Economic-environmental comparison of an alternative refrigeration system with respect to a conventional refrigeration system applied to the transport of perishables

Comparativa económica- ambiental de un sistema de refrigeración alternativo con respecto a un sistema de refrigeración convencional aplicados al transporte de perecederos

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Abstract

The growing demand of food, which cannot always be produced where it will be consumed, has caused the increase of the perishable supply chain in recent years. Most of the transportation and distribution processes of perishable food are carried out by means of refrigerated vehicles, which use vapor compression refrigeration systems powered by a diesel engine. This type of refrigerated transport systems consumes a large amount of fuel, since the cooling system needs additional energy to extract the heat from the refrigerated box, causing an increase in the cost of transporting goods and the emission of greenhouse gases. (GHG). Due to the above, research has been carried out on alternate refrigeration systems, such as the absorption system using thermal energy, with which it could reduce operating costs and the emission of GHG from the truck tract, using waste heat from it. In the present work is carried out an economic-environmental comparison of an alternative refrigeration system with respect to a conventional system, applied to the transport of perishables. This comparison includes the calculation of GHGs and fuel costs, determining the advantages and disadvantages of each of the systems

Refrigerated transport, Energy comparative, Reduction of greenhouse gases

Resumen

La creciente demanda de alimentos, que no siempre pueden producirse donde serán consumidos, ha generado que la cadena de suministro de perecederos aumente en los últimos años. La mayoría de los procesos de transporte y distribución de alimentos perecederos se realiza por medio de vehículos refrigerados, que emplean sistemas de refrigeración por compresión de vapor impulsados a través de un motor diésel. Este tipo de sistemas de transporte refrigerado consume una gran cantidad de combustible, ya que el sistema de refrigeración necesita energía adicional para extraer el calor de la caja refrigerada, provocando un incremento en el costo de transporte de mercancías y en la emisión de gases de efecto invernadero (GHG). Debido a lo anterior, actualmente se han realizado investigaciones sobre sistemas de refrigeración alternativos, como son los sistemas por absorción, que utiliza energía térmica para operar. Este tipo de sistemas de refrigeración podrían reducir costos de operación y de emisión de GHG si utilizaran calor residual del mismo tracto camión. En el presente trabajo se lleva a cabo una comparativa económica-ambiental de un sistema de refrigeración por absorción con respecto a un sistema convencional, aplicados al transporte de perecederos. La comparativa se realiza en base al cálculo de las GHG y los costos de combustible, cada uno de los sistemas.

Transporte refrigerado, Comparativa energética, Reducción de gases de efecto invernadero

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Introduction

The growing demand for food, which can not always be produced where it will be consumed, has caused the perishable supply chain to increase in recent years.

The majority of the processes of transport and distribution of perishable food is carried out by means of refrigerated vehicles, which use vapor compression refrigeration systems powered by a diesel engine.

The number of refrigerated transport units (TRU) in Mexico is estimated at 54,900 according to a study prepared by the Mexican Institute of Transportation in 2015. [Morales Perez, Carmen, et al. (2014). Characteristics of refrigerated transport in Mexico]

These mobile units consume a large amount of fuel, since the cooling system needs additional energy to extract the heat from the refrigerated box. Furthermore, a refrigerated transport unit needs more energy to operate than a similar unit without refrigeration, even with the cooling system off, because the mere fact of having refrigeration machinery and insulating material, the weight of the truck increases considerably.

On the other hand, the cost of transportation of perishable products is directly linked to the consumption and price of fuel. Since conventional refrigeration systems installed in transport units need a large amount of energy, to extract the heat from the box to be cooled and move a greater weight, the fuel consumption is high causing an increase in the cost of transport of goods and in the emission of greenhouse gases (GHG).

The potential of diverse non-conventional refrigeration technologies is currently being studied, which allows the use of alternate energies for their operation, thus reducing the consumption of fossil fuels and the emission of greenhouse gases.

One of these unconventional technologies is absorption cooling that uses thermal energy to operate, this can be solar or process waste heat, which reduces fuel costs and emission of greenhouse gases into the atmosphere.

In the present work, a characterization of two refrigeration systems applied to the transport of perishables is carried out; one with conventional compression refrigeration technology and the other with an alternative absorption cooling technology.

For both cases, a refrigerated truck-type transportation unit is proposed, which transports chicken meat as perishable through an established route. The results show a comparison between the greenhouse gas emissions (GHG) of each of the refrigeration technologies and the economic savings for fuel consumed, one over the other.

Methodology

The comparative study begins with the estimation of the fuel consumption by each of the technologies, for which the refrigeration capacity that one wants to produce and the necessary power supply must be calculated, for the operating temperature ranges. With the estimated fuel consumption, the operating costs and GHG emissions of each refrigeration system are determined.

For the calculation of the heat extracted by the refrigeration system, thermal loads of the product (chicken meat), and thermal load by transmission of walls are considered.

Once the heat to be extracted is obtained, for each one of the refrigeration technologies, an energy analysis is carried out for each of the thermal processes that occur throughout the refrigeration cycles. The analysis is done through mass and energy balances, considering the compositions in the mixtures and the effects of pressure and temperature.

With the energy analysis, the amount of fuel necessary for the operation of each of the systems is determined, and with this the analysis of greenhouse gas emissions (GHG) for the truck tract is carried out.

The calculation of emissions was based on the methodology of standard EN-16258 prepared by the European Association of shipping, transport, logistics and customs services (CLECAT). [EN 16258 (2012) "Methodology for calculation and declaration of energyconsumption and greenhouse gas emissions of transport services"]

In order to carry out a comparison between the resulting greenhouse gas emissions for each refrigeration system, these emissions are calculated for a truck tract with the same characteristics and operating conditions..

Finally, the economic comparison of the fuel consumption is carried out, the results offer an overview of the savings that would be had in an absorption refrigeration system on one of steam compression applied to the transport of perishables in Mexico.

Development

Characterization of the Refrigeration Chamber

The proposed configuration for the refrigeration chamber mounted on a truck tract, can be seen in table 1.

Height	2.5 m.
Width	2.5 m.
Base	14.5 m.

Table 1 Dimensiones de la Cámara Frigorífica
Source: Self Made

The perishable product to be transported is chicken meat, which goes through a pre-cooling process before entering the refrigerated box of the truck tract, at a temperature of 4 ° C.

Inside the refrigerated container the temperature must be kept between 0 and 5 ° C, which is the temperature range for the preservation of the organoleptic properties of chicken meat according to the ASHRAE manual [American Society of Heating, R. a. A. E. (2013). Ashrae handbook: Fundamentals Atlanta].

Based on the above considerations, the operating characteristics of the cold room can be seen in table 2.

Cooling chamber	
Product	chicken meat
Capacity	20 tons
Coolant flow rate	4 m/s
Storage temperatura	3° C
Thermal isolation	Polyurethane

Table 2 Operation characteristics of the camera
Source: Self Made

The ambient temperature during the transfer is considered between 11 ° C and 33 ° C, taking the maximum temperature for the calculation of thermal loads to ensure that the system operates correctly.

Estimation of the cooling capacity

The estimation of the cooling capacity, heat to be extracted from the chamber by the refrigeration system, is made by calculating the thermal loads involved in the process.

In general the system gains heat by the following thermal loads:

a) *Thermal load generated by transmission through walls:*

$$Q = A * U * \Delta T \quad (1)$$

Where:

Q = total heat of transmission through the walls [KW]
A = exhibition area [m^2]
U = Overall coefficient of heat transfer [W/m^2 K]
ΔT= temperature difference [K]

b) *Thermal load generated by product:*

$$Q_{sensible} = m * Cp * \Delta t \quad (2)$$

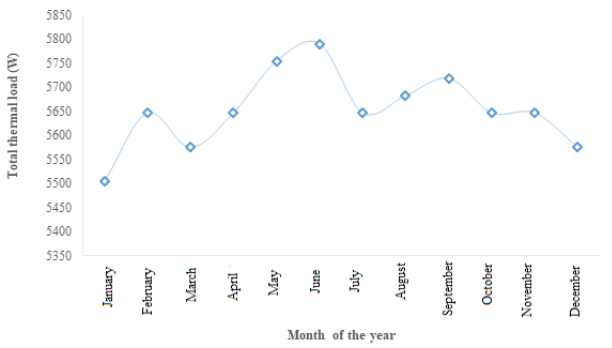
Where:

$Q_{sensible}$ = Heat extracted [KW]
m = mass of the product [kg/s]
Cp = specific heat above or below the freezing point [kJ/kg K]
ΔT = temperature difference. [K]

The thermal loads by equipment and infiltration are negligible, because the compressor is outside the cooling box and there is no opening of doors during the transfer.

The total thermal load, which defines the amount of heat that is extracted from the cooling chamber, is given by the following equation:

$$Q_{Total} = Q_{\ producto} + Q_{trasm\ por\ paredes} \quad (3)$$



Graphic 1 Total thermal load to be removed throughout the year
Source: Self Made

Figure 1 shows the behavior of the total thermal load that must be extracted from the refrigerated chamber in each month of the year. The largest amount of heat to extract is in the month of June, due to environmental conditions, and is 5.79 KW.

Energy Analysis of refrigeration cycles

a) Steam compression refrigeration cycle

A simple refrigeration cycle by heat compression is composed of four components: evaporator, compressor, condenser and expansion valve. Figure 2 shows the diagram of this cycle.

The heat to be extracted from the refrigerated chamber enters the evaporator, where it evaporates the flow of refrigerant flowing in a closed circuit. The refrigerant vapor enters the compressor increasing its pressure and increasing the condensation point, in order to be condensed at room temperature and transfer heat to the outside of the cycle.

The coolant flow, a steam-poor mixture, enters the expansion valve where it lowers its pressure and lowers the boiling point. The low pressure refrigerant enters the evaporator to extract the heat again and complete the cycle.

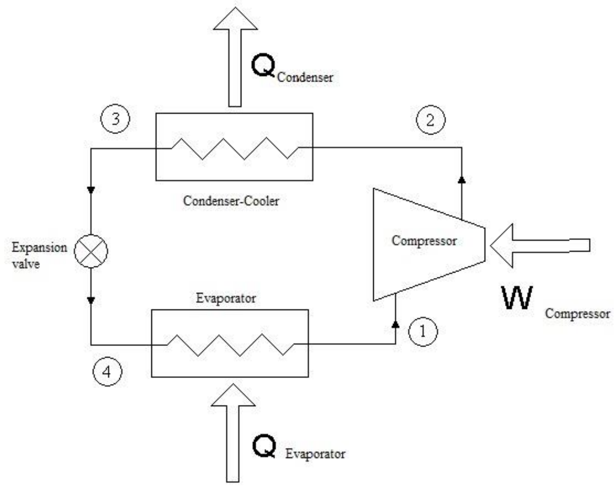


Figure 1 Simple compression refrigeration cycle
Source: Cengel, Y. A.; Boles, M.A.: Termodinámica. Mc Graw-Hill, 1996

The refrigerant that is considered in the analysis is R-404A, refrigerant belonging to the range of Hydrofluorocarbons, which is one of the most used for refrigeration in the transport of perishables.

The energy consumption is obtained from the work done by the compressor (W), through the mass flow and the enthalpies of the refrigerant at the inlet and outlet of the compressor.

Table 3 shows the results of the thermodynamic design for the refrigeration system at the proposed operating conditions.

Points	Place	P (kpa)	T (°C)	h (KJ/KG)	S (KJ/Kg K)
1	Evaporator outlet	519.36	-5	363.28	1.6102
2	Compressor output	1743.2	43.583	386.52	1.6102
3	Capacitor output	1743.2	38	256.84	1.909
4	Expansion valve outlet	519.36	-5	256.84	

Table 3 Thermodynamic analysis of the compression cooling system
Source: Self Made

The mass flow and compressor work are calculated by the following equations:

$$\dot{m} = \frac{Q_H}{h_{out\ comp} - h_{out\ evap}} \quad (4)$$

$$W_{comp} = \dot{m}\,(h_{out\ comp} - h_{in\ comp}) \quad (5)$$

Where:

Q_H = Total thermal load. [KW]
$h_{in\ comp}$ = Enthalpy to the compressor inlet. [kJ/kg]

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$h_{out\ evap}$ = Enthalpy at the entrance of the evaporator. [kJ/kg]
$h_{out\ comp}$ = Enthalpy at the compressor outlet. [kJ/kg]

To determine the electrical consumption of the refrigeration installation, the electric efficiency of the compressor must be taken into account, which is generally between 85% - 95%. [American Society of Heating, R. a. A. E. (2013). 2013 Ashrae handbook: Fundamentals Atlanta].

In this case, an electric efficiency of 90% was considered. Finally, the Coefficient of Operation (COP) of the system was calculated, this is the relation between the total thermal load extracted by the system [kW], and the power [kW] consumed by the compressor, which is given by:

$$COP = \frac{Q_{total}}{W_{compresor}} \quad (6)$$

Table 4 shows the results of the energy analysis of the vapor compression refrigeration system.

	Storage chamber
Thermal load	5.79 kW
Mechanical power of the compressor	1.13 kW
Electric power	1.26 kW
COP	4.58

Table 4 Energy consumption of the compression refrigeration system
Source: Self Made

b) Absorption cooling system cycle.

A system by absorption has the same components as one by vapor compression, where the refrigerant flows through a condenser, an expansion valve and an evaporator, except that the compressor is replaced by the assembly of an absorber, a pump, a generator and an expansion valve.

In the generator there is an increase in the temperature of the refrigerant-absorbent solution due to the heat transferred from a thermal energy source, producing a separation by evaporation of the refrigerant due to a lower miscibility than that of the absorbent fluid, leaving in the generator a liquid solution poor in refrigerant.

The refrigerant released in the gaseous state passes to the condenser where it is condensed, and then to the expansion valve where it undergoes a pressure drop.

The coolant-poor solution flows into the absorber, where it absorbs the refrigerant through an exothermic reaction.

The solution leaves the absorber and is compressed with a pump, where it increases its pressure taking it back to the generator and starts the cycle again. The work consumed by the cycle is only that which is necessary to operate the pump.

For the comparison, a simple regenerative absorption system with a binary NH3 / H2O mixture was considered, as shown in Figure 2.

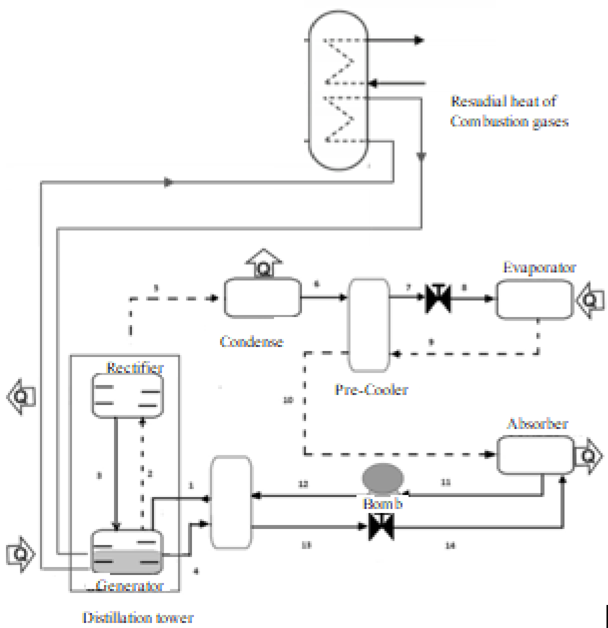

Figure 2 Absorption cooling system
Source: Self Made

This system includes a pre-cooler between the evaporator and the absorber, since it has a better thermal performance than one without regeneration.

The operating conditions of the absorption system must be those necessary to maintain the same heat extraction in the refrigerated chamber as obtained by the vapor compression system.

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The thermodynamic analysis of the absorption cooling system was carried out by mass and energy balances in each element of the cycle, for which the EES (Engineering Equation Solver) program was used to access the thermodynamic properties of the ammonia-water mixture of a simple and exact way. Table 5 shows the equations to determine the energy flows in each element of the system.

Component	Symbol	Equation
Evaporator	Q_E	$\dot{m}_{10}(h_{11}-h_{10})$
Absorber	Q_A	$\dot{m}_{12}(h_{12}-h_1)+\dot{m}_{10}(h_{11}-h_{10})+\dot{m}_{10}(h_1)+\dot{m}_6(h_1)$
Condenser	Q_C	$\dot{m}_7(h_7-h_8)$
Generator	Q_G	$\dot{m}_4(h_4)+\dot{m}_3(h_3))+\dot{m}_{14}(h_{14})$
Rectifier	Q_R	$\dot{m}_7(h_7)$
Solution pump	W_{hp}	$\dot{m}_1(h_2-h_1)$

Table 5 Energy flows in each component of the SRA
Source: Self Made

The energy balance is satisfied by the following equation:

$$Qg + Qe + Wp = Qa + Qc + Qr \quad (7)$$

The results for the energy balance of the refrigeration system per single effect absorption cycle, shown in Table 6, were obtained based on the ASHRAE method, where the following considerations are taken:

- System without pressure changes, except in the expansion valves and in the pump.
- In points 1, 4, 8, 11 and 14 it is considered saturated liquid, in 12 and 13 saturated steam.
- Heat losses or gains are not considered through the different components of the system and the ducts.
- The process in the expansion valves is considered iso-American.

Component	Symbol	Power (kW)
Evaporator	Q_E	5.79
Absorber	Q_A	8.21
Condenser	Q_C	5.53
Generator	Q_G	8.82
Rectifier	Q_R	.889
Solution pump	$\mathbf{W_{hp}}$	**.023**

Table 6 Results of thermodynamic analysis of the refrigeration system by absorption
Source: Self Made

Costs and emissions of greenhouse gases from refrigeration systems

To carry out the economic-environmental analysis, it was estimated the amount of fuel that both refrigerated apicado systems would consume. Table 7 shows the diesel fuel consumption for different types of refrigerated vehicles by compression, which use HFC 404a as a refrigerant, according to the Economic Committee of Internal Transportation of the United Nations (ATP).

Type of refrigerated vehicle	Fuel consumption per 100 km	Consumption percentage of the cooling system
	l/día	%
Van (7.5-17 ton)	26.9 – 31	18.9
Rigid vehicle (17-25 ton)	38.2	19.5-24.2
Articulated vehicle (<25 ton)	36.2	15.6

Table 7 Fuel consumption of refrigerated vehicles
Source: (Energy Efficiency in Transport Refrigeration in: Proceedings, International Congress of Refrigeration, Beijing, China, Paper)

The fuel costs for refrigerated transport units that operate, with refrigeration system by compression, and with refrigeration system by absorption, are calculated from equations (8) and (9), respectively.

$$Costo_{FRC} = C_{100Km} * D * P_f \quad (8)$$

$$Costo_{FRA} = (1 - C_{RC})C_{100Km} * D * P_f \quad (9)$$

Where: C_{100Km} is the fuel consumption per 100 km, D the distance traveled in Km, P_f the price of fuel and C_{RC} the fraction of fuel consumed by the compression refrigeration system.

Greenhouse gas emissions (GHG) are estimated from direct or indirect fuel consumption. Fuel consumption depends mainly on the design and quality of the cooling system, the insulation qualities of the refrigerated chamber and the operating practices. Direct fuel emissions depend on the type of vehicle, the load, the distance and the amount of fuel used (TTW), while the indirect emissions come from the production of the fuel, and play an important role when the carbon inventory is produced for transportation services (WTW).

From the equations (10) and (11) the GHG emissions are estimated for both refrigerated transport systems.

$$G_T = F * g_T \quad (10)$$

$$G_W = F * g_W \quad (11)$$

Where: G_T and G_W are the direct and indirect GHG emissions, respectively. F is the fuel consumption in liters, g_T the factor of direct emissions in kg of CO_2 emitted and g_W the emission factor is indirect in kg of CO_2 emitted.

The conversion factors necessary to calculate the emissions are taken from the methodology EN 16258, and are shown in Table 8.

Greenhouse gases	
TTW	WTW
kg CO2e/l	kg CO2e/l
2.67	3.62

Table 8 Factores de converción de GHG
Source: Standard EN 16258 "Methodology for calculation and declaration of energy consumption and greenhouse gas emissions of transport services"

Results

To estimate the economic cost of fuel consumption (diesel), we considered a refrigerated truck tract with a performance of 36 liters per 100 km (Table 6).

Where the refrigeration system consumes 15.6% of the total fuel, so the absorption refrigeration system, including the work of the pump, would save 4.9 liters of fuel per 100 km.

On the other hand, according to the study of C RepICE, A. Stumpf, it is proposed that refrigerated transport travel approximately 400 km per day, operating the vehicle 260 days a year, resulting in 104,000 km per year.

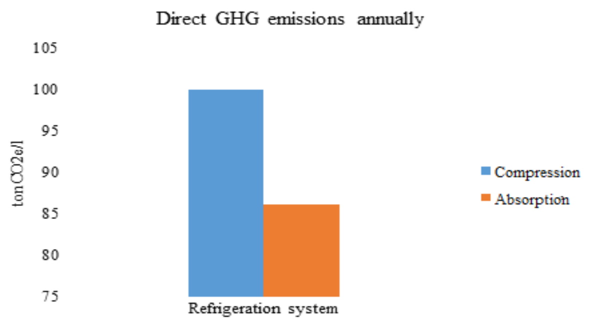
Table 8 shows the economic comparison between compression refrigeration (SRC) and absorption (SRA) systems.

	SRC		SRA	
Weather	Fuel (Lt)	Fuel cost ($)	Fuel (Lt)	Fuel cost ($)
Day	144	2,880	124.13	2,482.56
Week	720	14,400	620.64	12,412.8
Month	3,120	62,400	2689.44	53,788.8
Year	37,440	748,800	32,273.28	645,465.6

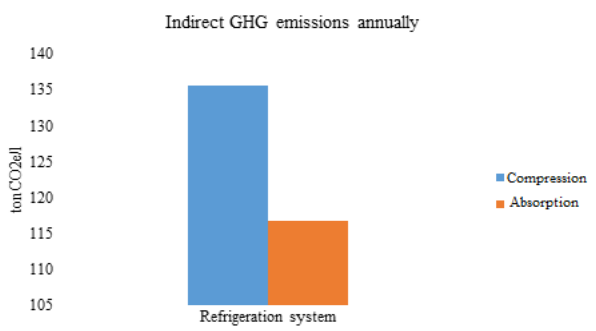
Table 9 Economic analysis of cooling systems (Considering diesel price at $ 20 lt)
Source: Own Elaboration

In the table it can be seen that annually the use of an absorption refrigeration system saves approximately $ 103,344 pesos for fuel (diesel).

Graphs 2 and 3 show the direct and indirect emissions, obtained from the fuel consumption per year, of two articulated trucks; one with compression cooling system and the other with absorption cooling system.



Graphic 2 Comparison of GHG direct annual emissions of articulated trucks with absorption and compression refrigeration systems
Source: Self Made



Graphic 3 Comparison of indirect annual GHG emissions from articulated trucks with absorption and compression refrigeration systems
Source: Self Made

From the results, shown in graphs (2) and (3), we can see that an absorption cooling system applied to the transport of perishables stops emitting about 34 tons of CO2 into the environment; 15 tons directly and 21 tons indirectly.

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Conclusion

Absorption refrigeration systems are currently being considered as an alternative to reduce greenhouse gas emissions, by incorporating solar thermal energy into the refrigeration industry.

However, absorption cooling is not limited to the use of solar energy, since it can occupy residual heat as an energy source. A diesel engine usually has a thermal efficiency of 30%, which means that 70% of the fuel's energy is lost in the form of heat. The recovery of only a small portion of this wasted energy would be enough to cover the refrigeration requirements of an articulated transport.

The use of waste heat to feed the absorption refrigeration system of articulated trucks would significantly reduce the amount of greenhouse gases emitted into the environment, approximately 11 million tons of CO2 per year, considering the approximately 50,000 refriged trucks reported by the company. Mexican Institute of Transport in 2015.

In addition to reducing emissions, the recovery of recurrent heat would also have an economic impact on the cost associated with the use of fuel, estimated at approximately $ 100,000 pesos per year for each refrigerated truck tract.

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