coefficient of the auxiliary engine,

u_j^k – waiting time of ship k in j,

s_j – service time in j.

$$C_p = f\left(n^2\right) \tag{13}$$

from where results that this cost depends on the number of cycles in recovery view (n).

$$C_{SP} = \sum_{j \in N} C_{SPC} y_j \left(\sum_{k \in K} \sum_{j \in N} x_{ij}^k - \frac{p_j}{Q} - \frac{q_j}{Q} \right) \tag{14}$$

This cost is calculated only if the customer's demand is spitted.

Above:

C_{SPC} – cost of split compensation for splitting immediately the costumer's needs,

y_j – customer demand ($y_j = 0$ is case of no splitting),

p_j – pick-up quantity from the supplier,

q_j – requested quantity by the seller,

Q – maximum load capacity of the vehicle in charge with transportation.

$$C_D = \sum_{k=1}^{K} \sum_{i=1}^{n} y_i^k u_p V_i \left(1 - e^{-F\left(t_i^k - t_0^k + w_i\right)} \right) \tag{15}$$

where:

u_p – unit price of perishables on board,

V_i – unloaded volume of perishables in port i,

F – coefficient of freshness attenuation,

t_i^k – arrival time of the vessel in port i,

t_0^k – departure time of the vessel from a distribution centre.

4. CONCLUSIONS

This paper took into consideration important aspect regarding cold chain logistics in the case of multimodal transportation.

This research might be a good algorithm for the approach of this activity and it has a strong multidisciplinary characteristic.

Scholars are able to understand this activity from engineering point of view and financial point of view.

Was discussed vapour compression refrigeration systems which are used in refrigeration transportation and are subject of sustainable improvement.

In order to achive the goal of proving consumers with quality and safe products at convenient prices, was described the cold chain logistic and were provided in detail all costs of chain transport.

The issue is approaced multidisciplinary since are prividen aspects related to:

- thermodynamic processes in refrigerating plants
- cycle representation
- energy analysis leading to the performance assessment

- environmental problems
- total cost of the activity, with its multimodal façade, resulting the involvement of the following costs:
  - port charge
  - shipping cost
  - vehicle cost
  - refrigeration cost
  - fuel consumption cost
  - carbon emossion cost
  - fuel cost of the refrigerator ship
  - penalty cost
  - split compensation cost
  - damage cost

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