

Cooling High Power Dissipating Artificial Intelligence (AI) Chips Using Refrigerant

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How to cite this paper: Mukatash, W., Kabbani, H., Massalt, J.M., Moscoso, M., Mejia Robles, M., Yang, T. and Nino, C. (2024) Cooling High Power Dissipating Artificial Intelligence (AI) Chips Using Refrigerant. *Journal of Electronics Cooling and Thermal Control*, 13, 35-49.
<https://doi.org/10.4236/jectc.2024.132002>

Received: May 5, 2024

Accepted: June 27, 2024

Published: June 30, 2024

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Abstract

High power dissipating artificial intelligence (AI) chips require significant cooling to operate at maximum performance. Current trends regarding the integration of AI, as well as the power/cooling demands of high-performing server systems pose an immense thermal challenge for cooling. The use of refrigerants as a direct-to-chip cooling method is investigated as a potential cooling solution for cooling AI chips. Using a vapor compression refrigeration system (VCRS), the coolant temperature will be sub-ambient thereby increasing the total cooling capacity. Coupled with the implementation of a direct-to-chip boiler, using refrigerants to cool AI server systems can materialize as a potential solution for current AI server cooling demands. In this study, a comparison of 8 different refrigerants: R-134a, R-153a, R-717, R-508B, R-22, R-12, R-410a, and R-1234yf is analyzed for optimal performance. A control theoretical VCRS model is created to assess variable refrigerants under the same operational conditions. From this model, the coefficient of performance (COP), required mass flow rate of refrigerant, work required by the compressor, and overall heat transfer coefficient is determined for all 8 refrigerants. Lastly, a comprehensive analysis is provided to determine the most optimal refrigerants for cooling applications. R-717, commonly known as Ammonia, was found to have the highest COP value thus proving to be the optimal refrigerant for cooling AI chips and high-performing server applications.

Keywords

Artificial Intelligence, Thermal Control, Server Systems, Vapor Compression Refrigeration Cycle, Server Cooling

1. Introduction

Artificial Intelligence has found a broad range of usage in many different indus-

tries. For instance, in the medical industry, AI technology can be used to aid in the rehabilitation of neurological diseases. Specifically, it allows rehabilitative equipment to adjust itself to an individual patient to best aid them in their recovery [1]. With an increased demand for the integration of AI within server systems, new-generation computing chips provoke a massive thermal challenge in regard to cooling [2]. Artificial intelligence increases the need of a component's bandwidth to produce more power, resulting in a major increase in thermal resistance [3]. As technology continues to advance to improve the efficiency and speed of delivering nuances of complex computations, the amount of heat being generated and needing to be cooled increases uniformly as a result. Currently, air cooling methods are ineffective in cooling high amounts of power dissipation and the possibility of malfunction or failure due to overheating as well as inefficiency is a substantial concern [4]. While liquid cooling methods are currently the most effective method of cooling, AI chip components are increasingly getting more powerful and hot. Following Moore's Law, with the amount of transistors increasing yearly and critical features of planar processes shrinking, the time for data signals to transverse decreases. This calls for processes to occur faster per unit area [5]. Thus, new thermal challenges will arise and new cooling methods must be investigated.

Electrical energy is considered to be the "heart or weak spot" of AI due to the energy consumption that is required by supercomputers such as Tianhe 1 and 2. The computing node for the Tianhe 2 has an energy consumption of 18 megawatts and over 20 megawatts with a cooling system [6]. With the advancement in technology, the power consumption can be expected to increase due to the increase in central processing units (CPU) and graphics processing units (GPU) because these components are fundamental to a computer's processing performance. As computers become more powerful, a development in cooling systems is also done to allow these machines to reach their maximum performance and to optimize energy consumption. This can be demonstrated as there are various developments in cooling systems such as air, liquid, and refrigerant.

Electronic cooling techniques using refrigeration are classified into four categories: using refrigerants to cool liquid or air, refrigerating heatsinks, using liquid nitrogen baths, and thermoelectric cooling [7]. In comparing the refrigeration of air or liquid technique to the refrigerated heatsink method, general findings are that using a refrigerated heatsink has a lower temperature at the cold surface. In addition, because the evaporator would be mounted directly on the electronic component, the electronic temperature is colder than the surrounding temperature and the refrigerated heatsink method is more compact than using a cooling fluid. For liquid nitrogen baths, immersion would require a dewar flask—a container made of insulated material. Special care is required for this method, to achieve advanced insulation—greater risk of leakage. Lastly, the capacity and overall effectiveness of the thermoelectric cooling method are minimal and not promising [8].

Notable systems that utilize refrigeration cooling include IBM server systems.

The first IBM system to employ refrigeration cooling techniques is the IBM S/390 G4 CMOS server system. The processing module is the element cooled by refrigeration; its form factor is $267 \times 267 \times 711 \text{ mm}^3$ and has a weight of 27 kg. To absorb moisture the evaporator contains 260 grams of silica gel. For this G4 server, the average process module temperature was about 40°C , which is 35°C lower than the air cooling system of the same design. These IBM server units have been tested and implemented to ensure high reliability [9].

In another study, a VCRS was built to cool down the CPU of a Notebook computer [10]. The working fluid used for this experiment was Isobutane, also known as R600a. Their refrigeration system consisted of the following components: An evaporator, a condenser, a throttling device in the form of a capillary tube, and a compressor. In addition to the components to make up the refrigeration cycle, sensors were attached at several points throughout the system to measure the temperature and pressure of each component. Several experiments were performed, each time making modifications to either a component or an operating condition. For example, in some experiments, the airflow at the condenser was increased or the evaporator power was decreased. The results of their experiment were evaluated through the COP. They were able to achieve a COP of 2.25 and greater depending on the variables changed. The highest COP achieved through their experimentation was 3.70 which occurred when the evaporator power was reduced. A slight increase in COP was also observed when the airflow at the condenser was increased. Comparing the measured COP and the ideal COP of a Carnot refrigeration system, they reached about 25% - 30% of the Carnot efficiency, which increased as the pressure ratio increased. They found that a higher pressure ratio could be achieved through having a higher gas temperature [10].

Refrigeration cooling can be a promising solution for the future of mass computation given the ability to operate at a sub-ambient temperature. With an understanding of the cooling capabilities of refrigerants in automotive vehicles and industrial refrigeration applications, the future of cooling potentially lies within refrigerants in the computing sphere as well. Recently, compact vapor compression refrigeration systems have struck the interest of many engineers as they flourish in both eliminating high heat flux as well as keeping device temperatures sub-ambient [11]. Utilizing the common components of a vapor compression refrigeration system: compressor, condenser, throttling device, and heat exchanger, a theoretical cooling system is used to analyze the most effective refrigerants in a VCRS.

Currently, many refrigerants are accessible on the market to provide the correct service and compatibility for specific applications. One limiting factor however is geographical location as certain geographical locations have laws to meet ecology and legislation requirements to reduce the global warming potential (GWP) [12]. In this study, a comparison of various refrigerants is studied for optimal cooling performance.

2. Vapor Compression Refrigeration Cooling

2.1. Fundamentals of Refrigeration Cycle

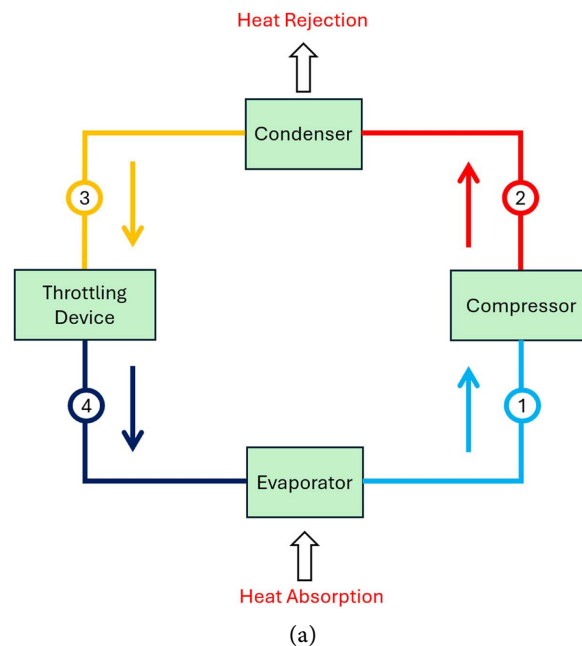
The most commonly used refrigeration cooling method is the vapor-compression refrigeration (VCR) cycle. Thus, in this study, we analyze how different refrigerants would behave in the ideal VCR cycle and compare their effectiveness. In this case study, a VCR cycle is used as a refrigeration system to cool AI chips. It consists of four main components: a compressor, a condenser, an expansion valve, and an evaporator as shown in **Figure 1**. The ideal VCR cycle consists of four processes:

1) Isentropic compression in the condenser (state from point 1 to 2): The refrigerant enters the compressor as a saturated vapor. The vapor is isentropically compressed to the condenser pressure, thereby increasing its temperature above its surrounding medium. This means there is no entropy change during the compression of the vapor.

2) Constant-pressure heat rejection in a condenser (state from point 2 to 3): The refrigerant enters the condenser as a superheated vapor and exits as a liquid due to heat rejection to the surroundings at constant pressure. The temperature of the refrigerant is still above the surroundings at state 3.

3) Throttling in an expansion device (state from point 3 to 4): A capillary tube or expansion valve is used to throttle the saturated liquid refrigerant to the evaporator pressure and bring its temperature below the refrigerated space temperature.

4) Constant-pressure heat absorption in an evaporator (state from point 4 to 1): The refrigerant is a low-quality saturated mixture as it passes through the evaporator. It absorbs the heat from the evaporator and completely evaporates, exiting the evaporator as a saturated vapor, ready to restart the cycle.



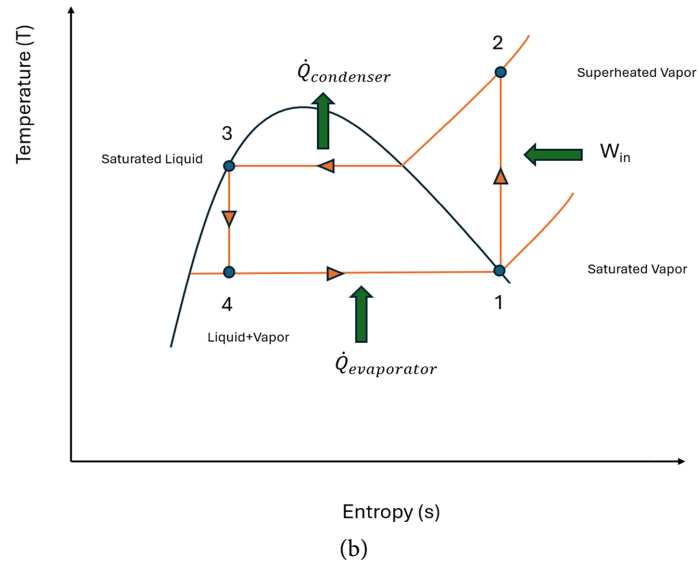


Figure 1. Ideal vapor-compression cycle schematic and T-s diagram.

The *Temperature (T) vs Entropy (s)* diagram in **Figure 1** helps illustrate the heat transfer occurring during the ideal VCR cycle. The area under the process between states 4 and 1, which is the constant pressure heat absorption in the evaporator, indicates the heat absorbed by the refrigerant in this process. The heat rejected by the condenser is represented by the area under the process between states 2 and 3. The COP, which is the benchmark for determining cooling efficiency, can be increased by increasing the evaporating temperature or lowering the condensing temperature [13].

The four processes of the VCR cycle are analyzed with steady-flow conditions as all components of the cycle are steady-flow devices. The refrigerant's kinetic and potential energy changes are deemed negligible as they are miniscule compared to the heat transfer and work terms. Thus, the unit mass steady-flow energy equation can be simplified to Equation (1). Here q_{in} and q_{out} are the heat in and heat out of the system respectively, w_{in} and w_{out} are the work done on and work done by the system respectively, and h_e and h_i are the enthalpies at the exit and inlet respectively.

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_e - h_i \quad \text{Equation (1)}$$

$$\text{COP}_R = \frac{q_L}{w_{net,in}} = \frac{h_1 - h_4}{h_2 - h_1} \quad \text{Equation (2)}$$

Treating the compressor as adiabatic, where no heat exchange occurs, the COP of refrigerators utilizing a VCR system can be represented as Equation 2. Note the evaporator and condenser do not involve any work and $h_1 = h_g @ P_1$ in this equation [13].

2.2. Vapor Compression Refrigeration System (VCRS) for AI Chip Cooling

Applying the VCR System described above, a theoretical model can be created to

simulate the performance of a selection of refrigerants which will be evaluated based on their COP. The COP of each refrigerant will be evaluated using Equation (3), where W is defined as the compressor work and Q_L is defined as the amount of heat being dissipated by the chip.

$$\text{COP} = \frac{Q_L}{W} \quad \text{Equation (3)}$$

The compressor work, W , is defined in Equation (4). Where \dot{m} is the mass flow rate of the refrigerant and h_1 and h_2 are the enthalpy before and after the compressor respectively.

$$W = \dot{m} \times (h_2 - h_1) \quad \text{Equation (4)}$$

The mass flow rate, \dot{m} , is evaluated using Equation (5). h_1 and h_4 are the enthalpy before and after the evaporator.

$$\dot{m} = \frac{Q_L}{h_1 - h_4} \quad \text{Equation (5)}$$

Outside of evaluating each refrigerant in terms of COP, the overall heat transfer coefficient, UA , of the condenser was determined using the Logarithmic Mean Temperature Difference (LMTD) Method, where T is the temperature at the respective point in the VCRC.

$$UA = \frac{Q_L}{\Delta T_{lm}} \quad \text{Equation (6)}$$

$$\Delta T_{lm} = \frac{(T_2 - T_3) - \Delta T}{\ln\left(\frac{(T_2 - T_3)}{\Delta T}\right)} \quad \text{Equation (7)}$$

For this model, each of the refrigerants was evaluated with a starting pressure, P_1 , of 0.14 MPa, and a compression ratio of 6 was assumed. Additionally, the state of the refrigerant at point 1 is assumed to be saturated vapor and the refrigerants' respective saturated vapor tables were used to find the temperature, entropy, and enthalpy at point 1.

At point 2 after exiting the compressor, the refrigerant has become a superheated gas with a pressure of 0.8 MPa (P_2) determined by the assumed compression ratio. Given that the entropy between point 1 and point 2 remains constant, the temperature and enthalpy at point 2 can be found using the superheated gas table for each respective refrigerant.

At point 3, the phase change of refrigerant has occurred and all heat is extracted from the system. The refrigerant becomes a saturated liquid while holding the same pressure of 0.8 MPa (P_3) as point 2. Using the saturated liquid tables of each refrigerant for P_3 , entropy and temperature can be determined as well as liquid enthalpy h_f for each refrigerant—which is the enthalpy for point 3.

Lastly, at point 4, the refrigerant has been throttled, bringing its pressure back to the starting pressure of 0.14 MPa while remaining at the same enthalpy as point 3. The temperature and entropy at point 4 were interpolated using the pressure table of each respective refrigerant.

The refrigerant respective property tables [13]-[22] are used to calculate different properties at different points of the refrigeration cycle. These properties are presented in the table below

Table 1. Ideal VCRS Properties for Refrigerants: R-134a, R-153a, R-717, R-508B, R-22, R-12, R-1234-yf, and R-410a at different points of the refrigeration cycle.

State Points Variables	R134a	R-153a	R-717 (ammonia)	R-508	R-22 (Freon-22)	R-12	R-1234-yf	R-410 A
Point 1	P1 (MPa)	0.14	0.14	0.14	0.14	0.14	0.14	0.14
	s1 (kJ/kgK)	0.9327	1.656	6	1.3957	1.809	0.71	1.597
	h1 (kJ/kg)	236.04	364	1428	254.5	391	177	348.7
	T1 (°C)	-18	-21	-27	-82	-34	-22.5	-22
	State	Saturated Vapor	Saturated Vapor	Saturated Vapor	Saturated Vapor	Saturated Vapor	Saturated Vapor	Saturated Vapor
Point 2	P2 (MPa)	0.8	0.8	0.8	0.8	0.8	~0.75	0.8
	s2 (kJ/kgK)	0.9327	1.656	6	1.3957	1.809	0.71	1.597
	h2 (kJ/kg)	272.05	398	1620	287.9	435	210	382.2
	T2 (°C)	35	33	73	-20	45	45	35
	State	Superheated	Superheated	Superheated	Superheated	Superheated	Superheated	Superheated
Point 3	P3 (MPa)	0.8	0.8	0.8	0.8	0.8	~0.75	0.8
	s3 (kJ/kgK)	0.35	1.136	1.2967	0.7712	1.076	0.245	1.144
	h3 (kJ/kg)	93.42	239.6	284.283	140	219.1	66	241.9
	T3 (°C)	31	29	18	-41	16	32.5	31
	State	Saturated Liquid	Saturated Liquid	Saturated Liquid	Saturated Liquid	Saturated Liquid	Saturated Liquid	Saturated Liquid
Point 4	P4 (MPa)	0.14	0.14	0.14	0.14	0.14	0.14	0.14
	s4 (kJ/kgK)	0.35	1.136	1.2967	0.7712	1.076	0.245	1.144
	h4 (kJ/kg) ~h3	93.42	239.6	284.283	140	219.1	66	241.9
	T4 (°C)	-19	-21	-27	-82	-34	-22.5	-22
	State	Liquid-Vapor Region	Liquid-Vapor Region	Liquid-Vapor Region	Liquid-Vapor Region	Liquid-Vapor Region	Liquid-Vapor Region	Liquid-Vapor Region

Using Equations (3)-(7), and the refrigerant's properties from **Table 1**, the performance, COP, Refrigerant flow rate, compressor work, and UA for the condenser for each refrigerant was determined. The calculation is based on 12°C temperature rise on the cooling fluid side and the results of this model can be seen in the following **Table 2**.

3. Comparison of Refrigerants

3.1. Performance of Refrigerants

Eight refrigerants were analyzed in this study. The COP was calculated individually with all of the results shown in **Table 1**. Freon R-717 (commonly known as Ammonia) was by far the most efficient with a COP of 5.96. The second

Table 2. Comparison for, COP, refrigerant flow rate, compressor work, and UA for different refrigerants.

State Points Variables	R134a	R-153a	R-717 (ammonia)	R-508	R-22 (Freon-22)	R-12	R-1234-yf	R-410 A
C.O.P =	3.96	3.66	5.96	3.43	3.91	3.36	3.19	4.17
Flow Rate Required at (g/s)/1 kW =	7.0116	8.0386	0.8743	8.7336	5.8173	9.0090	9.3633	4.8852
Calculations Compressor Work at (kW)/1 kW Cooling =	252.49	273.31	167.87	291.70	255.96	297.30	313.67	239.86
Condenser HX UA* (W/k)/1 kW =	0.137	0.137	0.035	0.062	0.052	0.082	0.137	0.051

highest COP was R-410A with a COP of 4.17, followed by R-134A at 3.96. R-22 has similar performance to that of R-134A, which has a COP value of 3.91. The COP values of refrigerants R-153A, R-508B, and R1234yf have a noticeable decrease in COP. Refrigerant R-153A has a COP value of 3.66 and R-508B has a COP value of 3.43. The lowest COP and least efficient refrigerant was R-1234YF with a COP value of 3.19. Having the lowest COP value corresponds to the fact that more energy is required to have an operable system. In other words, more energy is required to have a similar cooling output solely depending on the refrigerant used in the system. Based on the COP values, R-717 would be the ideal refrigerant for the refrigeration system of an AI server system.

In addition to the COP calculated, the compressor work was also determined. For this study, the compressor work required is listed as compressor work required (in Watts) needed per one kilowatt of cooling. In conjunction with the COP value, the compressor's work should have a low value to be considered an ideal refrigerant. Similar to the values obtained for COP, R-717 had an ideal work value of 167.87 kW. It is considered an ideal value because it requires the least amount of work from the compressor as compared to the other refrigerants. The second lowest value for the required work of the compressor was refrigerant R-410A at 239.86 kW, followed by R-134A at 252.49 kW. R-22 had a slightly higher work result than R-134A, which was 255.96 kW. The following refrigerant R-153A has a compressor work of 273.31 kW and R-508B has a value of 291.70 kW. The highest value is that of refrigerant R-1234YF at 313.67 kW. Since R-1234YF requires the highest work, more energy is required, as well as, having the lowest COP.

The calculated required flow rate is listed as the flow rate (grams per second) required per kilowatt of cooling. In terms of the value of the required flow rate, a lower flow rate is desired because it is the required flow rate to be able to cool the system, thus making it more efficient since it is able to cool with less refrigerant. Similar to the other results, Refrigerant R-717 had the best results because it had the lowest flow rate at 0.8743 g/s, which means it takes less refrigerant to cool the system. The other refrigerants analyzed are not as ideal as R-717 because the flow rate calculated is tremendously higher. The second lowest flow rate is R-410A at 4.8852 g/s. The flow rate is still considered high which demon-

strates the efficiency of R-717. Refrigerants R-22 and R-134A follow in the respective order with rates of 5.8173 g/s and 7.0116 g/s. The fourth best refrigerant is R-153A with a flow rate of 8.0386 g/s followed by R-508B with a flow rate of 8.7336 g/s. R-1234YF had the highest flow rate, which means the greatest flow rate is required to cool the whole system. The flow rate calculated for R-1234YF is 9.3633 g/s, which is significantly higher compared to R-717 and R-410A. They can cool the same amount with a remarkably lower flow rate.

Additionally, the heat transfer coefficient was calculated for a 12°C cross-cooling flow. Most of the results were relatively similar and below one, which makes sense since the refrigerant is used to cool and not necessarily to transfer heat. Ammonia had the lowest heat transfer coefficient with a value of 0.035 (W/k)/1 kW. This helps demonstrate why this refrigerant is able to cool at a much higher capacity than the other refrigerants. This is followed by R-410A and R-22 with a coefficient of 0.051 (W/k)/1 kW and 0.052 (W/k)/1 kW in their respective manner. These values are relatively similar to each other. The next highest coefficient is that of R-508B at 0.0602 (W/k)/1 kW. The next refrigerants all had the same value. Refrigerants R-134a, R-153a, and R-1234YF all had a coefficient of 0.137. It is about twice the value of the other refrigerants. These calculations assist in determining how the cooling capacity can be influenced by heat.

3.2. Environmental and Safety Analysis of Refrigerants

In addition to the calculated numerical analysis of refrigerants, further research and evaluations were done in regards to safety and environmental regulation the full results are shown in **Table 3**. Refrigerant R-717 proved to be an ideal coolant because it had the highest COP as well as the lowest required compressor work. R-717 also proved to be one of the more environmentally refrigerant because it has an Ozone Depleting Potential (ODP) equal to zero and a Global Warming Potential (GWP) below one. Having low ODP and GWP proves that R-717 is a relatively eco-friendly refrigerant. In addition to this, it has great thermodynamic properties as it has a high critical temperature of 132°C, high vapor density, and great heat transfer coefficients. In terms of flow rate, it had the best performance because it had the lowest value. However, the major drawback of R-717 is its toxicity. Toxicity is a major problem for R-717 because it has an airborne limit, or Threshold Limit Value of 25 ppm and with a concentration of 5 ppm, these negative effects can still be felt so any leak can be extremely dangerous. R-717 is also moderately flammable when there is an air concentration of 16% to 28% [23]. Thus, while the properties of R-717 are high-performing, safety concerns are still a major concern for this refrigerant.

Refrigerant R-513A is considered to be a direct replacement of R-134A. It has an ODP of 0 and a GWP of 573, which is relatively eco-friendly. When compared to the other refrigerants, its COP and compressor work are within the middle-performing threshold. When compared to its direct replacement, R-134A has a higher COP, lower work for the compressor, and a lower required flow rate. Another benefit of R-513A is that it is not flammable or toxic [24]. This re-

frigerant is relatively in the middle of the other seven refrigerants compared and it is safe for human use.

Refrigerant R-134A is a very common refrigerant that is used in a variety of refrigeration applications. It has recently received some scrutiny due to its environmental effects. It has an ODP of 0, but a GWP of 1430 [25]. Since it has a high GWP it is starting to get phased out for certain applications around the world. The European Union has banned it for mobile air conditioning systems [23]. Additionally, due to the Kyoto Protocol, refrigerants with a GWP over 150 would be banned by the United Nations [25]. This refrigerant is nonflammable and nontoxic [24]. Its COP was one of the highest and compressor work is one of the lowest. In terms of flow rate, it is within the median range. Despite the R-134A being relatively well and safe, it is not eco-friendly, which puts it at risk of being phased out completely.

Another refrigerant analyzed is R-508B. It has an ODP of 0, but a GWP of 12,000 [26]. Based on the GWP, it is one of the highest and least eco-friendly. To add to this it is mostly used for low-temperature refrigeration systems, which means that it has a limited cooling capacity and is not feasible to be used in a VCRS system [27]. While comparing it to the other refrigerants it had one of the lowest COPs and a high compressor work value. The application for this refrigeration system is limited and its performance is one of the lowest.

Along with R-134A, R-22 is one of the more commonly used refrigerants. It has an ODP of 0.034 and a GWP of 1780 [23]. Basing this refrigerant off the GWP is not that eco-friendly. To add to this, the US government has decided to phase out the production of this refrigerant and it can only be used if it is recycled [28]. R-22 is considered to be one of the refrigerants that require least maintenance [29]. When compared to the other refrigerants, it had the third lowest COP and flow rate. The work for the compressors was in the middle of the refrigerants. Despite being one of the more commonly used refrigerants, its detrimental effect on the ozone layer has prohibited its production and, therefore, cannot be used.

Refrigerant R-1234YF is considered to be one of the more promising refrigerants in terms of being environmentally friendly. It has an ODP of 0 and a GWP of 0.501. Based on the GWP, it has the lowest values out of all the refrigerants [30]. This refrigerant is slightly flammable but can be a risk for Mobile Air-Conditioning systems. Despite this, research is still being conducted that includes using more safety measures to avoid any risks [23]. When looking at the R-1234YF's performance it had the lowest COP and the highest work done by the compressor. This refrigerant is seen to be the replacement of R-134A; there is still more research that needs to be done to solidify this position.

R410A is a refrigerant that is common in air conditioning systems. It has a high cooling capacity and has low toxicity. It has a GWP of 2088 [31]. Similar to the other refrigerants it has an ODP of 0 [32]. This refrigerant had the second-highest COP and second-lowest flow rate. It is one of the more efficient ones. The work done by the compressor is the second lowest and along with the

COP, it demonstrates its efficiency in cooling systems. The biggest problem with this refrigerant is eco-friendly concerns, despite this, it is one of the better refrigerants analyzed.

Table 3. ODP & GWP for Refrigerants: R-134a, R-153a, R-717, R-508B, R-22, R-12, R-1234-yf, and R-410a.

	Ozone Depleting Potential (ODP)	Global Warming Potential (GWP)
R-134a	0	1430
R-153a	0	573
R-717	0	>1
R-508	0	12,000
R-22	0.034	1780
R-12	0.82	10,680
R-1234yf	0	>1
R-410a	0	2088

4. Conclusions

The rapid adoption of AI and computing has led to the need for faster and more sophisticated chips. The heat generated by these chips requires an effective cooling system that requires the implantation of a VCR system for cooling an AI Chip. The need to cool these AI chips has become ever so important; this study compared the efficiency of different refrigerants in a VCR system for chip cooling.

Compared to other cooling methods such as heatsinks, liquid nitrogen baths, and thermoelectric cooling; the research conducted focused on utilizing refrigeration direct-to-chip cooling results in colder temperatures. This paper explored the benefits of a VCR cooling system and the analysis of how various refrigerants perform against one another. We found refrigeration cooling to have a high cooling capacity at sub ambient operating temperatures. The selection of the used refrigerant is an integral component in the overall efficiency and performance of the system. Thus, the results of this study can be used in refrigerant selection for VCR systems that utilize refrigeration cooling.

High power dissipating AI chips require significant cooling to achieve maximum performance. This study presents a numerical and analytical comparison of 8 different refrigerants: R-134a, R-153a, R-717, R-508B, R-22, R-12, R-410a, and R-1234yf. The COP, work by the compressor, and required mass flow rate of each refrigerant were all analyzed to determine the efficiency and performance of each system. To test this, a theoretically controlled VCR system was used. Of the refrigerants analyzed the highest performing refrigerant is Ammonia (R-717) due to its high COP, less required flow rate, and less work required by the compressor. However, its danger to work with and negative environmental impact make it a non-ideal refrigerant for AI chip applications. Although R-1234YF was

the most promising in terms of safety and environmental impact, it has a lower COP and higher work on the compressor making it the most inefficient.

Future research will focus on expanding the efficiency of the cooling system and methods by which the system can perform closer to its ideal state and adapt to the ever-evolving demands of AI technologies. With continued research and development, the potential and need for this refrigeration cooling will emerge to be a suitable solution for reliability and maximum performance in the next AI-driven computers. This study aimed to evaluate refrigerant performance in cooling AI chips to create reliable methods of cooling these high-performing sophisticated chips and adapt them to future demands.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

- [1] Filippis, R.D. and Foysal, A.A. (2024) Harnessing the Power of Artificial Intelligence in Neuromuscular Disease Rehabilitation: A Comprehensive Review and Algorithmic Approach. *Advances in Bioscience and Biotechnology*, **15**, 289-309. <https://doi.org/10.4236/abb.2024.155018>
- [2] Wei, J. (2008) Challenges in Cooling Design of CPU Packages for High-Performance Servers. *Heat Transfer Engineering*, **29**, 178-187. <https://doi.org/10.1080/01457630701686727>
- [3] Moon, K., Son, H. and Lee, K. (2023) Advanced Packaging Technologies in Memory Applications for Future Generative AI Era. 2023 *International Electron Devices Meeting*, San Francisco, 09-13 December 2023, 1-4. <https://doi.org/10.1109/iedm45741.2023.10413890>
- [4] Kumar, R., Khatri, S.K. and Jose Divan, M. (2020) Effect of Cooling Systems on the Energy Efficiency of Data Centers: Machine Learning Optimisation. 2020 *International Conference on Computational Performance Evaluation*, Shillong, 02-04 July 2020, 596-600. <https://doi.org/10.1109/compe49325.2020.9200088>
- [5] Hutcheson, G.D. (2009) The Economic Implications of Moore's Law. In: Hull, R., Jagadish, S., *et al.*, Eds., *Springer Series in Materials Science*, Springer, 11-38. https://doi.org/10.1007/978-3-540-74559-4_2
- [6] Ren, H. (2022) Artificial Intelligence and Future Legal System: The Right to Access Electrical Energy of Artificial Intelligence. *Open Journal of Social Sciences*, **10**, 447-458. <https://doi.org/10.4236/jss.2022.1012030>
- [7] Scott, A.W. (1974) *Cooling of Electronic Equipment*. Wiley.
- [8] Trutassanawin, S. and Groll, E.A. (2004) Review of Refrigeration Technologies for High Heat Dissipation Electronics Cooling. <https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1677&context=iracc>
- [9] Schmidt, R.R. and Notohardjono, B.D. (2002) High-End Server Low-Temperature Cooling. *IBM Journal Research and Development*, **46**, 739-751. <https://doi.org/10.1147/rd.466.0739>
- [10] Mongia, R., Masahiro, K., DiStefano, E., Barry, J., Chen, W., Izenson, M., *et al.* (2006) Small Scale Refrigeration System for Electronics Cooling within a Notebook

- Computer. *Thermal and Thermomechanical Proceedings 10th Intersociety Conference on Phenomena in Electronics Systems* 2006, San Diego, 30 May-02 June 2006, 751-758. <https://doi.org/10.1109/itherm.2006.1645421>
- [11] Erkinaci, T., Coskun, F., Cotur, A., Onler, R. and Serincan, M.F. (2024) Experimental and Numerical Investigation of a Compact Vapor Compression Refrigeration System for Cooling of Avionics in Harsh Environments. *Applied Thermal Engineering*, **236**, Article 121663. <https://doi.org/10.1016/j.applthermaleng.2023.121663>
- [12] Čaja, A., Čajová Kantová, N., Kapjor, A. and Vantúch, M. (2022) Comparison of Performance Parameters of Four Types of Refrigerants. *MATEC Web of Conferences*, **369**, Article 04007. <https://doi.org/10.1051/mateconf/202236904007>
- [13] Çengel, Y.A. and Boles, M.A. (2019) *Thermodynamics: An Engineering Approach*. 9th Edition, Mcgraw-Hill Education.
- [14] The Chemours Company (2016) *Thermodynamic Properties of Opteon™ XP10 (R-513A) SI Units*.
- [15] The Engineering ToolBox (2005) *Ammonia-NH₃-Thermodynamic Properties*. https://www.engineeringtoolbox.com/ammonia-d_971.html
- [16] IIR (2008) Appendix A Thermodynamic Property Tables. In *Ammonia Data Book* 2nd Edition (pp. A1-A42). https://web.iir.org/membersonly/PDF/CO/databook_AppA.pdf
- [17] DuPont (2004) *Thermodynamic Properties of DuPont Suva 95 Refrigerant (R-508B)*.
- [18] The Chemours Company (2016) *Freon™ 22 Refrigerant (R-22) Thermodynamic Properties (SI Units)*.
- [19] Bhattacharjee, S. (2023) Temperature Saturation Table, R-12. <https://energy.sdsu.edu/testhome/tablesModule/tablesPC/TSatR12.html>
- [20] Bhattacharjee, S. (2023) Superheated Vapor Table, R-12. <https://energy.sdsu.edu/testhome/tablesModule/tablesPC/superR12.html>
- [21] The Chemours Company (2023) *Freon™ 410A Refrigerant (R-410A) Thermodynamic Properties (SI Units)*.
- [22] The Chemours Company (2018) *Opteon™ YF Automotive Refrigerant (HFO-1234yf) Thermodynamic Properties of Opteon™ YF SI Units*.
- [23] Ciconkov, R. (2018) Refrigerants: There is still No Vision for Sustainable Solutions. *International Journal of Refrigeration*, **86**, 441-448. <https://doi.org/10.1016/j.ijrefrig.2017.12.006>
- [24] Cole, B. (2023) R-513A Refrigerant Fact & Info Sheet. <https://refrigeranthq.com/r-513a-refrigerant-fact-info-sheet/>
- [25] Vaghela, J.K. (2017) Comparative Evaluation of an Automobile Air—Conditioning System Using r134a and its Alternative Refrigerants. *Energy Procedia*, **109**, 153-160.
- [26] Niu, B. and Zhang, Y. (2007) Experimental Study of the Refrigeration Cycle Performance for the R744/R290 Mixtures. *International Journal of Refrigeration*, **30**, 37-42.
- [27] Hense, D.L. and Karnopp, J. (2022) Refrigerant Replacement from HFC to HC in a Medical Ultra-Low Temperature Appliance: Experimental and Simulation Approach. <https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=3375&context=iracc>
- [28] Environmental Protection Agency (2024) Phasing Out HCFC Refrigerants to Protect the Ozone Layer. https://www.epa.gov/sites/default/files/2015-07/documents/phasing_out_hcfc_refri

[gerants to protect the ozone layer.pdf](#)

- [29] Cabello, R., Torrella, E., Llopis, R., Sánchez, D. and Larumbe, J.A. (2013) Energy Influence of the IHX with R22 Drop-In and Long-Term Substitutes in Refrigeration Plants. *Applied Thermal Engineering*, **50**, 260-267. <https://doi.org/10.1016/j.applthermaleng.2012.06.008>
- [30] Blanco Ojeda, F.W.A., Almeida Queiroz, M.V., Marcucci Pico, D.F., dos Reis Parise, J.A. and Bandarra Filho, E.P. (2022) Experimental Evaluation of Low-Gwp Refrigerants R513A, R1234yf and R436A as Alternatives for R134a in a Cascade Refrigeration Cycle with R744. *International Journal of Refrigeration*, **144**, 175-187. <https://doi.org/10.1016/j.ijrefrig.2022.08.010>
- [31] Heredia-Aricapa, Y., Belman-Flores, J.M., Mota-Babiloni, A., Serrano-Arellano, J. and García-Pabón, J.J. (2020) Overview of Low GWP Mixtures for the Replacement of HFC Refrigerants: R134a, R404A and R410a. *International Journal of Refrigeration*, **111**, 113-123. <https://doi.org/10.1016/j.ijrefrig.2019.11.012>
- [32] Chen, W. (2008) A Comparative Study on the Performance and Environmental Characteristics of R410A and R22 Residential Air Conditioners. *Applied Thermal Engineering*, **28**, 1-7. <https://doi.org/10.1016/j.applthermaleng.2007.07.018>

Variables List

q_{in} = heat in

q_{out} = heat out

w_{in} = work done on the system

w_{out} = work done by the system

h_e = enthalpy at the exit

h_i = enthalpy at the inlet

q_L = heat dissipated

$w_{net,in}$ = net work of system

h_n = enthalpy at given a “n” point in the cycle (refer to **Figure 1**)

Q_L = heat dissipated by the chip

W = compressor work

\dot{m} = mass flow rate of refrigerant

COP = coefficient of performance

UA = overall heat transfer coefficient

T = temperature at the respective point in the VCRES

P = pressure at the respective point in the VCRES