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Research Article

Optimization of a Cooling Storage Room Coupled with an Absorption Solar Cooling System for Fish and Onions Preservation

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Abstract

The integration of solar cooling system into the food preservation system is an important step towards energy sustainability. Study aims are to design a cooling system combining solar thermal energy, an absorption cooling system and cooling rooms. The cooling rooms studied are containers intended to preserve fish and onions with storage capacities of 1000 kg and 2000 kg respectively. A modeling of the different subsystems was done and the energy balances established. The model simulation is done with Engineering Equation Solver (EES). The results obtained show that for solar thermal collector efficiency between 0.6 and 0.7, the area of the solar thermal field can be optimized to 45 m^2 and 70 m^2 respectively for the preservation of onions and fish. Similarly, for solar irradiation between 5 KWh/m^2 and 6 KWh/m^2, the area of the solar thermal field decreases from 100 m^2 to 40 m^2 and from 160 m^2 to 60 m^2 respectively for the cold room intended to preserve onions and fish. For thermal loads greater than 50 KWh and 80 KWh respectively for onions and fish, the area of the solar field increases linearly with the increase in thermal loads.

Keywords

Cooling System, Cooling Rooms, Fish, Onions, Solar Thermal Collector, Thermal Loads

1. Introduction

With population growth, food and energy needs will increase by 35 to 56% between 2010 and 2050 [1, 2]. Likewise, The rapidly increasing population witnessed at a global level poses a significant challenge to the equally important tasks of preserving the environment and sustaining the food supply. According to Food and Agriculture Organization of United Nations, projections indicate a substantial population growth of 2.3 billion people in 2050. This exponential surge not only directly affects daily food demand but also amplifies energy consumption [3, 4]. As the need for food and demand for energy rises in tandem with population growth, it becomes crucial to explore sustainable solutions for preserving and storing perishable items to meet the evolving demands of a larger and more dynamic global population [3]. So feeding the

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world's growing population is widely acknowledged to be one of the problems facing humanity. In this respect, food preservation plays a major role in addressing world hunger [5]. Post-harvest losses in the food supply chain vary considerably. In developing countries, a large proportion is lost due to a lack of agricultural storage infrastructure. In developed countries, food losses are high at the consumer end and low in the mid-chain, thanks to the availability of storage infrastructure [6]. Fish preservation requires meticulous care, from catch to final consumption. Cooling systems play a crucial role in this process. They consume a considerable amount of energy, thus contributing to operating costs [7, 8]. With the development of the global maritime economy, the ocean fishery supply chain has been a focus and has been studied by many scholars [9]. The fishing industry, with its significant growth rate, plays a crucial role in the economies of African countries. Despite the immense potential offered by both inland and sea-level fishing, a substantial amount of fish is being wasted due to insufficient refrigeration [10]. Various methods have used to preserve food to slow down its deterioration and ensure its safety. Food preservation encompasses a series of processes aimed at preserving the organoleptic and nutritional properties as well as the edibility of products, while avoiding the risk of food poisoning. However, most traditional cold production systems rely on the use of fossil fuels, resulting in high energy consumption and a contribution to the greenhouse effect, which raises serious environmental issues. Cooling system is one of the largest consumers of energy. It represents 15 to 17% of global energy. Energy costs not only impact profitability but also increase the carbon footprint [11].

Horticultural product undergoes several critical stages in the food supply chain (FSC), including harvesting, post-harvest handling, storage, packaging, logistics operations such as loading and unloading, and transportation, before reaching the end consumer. Inefficiencies in these processes contribute to postharvest losses (PHL), adversely impacting the entire FSC [12, 13]. Onion (*Allium cepa* L.) is a widely consumed vegetable [14]. Onions are recognized for their various biological activities, such as antioxidant which are mediated by their contents of sulfur, phenolic, and selenium compounds. Onions are highly perishable. They are subject to post-harvest losses, such as sprouting and weight loss, which together contribute to nearly 23 to 25% of total losses. This phenomenon can be attributed to climatic hazards and the lack of efficient storage systems. Consequently, high price volatility is often noted [15]. Onion bulb is an important vegetable crops in the world [16]. Due to their high moisture content, fresh onions are prone to rapid deterioration. Their storage is complex and is governed by many factors before and after harvest [17]. Globally, 33% of food production is wasted. The lack of sustainable after-harvesting practices, such as cooling and drying, wastes 50% of fruits and vegetables at the farm level [18, 19]. Furthermore, a large portion of the world's population lives in remote areas where access to electricity remains limited and expensive. This lack of energy infrastructure poses a major challenge for food preservation in these regions. Faced with this challenge, the use of solar energy, wind, geothermal, and biomass is emerging as a viable and sustainable solution.

Technological advances have made it possible to develop solar refrigeration systems, which harness solar energy to maintain food at an optimal storage temperature. Solar refrigeration, particularly suited to food preservation, offers the advantage of reducing the carbon footprint and lowering the energy costs associated with refrigeration. An initial design stage involves modeling and simulating to achieve efficient cold storage. Research about the optimization of cold storage for household refrigerators was combined with mathematical modeling or simulation cycle in engineering equation solver software [20-22]. Cold storage containers are designed with compact dimensions and use solar PV as their primary energy source [23]. As consumer awareness of sustainable food supply grows, food distribution systems must enhance their environmental performance while maintaining economic competitiveness [24]. By 2050, urban populations will reach 80% of the global total population (UN DESA, 2014), highlighting the urgency of promoting energy conservation, emission reduction, and low-carbon development in cities to mitigate global climate change, while ensuring global food self-sufficiency [25]. Climate change also requires urgent action to reduce greenhouse gas emissions. In this critical context, solar air conditioning stands out as a cutting-edge technology, offering an innovative solution to cooling needs while also aligning with a sustainable approach. Solar cooling system harnesses the abundance and free availability of solar energy. It represents a major technological advance in the field of climate engineering [26, 27]. Its integration into residential and office buildings is not only a response to the need of reduction greenhouse gas, but also part of a vision of energy autonomy. Traditional air conditioning systems, although widespread, are large consumers of energy. In contrast, solar air conditioning offers a dual promise: sustainable thermal comfort and a minimized environmental footprint. These technologies, in harmony with the principles of sustainable development, enabling the implementation of green and energy-efficient buildings. Solar assisted absorption chillers are considered as the one of the most applicable methods for benefiting the solar energy for cooling purposes, especially in regions with a high amount of solar radiation [28]. This work is interested on solar refrigeration for the preservation of agri-food products, more specifically fish and onions. Thus, in the materials and methods section, we will study the thermal loads of the cold storage room and evaluate the energy requirements necessary to maintain an adequate set temperature. The results obtained will be analyzed.

2. Materials and Methods

2.1. System Description

The system is composed of five subsystems, as shown in Figure 1.

2.1.1. Solar Thermal Field Subsystem

The solar thermal field converts the received solar radiation into heat. This heat is transferred to the working fluid.

2.1.2. Hot Storage Tank Subsystem

The hot storage tank is a thermal energy reserve. It provides the heat required by the absorption machine during days when solar irradiation is low.

2.1.3. Absorption Cooling Subsystem

The absorption machine produces cold using a couple like ammoniac and water.

2.1.4. Pump Subsystem

The pump ensures the circulation of the water cooled by the absorption cooling system to the fan coils of the cooling rooms so that it can absorb the heat and efficiently cools the rooms.

2.1.5. Fan Coil Subsystem

Fan coils play a key role in the distribution of cold in the cooling rooms. Their main function is to transfer the cold produced by the absorption cooling system to the ambient air of the room.

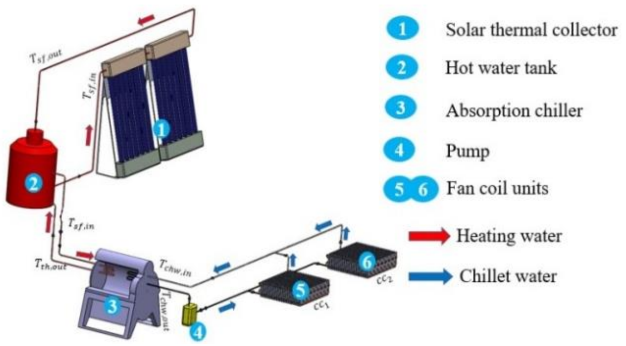

Figure 1. *Diagram of solar absorption cooling system coupled with a cooling room.*

2.2. Heat Balance

The heat balance allows us to assess heat exchanges within the various subsystems. A heat balance will be performed for each subsystem. This balance aims to quantify heat losses and gains, as well as to assess the efficiency of the system. This approach will help to optimize system performance, better understand energy needs, and ensure more efficient heat and cold management in the various parts of the process.

2.2.1. Thermal Solar Field Subsystem

Thermal solar collector is a device used to receive and collect solar energy and convert it into heat. The power absorbed by the solar collector field is given by the equation (1).

$$Q_{Col} = \eta_{Col} * I_r * A_{Col} \tag{1}$$

2.2.2. Absorption Cooling Subsystem

The energy balance of the absorption cooling subsystem allows cold production. This system uses ammonia and water as shown in Figure 2. The objective is to understand how thermal energy coming from solar thermal collectors is used to produce cold and to understand the energy losses or gains during the process. The energy balance helps to evaluate the system's performance, identify potential energy losses, and improve its efficiency.

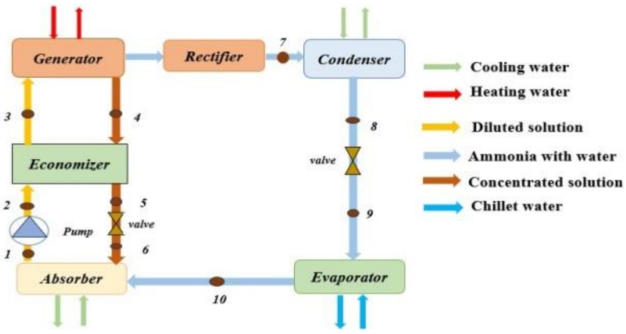

Figure 2. *Schematic diagram of an absorption cooling system.*

Equation (2) gives Coefficient of performance.

$$COP = \frac{\dot{Q}_e}{\dot{Q}_g + \dot{W}_p} \tag{2}$$

With:

$$\dot{Q}_e = \dot{m}_{e,wi} * C_p * \left(T_{e,wi} - T_{e,wo}\right) \tag{3}$$

$$\dot{Q}_g = \dot{m}_{g,wi} * C_p * \left(T_{g,wi} - T_{g,wo}\right) \tag{4}$$

$$\dot{W}_p = \dot{m}_1 * (h_2 - h_1) \tag{5}$$

Evaporator: This is a heat exchanger responsible for cooling the warehouse by absorbing its heat. It takes place in a tubular circuit within the refrigerator enclosure. The working fluid becomes steam at the outlet of the evaporator. Thus the cooling capacity of the evaporator is given by the equation (6).

$$Q_e = (h_{10} - h_9) \quad (6)$$

Similarly, the mass balance at the evaporator is written by:

$$\dot{m}_f = \dot{m}_{10} = \dot{m}_9 \quad (7)$$

Absorber: The vapor at the evaporator outlet is absorbed by the absorber. The energy balance at the absorber is given by equation (8).

$$\dot{Q}_{ab} = \dot{m}_{10}.h_{10} + \dot{m}_6.h_6 - \dot{m}_1.h_1 \quad (8)$$

The mass balance can also be established by:

$$\dot{m}_6 = \dot{m}_{10} + \dot{m}_1 \quad (9)$$

Generator: It acts as a solution separator. The refrigerant vaporizes and passes into the condenser. The energy and mass balances are given by equations (10) and (11).

$$\dot{Q}_g = \dot{m}_4.h_4 + \dot{m}_7.h_7 - \dot{m}_3.h_3 \quad (10)$$

$$\dot{m}_3 = \dot{m}_4 + \dot{m}_7 \quad (11)$$

Condenser: The steam coming from the generator is condensed after passing through the condenser. The energy and mass balances are given by equations (12) and (13) respectively.

$$\dot{Q}_c = \dot{m}_f.(h_7 - h_8) \quad (12)$$

$$\dot{m}_f = \dot{m}_7 = \dot{m}_8 \quad (13)$$

2.2.3. Cooling Room Subsystem

The energy balance of the cooling room allows to know all the heat that must be evacuated to maintain cooling room at the set temperature. Depending on the type of food and the required storage temperature, one note two types of cooling room:

1) Positive cooling room that maintains an interior temperature above 0 ℃,
2) Negative cooling room that maintains an interior temperature below 0 ℃,

It is important to manage heat in cooling rooms to ensure efficient cooling and maintain the quality of stored products. In this study, we chose fish and onions because they are widely consumed products in Senegal. These products often encounter storage problems due to the country's hot and humid climatic conditions. Fish, which is particularly sensitive to heat, requires strict refrigeration for its preservation. Onions, although less fragile, must be stored in a cool environment. Fish is usually kept at sub-zero temperatures for long-term preservation, but here we aim to keep it fresh for 10 hours at a suitable temperature. A temperature of 4 ℃ was chosen for fish and onions because it is ideal for temporary storage of 10 hours. This duration was chosen to meet the needs in the fishing sector such as fishmongers and traders who do not require long term refrigeration. The cooling rooms studied are containers designed to store fish and onions. They are well insulated and have 6 m longer, wide 4 m and 3 m higher. They have a storage capacity of 2000 kg for fish and 1000 kg for onion. The calculation of heat balance of cooling is carried out from the thermal loads which are divided into external and internal loads. In this study, the external loads are assumed to be negligible due to the insulation. Thus, only the internal loads given in table 1 will be taken into account.

Table 1. *Simulation parameters.*

Parameters	Foodstuffs	
	Fish	Onion
Temperature of incoming food [$°C$]	25	25
Cooling room temperature [$°C$]	+4	+4
Mass of incoming products [kg]	2000	1000
Specific heat capacity [$kJ/kg * K$]	2,93	3,81
Thermal load due to lighting [kWh]	0,75	0,75
Heat load due to incoming food [kWh]	34,18	22,225
Heat load due to respiration of foodstuffs [kWh]	116,11	77,98
Heat load due to workers [kWh]	0,512	0,512
Total internal thermal loads [kWh]	151,552	101,467
Intermediate cooling capacity [kW]	15,16	10,15
Required cooling capacity [kW]	18,19	12,18

The knowing of the required cooling power makes it possible to determine the energy requirement which is given by equation (13).

$$B_{ener} = \frac{P_r}{\eta_{dis}} t_d \quad (14)$$

The area of the required solar thermal field to respond to the operation of the system must be evaluated. It is given by equation (15).

$$A = \frac{B_{ener}}{\eta_{Col} * I_r} \quad (15)$$

Table 2 gives the energy requirements and the required surfaces of the two containers, for the foodstuffs considered.

Table 2. Simulation parameters for solar thermal collectors.

Parameters	Foodstuffs	
	fish	Onion
B_{ener} $[kWh]$	202,11	135,33
A $[m^2]$	66,84	44,75

3. Results and Discussions

EES was used to simulate the operation of the absorption cooling system. The thermodynamic cycle was modeled, and calculations of energy balance determined the effect of physical parameters such as temperature on the system components.

To validate the absorption cooling subsystem, we performed a numerical simulation and the results obtained are compared with those in the literature. The compared results are given in tables 3 and 4.

Table 3. Comparison of the results of our work with the results of other authors.

	Vinay Kumar et al. [29]				J. Aman et al. [30]				our work			
Etats	$T[°C]$	x	$h[kJ/kg]$	$P[kpa]$	$T[°C]$	x	$h[kJ/kg]$	$P[kpa]$	$T[°C]$	x	$h[kJ/kg]$	$P[kpa]$
1	30	0,54	-104,9	455,5	30	0,55	-114,25	461,67	35	0,4856	-83,7	400
2	30	0,54	-104,2	1172,2	30	0,55	-114,25	1166,92	35,26	0,4856	-80,9	1600
3	65,6	0,54	58,8	1172,2	62	0,55	35,42	1166,92	41,26	0,4856	202,2	1600
4	84	0,45	143,2	1172,2	80	0,439	110,85	1166,92	85	0,4899	146,1	1600
5	40,8	0,45	-50,84	1172,2	40	0,439	-77,13	1166,92	78	0,4899	117,1	1600
6	40,8	0,45	-50,84	455,5	40	0,439	-77,13	461,67	44,32	0,4899	117,1	400
7	84	0,89	1637	1172,2	80	1	1627	1166,92	85	0,984	1442	1600
8	30	0,89	341,6	1172,2	30	1	340,78	1166,92	41,68	0,984	301,6	1600
9	-2	0,89	341,6	455,5	2	1	340,78	461,67	-1,2	0,984	301,6	400
10	-2	0,89	1460	455,5	2	1	1465,85	461,67	2	0,984	1130	400

Table 3 shows a slight difference between the results. This difference could be attributed to several factors, including simulation assumptions, operating conditions such as hot and cold source temperatures, or working fluid properties. It is also possible that other studies used more detailed numerical models or different calculation approaches. However, we note that the trends observed in our results are generally consistent with literature results.

Table 4. Comparison of the COP of our work and those of other works.

Parameters	Evangelos Bellos et al. [31]	Vinay Kumar et al. [29]	our work
T_{gen} (℃)	80	80	85
T_{evap} (℃)	2	2	2
T_{abs} (℃)	30	30	35
T_{cond} (℃)	30	30	41,68
COP	0,5859	0,65	0,69

Although this study uses the same working fluid pair (ammonia-water) as those reported in the literature, a very slight difference was observed in the coefficient of performance values as shown in table 4. Although the working fluids are identical, the operational conditions of the absorption cooling system, such as operating temperatures and component pressures, may vary from study to study, which has a direct impact on the COP.

Effect of condenser temperature on COP is given in Figure 3.

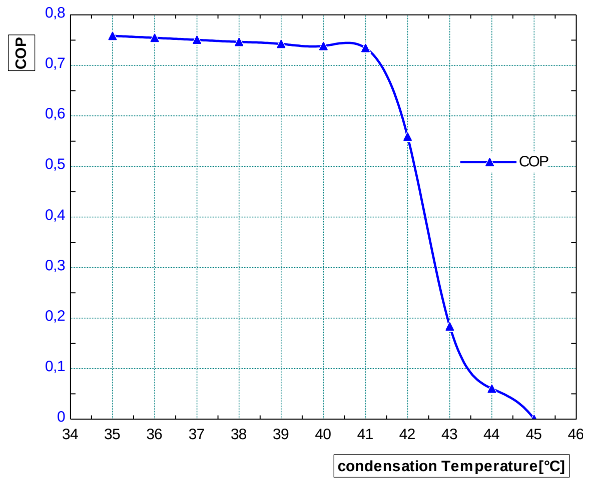

Figure 3. *Coefficient of performance as a function of condenser temperature.*

Figure 3 gives effect of condenser temperature on the COP. When the condenser temperature increases, the COP remains constant and is equal to 0.7. When condenser temperature exceeds 40 ℃, the COP decreases considerably. Therefore, for the system better work, the condenser must not reach certain temperatures.

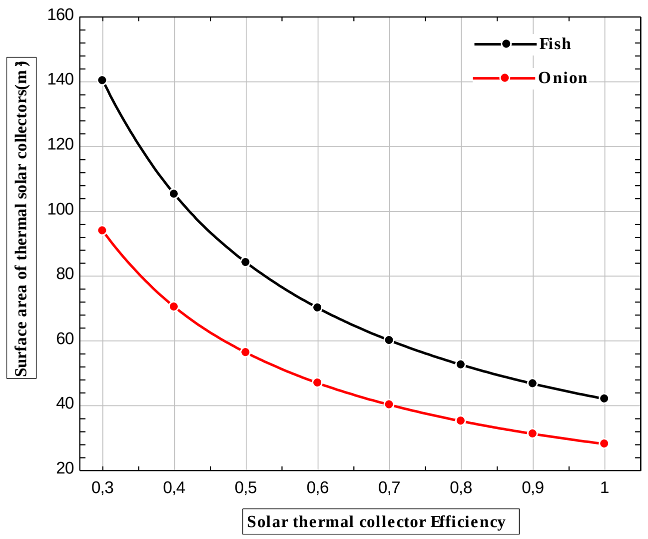

Figure 4. *Variation of solar thermal area as a function of solar thermal efficiency.*

The variation of the solar thermal area as a function of solar thermal efficiency is given in Figure 4.

Figure 4 shows that as thermal collector efficiency increases, the area required to meet the given energy demand decreases. The thermal efficiency of solar thermal collectors is between 0.6 and 0.7. For such efficiency, the area of the solar thermal field can be optimized to 45 m^2 to meet the energy needs of the cooling room intended to preserve onions and to 70 m^2 for the cooling room intended to preserve fish. A higher efficiency means that each square meter of solar thermal collector is more efficient in receiving and converting solar radiation into working heat. Therefore, less solar thermal collector area is required to provide the same amount of thermal energy required.

The variation of solar irradiation as a function of solar thermal area is given in Figure 5.

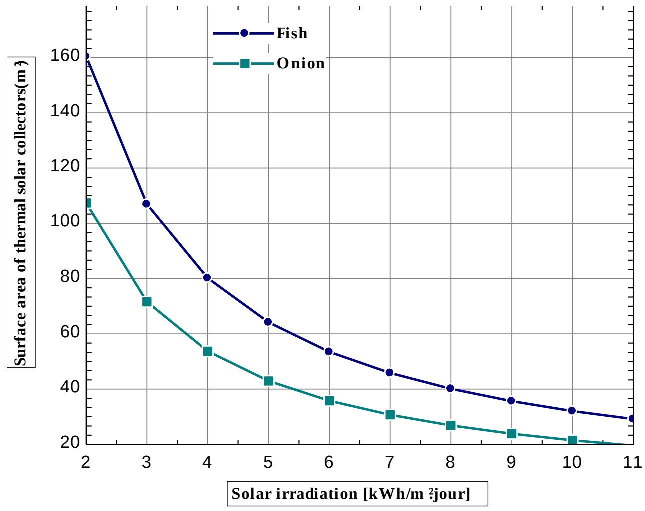

Figure 5. *Variation of solar thermal collector area as a function of solar irradiation.*

Solar irradiation varies greatly from one region to another, depending on several factors such as latitude, season and local weather conditions. In Senegal, the average value of solar irradiation varies between 5 kWh/m^2 and 6 kWh/m^2. Figure 5 shows that for solar irradiation between 5 kWh/m^2 and 6 kWh/m^2, the area of the solar thermal field decreases from 100 m^2 to 40 m^2 and 160 m^2 to 60 m^2 respectively for cooling room intended to preserve onions and cooling room intended to preserve fish. Thus, the area of the solar thermal field required to ensure a better work of the system can be reduced in sunny areas.

The variation of solar thermal area as a function of thermal loads is given in Figure 6.

Figure 6 shows a linear relationship between the thermal loads and the area of the required solar collectors. For thermal loads of 50 kWh, the area of the solar thermal field remains constant at 25 m^2 for the cooling room intended for the preservation of onions. This same area is capable to operate the cooling room intended for the preservation of fish up to a thermal load equal to 80 kWh. For thermal loads greater than 50 kWh and 80 kWh for onions and fish respectively, the area of the solar thermal field increases linearly with the increase in thermal loads.

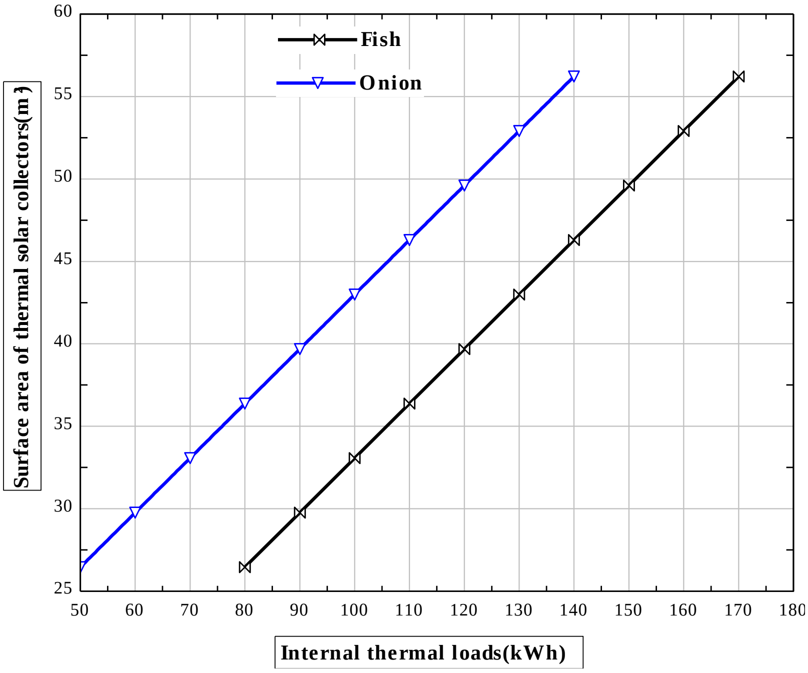

Figure 6. *Variation of solar thermal area as a function of thermal loads.*

The variation of the solar thermal area as a function of relative humidity in cooling rooms is given in Figure 7.

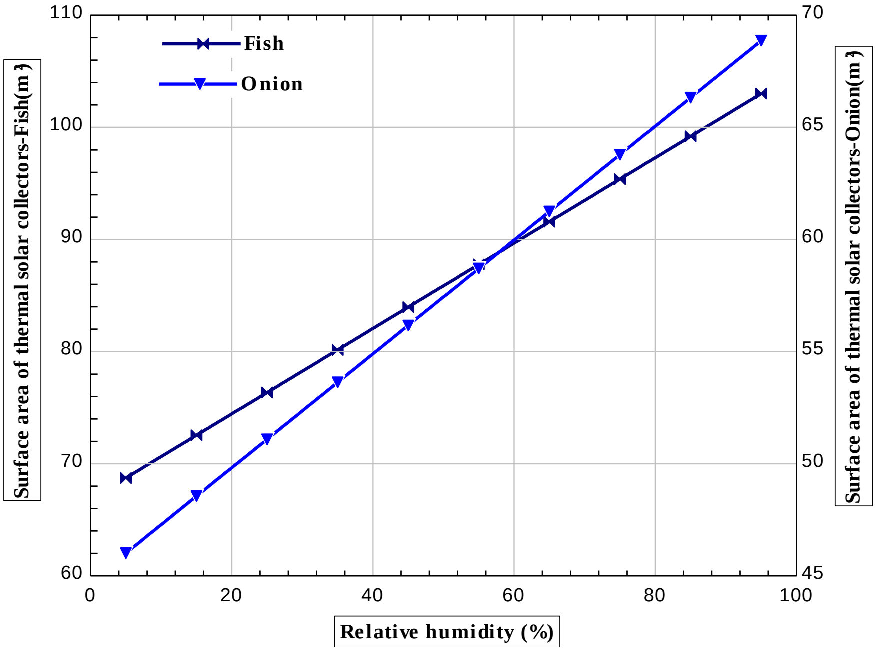

Figure 7. *Influence of relative humidity in cooling rooms as a function of solar thermal area.*

Figure 7 shows that an increase of the relative humidity of cooling rooms leads to an increase of the area of the solar collectors to provide the required energy. Increased humidity requires more solar collectors to maintain an optimal temperature for product preservation. This is because as humidity in the cooling room increases, the humid air retains more heat. It make difficult to maintain the desired temperature. In addition, products such as fish or onions generate additional residual heat, which increases the thermal load. Therefore, to maintain the temperature under control despite higher humidity, a larger area is required. Air exchange can also be used.

Figure 8 is a comparison of the thermal loads and cooling capacities of the two cooling chambers.

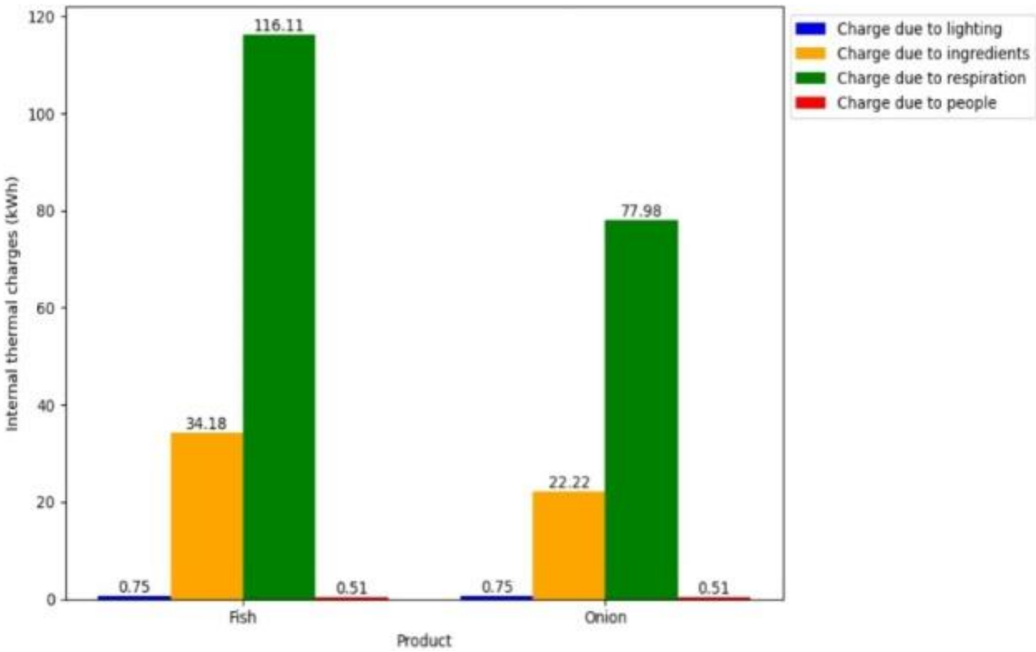

Figure 8. *Internal thermal loads for fish and onion.*

Figure 8 compares the internal heat loads of fish and onions.

The heat loads considered are lighting, incoming food, and occupants.

The heat load due to lighting is identical in the two cooling rooms, with a value of 0.75 kWh. This indicates that lighting has an identical impact on cooling rooms studied. Regarding the load due to incoming food, it is higher for fish than onions. Regarding the load due to food respiration, it is also higher for fish than onions. Fish generates a greater heat load in the cooling room. The heat load generated by occupants in the cooling rooms is relatively low. In summary, Figure 8 shows that the loads due to incoming food and food respiration are greater for fish, requiring greater cooling capacity to maintain the storage temperature. These differences in thermal loads directly translate into higher cooling power requirements for storing fish (18.19 kW) compared to onions (12.18 kW).

4. Conclusion

The integration of solar cooling system into the food preservation system represents a significant step towards energy sustainability. This study focuses on two container-shaped cooling rooms designed to preserve fish and onions, with storage capacities of 1,000 kg and 2,000 kg. The different subsystems were modeled and energy balances were established. The model simulation is done using the Engineering Equation Solver. The results obtained show that for solar thermal collector efficiency between 0.6 and 0.7, the area of the solar thermal field can be optimized to 45 m^2 and 70 m^2 respectively for the preservation of onions and fish. Similarly, for solar irradiation between 5 KWh/m^2 and 6 KWh/m^2, the area of the solar thermal field decreases from 100 m^2 to 40 m^2 and from 160 m^2 to 60 m^2 respectively for the cold room intended to preserve onions and fish. For thermal loads greater than 50 KWh and 80 KWh respectively for onions and fish, the area of the solar field increases linearly with the increase in thermal loads. However, adapting solar cooling solutions to local climate variations, as well as managing thermal loads specific to each type of product (fish, onion) remain key elements to optimize. This optimization will ensure the sustainability and profitability of the installations.

Abbreviations

h	Enthalpie (kj/Kg)
Q_Col	Power Received (W)
η_Col	Thermal Collector Efficiency
I_r	Direct Normal Solar Irradiation (W/m^2)

A_Col	Solar Thermal Field Area (m^2)
C_p	Specific Heat (kJ/kg*K)
P	Cooling Capacity [kW]
Q˙	Energy (J)
W˙	Energy (J)
m˙	Mass Flow (kg/s)
t	Time (s)
T	Temperature (°C)
ab	Absorber
c	Condenser
Col	Collector
d	Day
dis	Distribution
e	Evaporator
ener	Energy
g	Generator
p	Pump
r	Required
w	Water

Author Contributions

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Serigne Thiao: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing

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Diouma Kobor: Project administration, Supervision, Validation, Visualization

Issakha Youm: Project administration, Supervision, Validation, Visualization, Writing - review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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