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Evaporative Cooling Driven by a Venturi Tube Revisited; Assessing the Performance of Different Refrigerant-Circulating Pairs

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Abstract-This study presents the design, construction, and evaluation of a Venturi Evaporative Cooling System (VECS). The system utilizes a venturi tube to create vacuum conditions that lower the boiling point of refrigerants and promote evaporation. The efficiency of different circulating-refrigerating pairs of liquids is explored and a simple refrigerating cycle is proposed. The performance of the system was assessed by measuring temperature changes within a closed environment, examining the impact of vacuum conditions produced by two circulating fluids (water and ethylene glycol) on the boiling point of three different working substances or refrigerants (ethanol, acetone, and diethyl ether), and determining the coefficient of performance (COP) to gauge the efficiency of the cooling system. The best vacuum achieved was 44.58 kPa using ethylene glycol as the circulating liquid. The lowest temperatures reached were -31°C in the liquid phase using diethyl ether as the refrigerant and -18°C in the enclosed atmosphere. The highest COP attained was 0.00202 for diethyl ether, in comparison with a COP of 1.98 x 10-5 for ethanol (the lowest performance). Further investigation is required to explore the use of different low viscosity circulating-refrigerating immiscible fluid pairs to attain lower pressures and higher evaporation rates, free of non-condensing gases closed environments to further increase the evaporation rate of the refrigerant, use of expansion valves or pumps to complete the cycle to avoid working in batches, and more efficient components in order to achieve better performance of the proposed cycle.

Keywords: Evaporative cooling, venturi ejector, vacuum, ethanol, acetone, ethyl ether.

Nomenclature

Symbol	Represents	Units
Q	Heat	J
W	Work	J
C_{lr}	Refrigerant latent heat of vaporization	J/kg
C_{pr}	Refrigerant heat capacity	J/kg ºK
C_{ch}	Chamber walls heat capacity	J/kg ºK
m_r	Refrigerant mass	Kg

Symbol	Represents	Units
T	Temperature	º C
COP	Coeficient of Performance	Dimentionless
I	Electric current	A
V_{rms}	Root medium squared voltaje	V
T	Time	s
m_{ch}	Chamber inner walls mass	Kg

1. Introduction

1.1. *Refrigeration; A Cool Solution*

Refrigeration, as a means of food preservation, initially gained significant momentum in the brewery industry, which had the highest demand for ice. Its purpose was to prolong the shelf life of beer. It quickly expanded its use in preserving meat, fish, and other foods by freezing them for long-term storage and transport. Finally, worldwide usage of domestic refrigerators became possible after the Second World War, thanks to the growth of the electric grid and the lowering prices of refrigerating units. Furthermore, the increasing availability of cheap electricity and the rapid development of cities crowded with skyscrapers promoted the usage of luxurious systems, such as air conditioning devices for human thermal comfort and temperature regulation [1], to create comfortable and controlled atmospheres within them. Less attention was paid to passive control of the interior ambient temperature of buildings, as architectural design focused on creating grandiose spaces where thermal comfort was achieved through devices that consume a large amount of electrical energy produced mainly by fossil fuels [2]. In the United States, approximately one-sixth [400 terawatt-hours (TWh), equivalent to about 80 million metric tons of carbon (MtC) emissions, corresponding to about $40 billion US Dollars per year] of all electricity generated is used for air conditioning buildings [3]. In 2019, CO2 emissions from the operation of buildings reached their highest level yet at around 10 Gt CO2, accounting for 28% of total global energy-related CO_2 emissions [4].

Environmental and economic challenges

The race for higher, faster, bigger, and stronger in every human invention continued during the second industrial revolution, fueled by the new, abundant, cheap, and readily available fuel: crude oil and its derivatives, such as gasoline, diesel, and other hydrocarbons. Furthermore, the 20th century witnessed a wasteful party fueled by cheap fossil fuels, which were extensively used for manufacturing, transportation, and goods processing, as well as for providing services. It was not until the beginning of the second half of the 20th century that Hubbert [5] demonstrated the main physical factors involved in the evolution of oil production: growth, peak, decline, and eventual exhaustion of an oil field. It was predicted that these factors would extrapolate into a global decline of oil production at the beginning of the 21st century. As a result, energy efficiency became an important issue, as obtaining cheaper oil was no longer sustainable due to the eventual depletion of oil sources [6]. Even more, this party started to come to its end with a well-known side effect: the pollution of the Earth's thin and delicate atmosphere with the greenhouse gas CO_2, causing a retrograde change of the atmospheric composition towards pre-photosynthetic eras values (2.7 billion of years ago). At those epochs the CO_2 started to be sequestered (simultaneously initiating the Great Oxidation Event) by the recently appeared autotrophic microorganisms Cyanobacteria and their relatives, into the fossil hydrocarbons we desperately consume as fuels today. This CO_2 liberated after eons, changes the optical properties of the atmosphere turning it more opaque to infrared wavelengths, and thus shifting the radiative equilibrium between the Sun, the Earth, and the outer space towards higher equilibrium temperatures of the Earth, and threatening its climate system.

Furthermore, in the current scenario of hybrid wars [7] aimed at controlling fuel markets, production territories, governments, logistics, transportation means, and the currency used for fuel trade, energy tariffs have skyrocketed. This has compelled developed countries to urgently implement energy-saving measures at people's homes, workplaces, and businesses. For example, measures include reducing the power used for heating buildings and pools, as well as minimizing the use of air conditioning devices. Thus, nowadays, the urgency of increasing the efficiency of cooling and heating devices, transport systems, and manufacturing processes has become of paramount importance.

Technological efforts towards renewables and increased efficiency

Most of the world's conventional cooling systems are driven by Vapor Compression Cycle Devices (VCCD), which consume a significant amount of electricity, contributing to high loads on the electricity transmission grid during hot seasons [8] and comfortably cools our living spaces at expenses of heating our surrounding environment.

Substituting conventional cooling systems with direct renewable energy sources, such as thermal solar energy-driven cooling systems, represents a key solution for the environmental and energy associated problems we currently face [9]. In response to these problems, various innovations in conventional cooling devices, aiming to improve their efficiency or in combination with renewable energy sources, have emerged in the market [10]. Mungier et al. [11] present a design guide for cooling systems that addresses the same environmental objective.

Some progress has been reported in solar cooling systems utilizing adsorption [12-16]. These systems exhibit good performance, but they are limited by cumbersome operation and slow adsorption kinetics, which are some of the disadvantages associated with this approach.

In this paper, we revisit evaporation cooling assisted by the partial vacuum provided by a Venturi tube or liquid ejector, exploring the possibility of a simpler solution for cooling devices that could be competitive if further developed, and could be added to the currently available portfolio of cooling technologies.

1.2 *Evaporative Cooling*

The latent heat of evaporation, also known as evaporation enthalpy, is the amount of energy that a given quantity of liquid substance requires to change its state from liquid to vapor or gas. Refrigerants commonly used in cooling systems are liquids with low boiling points or low vapor pressures. These liquids can easily undergo boiling when they come into thermal contact with the food, absorbing heat from it, transitioning into a gaseous state. Upon compression, they return to their liquid state and release the excess heat to the atmosphere [17]. Thus, reducing the pressure on a refrigerant liquid causes it to start boiling, resulting in a decrease in temperature due to the expenditure of its internal energy or heat from the surroundings. The resulting vapor is then extracted and compressed, a process that increases its temperature. However, this high-temperature gas is subsequently cooled (while maintaining a high pressure) by releasing excess heat to the atmosphere, thereby causing the refrigerant to condense back into a liquid phase. The liquid refrigerant is then directed to the low-pressure chamber or evaporator, and the cycle repeats.

The low- and high-pressure stages of expansion and compression parts of the cycle are commonly achieved by means of a piston pump, as in the VCCD. However, this can also be done by means of a venturi tube, in which a moving or circulating fluid can be seen as a continuous fluid piston. In the venturi tube, sometimes called an ejector or eductor, the fluid is propelled through a nozzle, increasing the velocity of the flowing fluid (due to the mass conservation principle). The circulating fluid can be a liquid or gas. If gas is used, it must reach supersonic speeds for optimal ejector performance. However, the intricate balance among the various geometric and dynamic parameters involved in the multiphase flow within the ejector makes it a complex engineering piece, which operates within precisely controlled values of the flow parameters [18]. Due to the high kinetic energy of the circulating fluid at the nozzle outlet, the refrigerant vapors are entrained by this high-speed stream, creating a low-pressure zone that carries out the expansion phase of the cycle. After the refrigerant vapor molecules have been entrained by the circulating fluid stream, which is maintained at ambient temperature through thermal contact with the atmosphere, they condense and dissolve into the circulating fluid if they are mutually miscible. However, if they are mutually immiscible, they separate based on their specific gravity. Thus, the condensation phase of the cycle is achieved without the need for a compression stage. After the separation of the refrigerant from the circulating liquid (by means of distillation in the case of miscible liquids or by their density contrast in the case of immiscible liquids), the cycle begins again when the refrigerant is injected into the evaporator.

According to Alfred Kornfeld [19], in 1916 Einstein first proposed a small immersion cooler that required no conventional power source. It operated solely on the flow of water from the tap, as a response to the complex nature of absorption designs [19]. This marked the first instance of using a venturi tube in a refrigerating device to produce a partial vacuum and allow a low boiling point liquid to evaporate at ambient and lower temperatures, thus acting as a refrigerant.

In the same line of thought, Oliveira et al. [10] proposed a refrigeration cycle that utilizes water as the circulating fluid and water as the refrigerant. This approach is particularly suitable for rural areas where access to electricity is difficult but there is an abundance of running water, as is often the case in many areas of Brazil. However, the most common use of renewables for cooling purposes remains the Vapor Compression Cycle (VCC) driven by an electric motor, which in turn can be powered by photovoltaic solar panels. The promising solution to degradation of ecological environments is the generation of energy through renewable sources and its applications [20]. An example of this is solar water pumping for irrigation, which is widely used thanks to the significant cost reduction of photovoltaic modules and the simultaneous increase in fossil fuel and electricity costs that have occurred over the last decade [18]. Furthermore, PV water pumping systems are reliable, long-lasting, and require low maintenance. However, the potential for using solar pumping for cooling applications remains unexplored due to the expected low coefficient of performance (COP) that can be achieved [12]. In this context, VECS need to be reevaluated at the light of a diversifying pool of new technologies, due to their robustness, simplicity, easiness of implementation and potential for improving in performance in comparison to adsorption schemes or other current cooling technologies, being these the main attributes that makes closed circuit VECS promising devices. It should be remarked that from a long list of published papers on ejector refrigeration technologies (see for example the comprehensive review made by Abdulateef and coworkers [21] and the references therein), the ejector always works at supersonic speeds and there is not a single cycle using a pair of different liquids; one as the motive or primary flow and the other as the entrained or secondary flow, which is precisely the case of the present paper.

In this paper, a cooling refrigeration system based on a venturi ejector with a circulating liquid fluid (CF) was developed and tested using various combinations of refrigerant and CF as working pairs. The purpose was to evaluate its performance under different conditions and its suitability as a demonstrative experiment in thermodynamics. The Coefficient of Performance (COP) for each pair was determined to allow for comparison with other refrigeration cycles, and the advantages and disadvantages are discussed.

2. Materials and Methods

2.1 Experimental Setup

The refrigeration system we built is open, which means that the recovery stage of the refrigerant is omitted after condensing it into the CF. However, this stage could be achieved through solar distillation or gravity separation, depending on whether the working pair is miscible or immiscible, respectively. The system is composed of several parts.

1. Vacuum system: It is based on an ejector or venturi tube (½ inch nominal diameter) made of polyethylene, designed for dosing fertilizing products for irrigation purposes. In this system, a circulating fluid is driven through the nozzle by a centrifugal pump (Pretul, 350). The centrifugal pump is powered by an electric current supplied by 250 W photovoltaic panels. A large (0.8 x 1.5 m) aluminum flat mirror is placed in front of the panels and oriented to redirect (concentrate) sunlight towards the PV panel in order to increase the electric power output of the PV panel and provide the necessary current during the starting transient. The panel output is connected to a Solar pumping inverter Model Spring 5500 JFY, which directly powers the centrifugal pump. The flow of the CF produces a partial vacuum of 60.8 kPa for water and 44.5 kPa for ethylene-glycol when operating at 120 V AC

and a current of 1.7 Amp, equivalent to 204 W of power. The normal operating flow rate is 14 l/min, with an inlet diameter of 13 mm narrowing off to a nozzle diameter of 5 mm, resulting in a CF velocity of 11.7 m/s (equivalent to a 7 m water pressure height), and widening up again to its original 13 mm at the outlet. The CF is sourced from a 20.l reservoir, which acts as a condenser, and circulates through the ejector, returning to the same tank in a closed loop. This tank is open to the atmospheric air and has good thermal contact with the surrounding air to dissipate any excess heat.

2. Evaporator: The evaporation chamber consists of a 500 ml evacuated metalized-glass Dewar flask, which is hermetically sealed with a rubber cap. The refrigerant liquid is initially placed in this chamber. The chamber is connected to the low-pressure port of the venturi ejector (13 mm of inlet diameter and 5 mm diameter at the nozzle) using a vacuum hose. Two digital temperature sensors are located within the evaporation chamber: one at the bottom, in contact with the liquid refrigerant, and the second near the top, in thermal contact with the vapor phase of the refrigerant.

3. Condenser: It consists of a closed chamber 20 x 25 x 40 cm filled with the circulating fluid (either ethylene glycol or water). The centrifugal pump draws the CF from the bottom of the condenser chamber, circulates it through the venturi tube, and returns it to the condenser chamber from above. An oil trap configuration within the condenser facilitates the coalescence of oily droplets and their gravity separation, thanks to the almost quiescent flow within it.

After the entire refrigerant liquid is transferred to the condensation chamber through the operation of the venturi tube, the cycle is restarted by manually retrieving the floating refrigerant fluid.

4. Gauge pressure system: This system consists of a manometer connected to the evaporation chamber to measure the actual pressure within the chamber.

5. Data logging and measuring system: This system consists of an Arduino UNO interface that records in coma separated values CSV format, in a .txt file, within a SD memory card, the temperature data from two digital temperature sensors (Ds18b20) connected to two Arduino ports, every 10 seconds. Both sensors are located inside the evaporation chamber, one at the bottom in contact with the refrigerant liquid and the other far from the refrigerant surface and close to the neck of the Dewar flask (evaporator). The recorded data is then transferred in real time via USB, or directly downloaded from the SD memory card (at the end of the experiment), and displayed on a spreadsheet in a personal computer for analysis. Calibration was done by the sensor's provider, but was checked for boiling and freezing point of water at the local atmospheric pressure and intermediate points, by means a laboratory mercury thermometer. A K type thermocouple connected to a commercial Steren multimeter was used to check for thermal loses along the tubing. The Ds18b20 sensors have ±0.25º C of uncertainty, while the K type thermocouple has ±2º C of uncertainty.

The system is illustrated in Fig. 1 and operates when the centrifugal pump propels the circulating fluid throughout the venturi tube(s). The system has been tested with water and ethylene glycol as circulating fluids, with the latter placed on top due to its lower density. It is important to remark that our cycle is open.

If we refer to Fig. 2, showing the centrifugal pump A, the condenser and separation chamber B, the venturi tube C, and the refrigeration chamber D, after switching on the centrifugal pump A, the circulating fluid starts flowing in a closed circuit throughout the venturi tube C and discharges into a reservoir, B. This reservoir serves as both a condenser, exchanging heat with the atmosphere, and an oil trap that facilitates the separation of the circulating and refrigerating fluids based on their different densities, specifically when they are mutually immiscible. In the present study, the refrigerating fluid condenses and floats up, due to its lower density, in the uppermost part of this chamber, allowing for its subsequent recovery and injection into the evaporation chamber.

The main criteria for choosing a circulating fluid are twofold: firstly, their viscosity must be as low as possible to be efficiently pumped and acquire high speeds within the ejector without undergoing cavitation. Secondly, their boiling point should be as high as possible to lower the pressure within the ejector without evaporating itself, allowing for a larger pressure drop. Conversely, for the selection of the refrigerant fluid, a low boiling point is desirable, a large heat of evaporation, and being immiscible or poorly miscible with the circulating fluid. For the present study two circulating fluids (water and ethylene glycol), and three different refrigerating liquids (acetone, ethanol, and diethyl ether) where used. Table 1 shows the boiling points of the selected refrigerant liquids. In all cases 30 ml of the refrigerating fluid were placed in the evaporation chamber at the beginning of each experiment and the condenser chamber was filled with 12 l of water or ethylene glycol as the CF.

The pressure reached in the evaporation chamber during pump operation was 44.5 KPa for ethylene glycol as the circulating fluid (CF) and 60.8 KPa for water. Consequently, using ethylene glycol as the circulating fluid offers several advantages. Firstly, it creates a much better vacuum, resulting

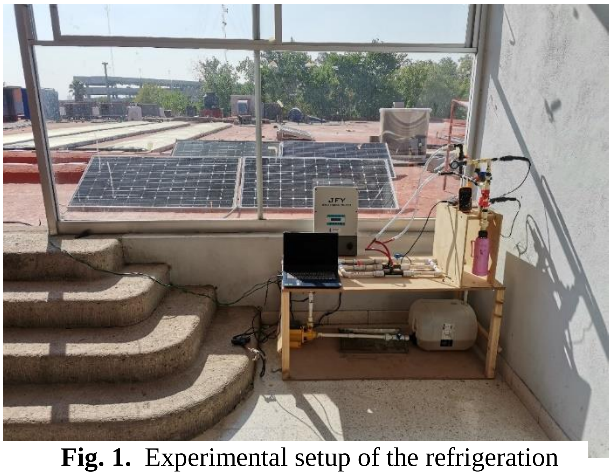

Fig. 1. Experimental setup of the refrigeration device.

in a further reduction of the boiling point of the refrigerant evaporation chamber. Additionally, ethylene glycol exhibits a significantly larger density contrast compared to the refrigerant fluids, which facilitates easier and faster gravity separation.

All tests were conducted for two hours, and measurements from the sensors were recorded every 3 seconds. At the end of each test, the weight of the refrigerant liquid was measured to determine the heat required for evaporating the mass transferred to the condenser.

2.2 Energy Analysis.

The Coefficient of Performance (COP) for refrigerating systems assesses the efficiency of cooling and is defined as the ratio of the heat extracted from the region to be refrigerated (evaporation chamber) to the work supplied for achieving this heat transfer. In our system, the COP can be determined by measuring the total heat extracted from the evaporation chamber during refrigerant evaporation and the total energy supplied to the centrifugal pump within the testing time interval. To determine the COP, several measurements are taken, including the total evaporated mass of the refrigerant (for latent heat determination), the initial and final temperatures of the evaporation chamber (for specific heat determination), the current supplied to the centrifugal pump at a constant RMS voltage of operation (for determining the total energy supplied to the pump), and the mass of the refrigerant liquid. The COP can then be calculated using Eq. (1):

$$COP = \frac{Q}{W} \quad (1)$$

Where Q is the heat extracted from the evaporation chamber and W is the work supplied by the centrifugal pump, both quantities given in Joules.

$$Q = C_{lr} m_r = \left(C_{pr} m_r + C_{ch} m_{ch}\right) \Delta T \quad (2)$$

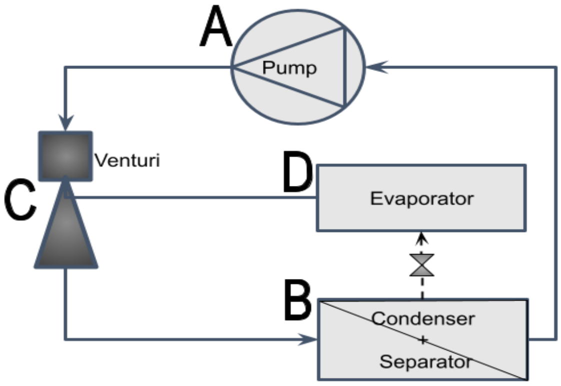

Fig. 2. Schematic diagram of the refrigerating system.

Being $C_{lr} m_r$ the latent heat of evaporation of the refrigerant times the total evaporated mass of the refrigerant, which must be equal to the specific heat of the refrigerant times the total mass of it $C_{pr} m_r$ times the change of temperature ΔT, plus the heat withdrawn from the chamber to cool it down from ambient to the final temperature reached within the evaporation chamber, or $C_{ch} m_{ch} \Delta T$, being the work equal to the current I times the RMS voltage V_{RMS} multiplied by the duration time τ of the experiment, or

$$W = I V_{RMS} \tau \quad (3)$$

Thus, the Coefficient of Performance or COP equation gives us:

$$COP = \frac{C_{lr} m_{er} \Delta T}{I V_{RMS} \tau} \quad (4)$$

which is a dimensionless number since both, numerator and denominator are in Joules. Eqs. 1 to 4 can be found or derived in [21] and references therein.

Table 1. Physical properties of the different substances used as circulating and refrigerating fluids being Ethanol, Acetone, and diethyl Ether

Name	Formula	Density Kg/m³	Boiling Point NCTP °C	Miscibility in	
				Water	Ethylene Glycol
Ethylene Glycol	$C_2H_6O_2$	1116	197	Yes	Yes
Water	H_2O	1000	100	Yes	Yes
Ethanol	C_2H_5OH	789	70	Yes	Yes
Acetone	C_3H_6O	784	56.0	Yes	Yes
Diethyl Ether	$C_4H_{10}O$	736	34.6	6.9 g/0.1 l	No

3. Results and Discussion

The system was tested for acetone, ethanol and diethyl ether as refrigerants using water and ethylene glycol as the circulating fluid throughout the venturi tubes.

Figure 3, shows the cooling curves of the three different refrigerating liquids: ethanol, acetone, and diethyl ether. The curves are compared for both water (shown as black continuous lines) and ethylene glycol (shown as red continuous lines) circulating fluids.

As can be seen in all three cases, the use of water as the circulating fluid yields very poor results, while the cooling effect produced with ethylene glycol is much more pronounced.

Table 2 shows the boiling point of the three refrigerants used at the minimum pressure achievable by the venturi tube when ethylene glycol is circulated by the centrifugal pump. The pressure of 44.583 kPa was determined from the published Vapor-Pressure vs Temperature curves [22]. This pressure is reached within the first few minutes of operation of the venturi tube and remains stable throughout the rest of the experiment.

3.1. Cooling Curves Analysis

3.1.1. Ethanol

In Figure 4, the cooling dynamics of ethanol using ethylene glycol as the circulating fluid are shown. Temperature measurements were made with a sensor in contact with the cooling fluid (red) and a vapor phase sensor near the neck of the evaporation chamber (black) are presented as a function of the elapsed time. It can be observed that the liquid ethanol only cooled down by 5.5ºC in two hours, while the ethanol vapor near the lid of the evaporation chamber experienced a cooling of only 2ºC. These results indicate that ethanol is a poor refrigerant at room temperature and atmospheric pressure, as well as at the operating pressure of our system.

Table 2. Reported boiling points of the three refrigerant fluids at the minimum working pressure achieved by the venturi tube

Refrigerant	Boiling point at	
	101 KPa	**44.5 KPa**
Acetone	56º C	34º C
Ethanol	70º C	56º C
Diethyl Ether	34.6º C	12º C

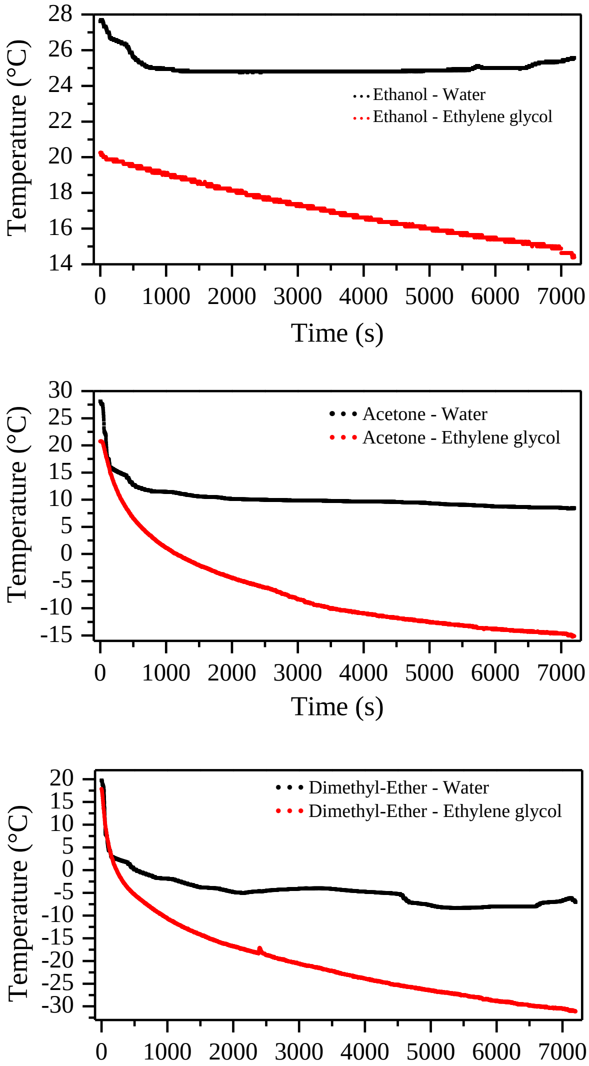

Fig. 3. Cooling curves obtained for the six different pairs of circulating and refrigerating fluids.

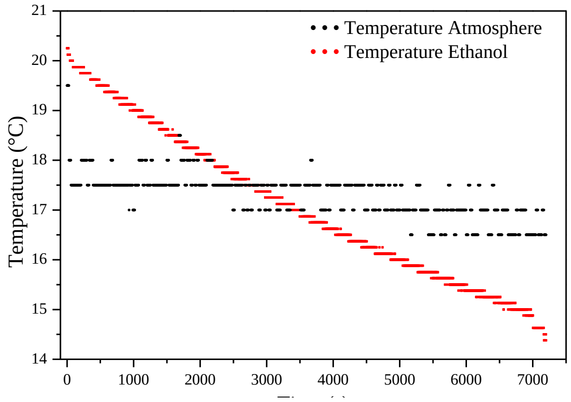

Fig. 4. Cooling curve for ethanol and ethylene glycol pair.

3.1.2. Acetone

If acetone is used as the refrigerant, a much more pronounced descending slope of the temperature vs. time curve is observed during the experiment, as shown in Fig. 5. In this case, the temperature in the refrigerating liquid has decreased from 20ºC to -15ºC, while the temperature of the vapor phase near the neck of the evaporation chamber has decreased to -5ºC after two hours. This indicates that acetone has a faster evaporation rate due to its lower boiling point at the minimum pressure achieved by the venturi system. However, it is important to note that the boiling point of acetone at this working pressure remains above zero degrees Celsius at 34ºC. Despite this, the liquid acetone has reduced its temperature to -14.5ºC, which is approximately 50ºC below its boiling point at that pressure [23].

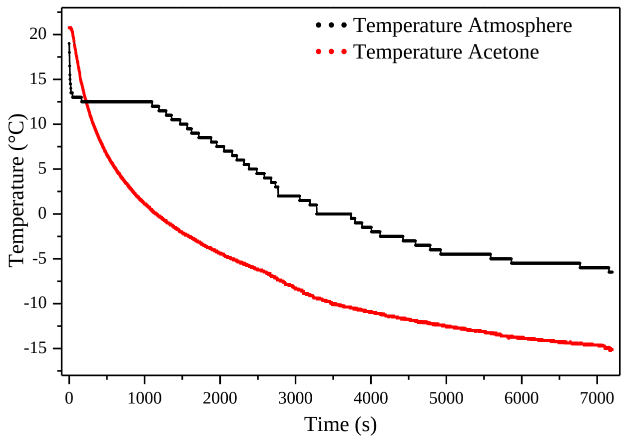

Fig. 5. Cooling curve for acetone and ethylene glycol pair.

3.1.3. Diethyl- ether

In Figure 6, the cooling curve for diethyl ether, or simply ether, is presented. During the two-hour experiment, a significant drop in temperature of 51ºC is observed in the liquid refrigerant, starting from 20ºC and reaching -31ºC (ten times the temperature difference achieved by ethanol). However, it is important to note that the vapor pressure equilibrium temperature of diethyl ether is 12ºC for a pressure of 44.5 kPa, as calculated in the Dortmund Data Base Calculator using the Antoine equation [24]

$P = 10^{7.1-\left(\frac{946.9}{248.6+T}\right)}$, the temperature of the liquid diethyl ether within the evaporation chamber reaches much lower values.

The rapid and drastic cooling within the evaporation chamber occurs quickly because the chamber's walls, initially at room temperature, start transferring heat to the refrigerant as soon as the pressure in the chamber decreases due to the action of the venturi tube on the ether vapor. The temperature of the chamber's walls is sufficient to evaporate the ether without boiling it at this low pressure, as the ether attempts to reach thermodynamic equilibrium. The ether vapor is then carried by the circulating fluid within the venturi tube and

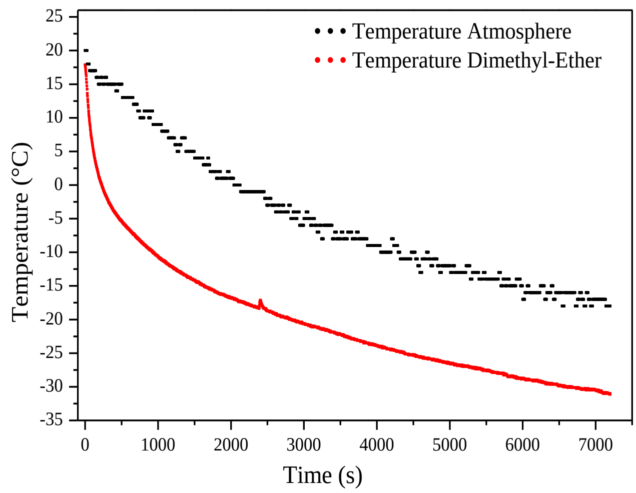

Fig. 6. Cooling curve for diethyl ether and ethylene glycol.

transported to the condensation chamber, where the temperature is maintained at room temperature due to good thermal contact with the surrounding air. Since the pressure in the condensation chamber is atmospheric, the ether vapors condense into small droplets, which subsequently coalesce into larger ones and float in the denser ethylene glycol circulating fluid. This significant difference in density between the circulating and refrigerating fluids, combined with their immiscibility, allows for the gravity-driven separation of both fluids, enabling the recovery of the refrigerant for reuse by injecting it back into the evaporation chamber.

In spite of the intense sensory experience of cooling down the skin of hands produced by evaporation after sanitizing with ethanol, it has been found to be the least efficient refrigerant among the three substances investigated.

The best refrigerant among the three substances explored is clearly diethyl ether, primarily due to its lowest boiling point. Since all three substances are flammable, there is no advantage in using a different one. However, diethyl ether stands out as the only one that is immiscible with the circulating fluid.

Ethanol and acetone have exhibited a relatively weak to moderate cooling effect, whereas diethyl ether has demonstrated a significant and rapid cooling effect upon reducing the pressure using the venturi tube.

Additionally, the fact that diethyl ether is immiscible with ethylene glycol simplifies the condensation and separation process, facilitating the recovery of both liquids. Entrainment of refrigerator's vapor can be enhanced by increasing the molecular weight of the CF or it is speed, and choosing a CF with very low vapor pressure. Usually, the refrigerant is used as well as the CF through the ejector, which has the advantage of having good entrainment with its own vapor phase, but has the disadvantage of having a low vapor pressure. In this way using different liquids for working as refrigerant and CF, allows to enhance the entrainment of the first without increasing the speed of the second.

3.2. *Performance Assessment*

In Table 3, the evaporated volume and mass of the refrigerant, as well as the COP values obtained using Eq. 3, are presented for the conducted experiments. As expected, the highest COP value was achieved when using the diethyl ether - ethylene glycol combination. In alignment with existing technologies, refrigerants with lower boiling points (more volatile) perform better. Besides, nonpolar volatile refrigerants are more likely to be immiscible with the circulating fluid (water or ethylene glycol). This is beneficial since, if the pair of circulating fluids/refrigerants chosen are mutually miscible, then the separation method is distillation, which is a cumbersome and energetically demanding process, leading to even lower COP values of the system. However, if they are not miscible with each other, the separation of both liquids proceeds spontaneously due to their differences in specific density, which implies that no more energy is spent to cool the thermal load. In this sense, the search for a pair of immiscible liquids with a high-boiling circulating fluid and a low-boiling cooling fluid would represent the ideal choice. The COP values obtained for the three investigated refrigerants were relatively low. However, there is ample room for improvement, including the use of refrigerants with boiling points below 0ºC, the implementation of solar pumps designed for enhanced efficiency without the need for DC to AC current inversion stages, the utilization of tailor-made venturi tubes in series for achieving lower pressures, improvements in connection hermeticity, and thermal insulation of piping, among other possibilities.

The lower the boiling point of a substance, the higher their vapor pressure and volatility. Substances with high volatility tend to evaporate more rapidly under partial vacuum conditions. Therefore, selecting a commercial refrigerant with a very low boiling point and a circulating fluid with low vapor pressure can be advantageous as a pair of working fluids.

In summary, the low boiling points and volatility of organic solvents make them ideal for extracting heat from the surroundings, changing their phase and facilitating easy transportation of both the solvent and the heat. The most common method used for this purpose is the compressor-driven refrigeration system, where an electric motor drives the compression process. However, venturi tubes have also been utilized in industrial applications, using compressed air or vapor. These venturi tubes create a vacuum by mechanically generating high-speed fluid flow that entrains the vapor phase of the refrigerant, allowing it to be transported to a condensation chamber where heat exchange with the surrounding atmosphere occurs. Another method involves the use of diffusion pumps, which use fluid ejection at high speeds to create a vacuum and drag the vapor towards the condensation chamber. Even though the COP of a Peltier element is around 0.1 for the 50ºC temperature difference achieved in our experiments, it is still two orders of magnitude higher than our best result.

Table 3. COP evaluation

Substance	$V_{evaporated}$ ±0.5 (mL)	$M_{evaporated}$ ±0.0005(kg)	COP
Ethanol	2.5	0.00197	1.98e-5
Acetone	12.5	0.0098	0.000513
Diethyl Ether	22.5	0.01604	0.00211

The Venturi evaporative cooling system presents lower Coefficient of Performance (COP) values than, for example, adsorption refrigeration systems. However, VEC is a faster and continuous refrigeration technique that works without high-pressure containers or dangerous chemical refrigerants. Even though propylene glycol was not investigated, it has similar desirable physical properties to those of ethylene glycol, such as moderate viscosity but a high boiling point. Furthermore, it is non-toxic and represents a very low environmental or health hazard in case of a spill. Nonetheless, these low values of COP means that our system requires much work to transfer heat from the evaporation chamber towards the surrounding atmosphere and in its present form cannot be seen as part of the solution of the environmental and energetic side effects of our refrigeration needs. However, the simplicity of our system makes it a promising candidate for further improvement and research. Further development is needed before considering the real cost-effectiveness of VECs. Nevertheless, they show promise in replacing moving piston compressor systems that require maintenance and high-pressure systems to work properly. Industries such as tourism, food, and manufacturing could benefit.

To achieve this, several enhancements need to be implemented. These include gravity separation containers, such as oil traps, for the recovery of refrigerants, as well as automatic injection systems for refrigerants into the evaporation chamber using pressure- or temperature-guided valves. These improvements would allow for the widespread application of these systems. Revisiting old ideas with a fresh perspective proves to be a valuable tool in teaching and research. The experience of using a three-dollar venturi tube to create a refrigerator and achieve temperatures as low as -30ºC using common substances and basic CPVC cemented plumbing is incredibly educational. It effectively demonstrates thermodynamic principles through simple experimental devices and invokes a common sensory experience.

Looking ahead, there is an opportunity for further exploration. The use of synthetic low-viscosity carbon and silicon oils, combined with low-boiling-point refrigerants in enclosed atmospheres (free from non-condensing gases), along with tailor-made Venturi ejectors, should be investigated to improve the system's performance.

4. Conclusions

We have developed a refrigeration system based on evaporation, utilizing a venturi tube, a circulating fluid, and a refrigerant fluid. While our setup was initially configured as an open circuit, an enclosed environment free of non-condensing gases for circulating fluid and refrigerant has not been investigated. However, this represents a future research goal: to be able to operate in a closed circuit by incorporating an expansion valve and modifying the geometry of the condenser chamber. This will enable us to achieve and maintain temperatures as low as -30ºC in the evaporation chamber. Among the different combinations of circulating and refrigerating fluids explored, the diethyl ether - ethylene glycol pair has proven to be the most suitable. This is primarily due to the remarkably low vapor pressure equilibrium temperature (at which the refrigerant vapor and its liquid phase coexist at a specific pressure) of diethyl ether at the minimum working pressure attained when circulating it through the venturi tube. Besides, diethyl ether and ethylene glycol are mutually immiscible and have a large density contrast, facilitating enormously the separation of both fluids after condensation of the first.

The achieved coefficients of performance (COPs) in our experiments were relatively low, primarily due to the limitations of the materials and devices employed (presence of non-condensable gases in a non-hermetic condenser chamber, poor thermal isolation of the tubbing used, and the use of domestic irrigation pumps and venturi tubes). However, we recognize that there is significant potential for improving the COPs in future iterations of our system. One avenue for improvement is to explore a closed-loop refrigeration cycle. Encasing the whole system in a closed environment free of non-condensing gases would allow closing the refrigeration circuit by connecting the density separation chamber (within the condenser) with the evaporator to feed the newly condensed refrigerant into the evaporator for continuous operation of the system. An expansion valve, driven by the temperature of the evaporation chamber, will keep the flow of refrigerant into the evaporator constant and can be used to turn off and on the circulating pump as a function of the evaporator chamber's temperature. Furthermore, a proper selection of a DC-solar pump would avoid the use of inverting stages [25], resulting in increased efficiency of the pumping process and, in turn, the overall COP of the system. Additionally, incorporating more efficient pumps, optimizing the design of the venturi elements, and implementing a precise control system for injecting the recovered diethyl ether refrigerant into the evaporation chamber are all areas that will be explored in future experiments. With these improvements is clear that the overall performance and efficiency of the system will be increased by avoiding heating of the CF, heat loses along the tubbing, achieving higher CF speeds in the venturi and in turn lower pressures in the evaporation chamber leading to improved COPs as less energy is wasted and more efficiently used in cooling.

All data presented in this paper is open and readily available at [26].

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