



INFLUENCE OF AMBIENT TEMPERATURE VARIATION ON THE ENERGY EFFICIENCY AND THERMAL PERFORMANCE OF COOLING SYSTEMS IN CRITICAL ENVIRONMENTS: A THERMODYNAMIC ANALYSIS OF MINING FACILITIES AND DATA CENTERS

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Abstract: Cooling systems are essential elements of energy intensive constructs like underground mines and data centres where the ambient temperature change has a direct impact on refrigeration performance, compressor work load and energy efficiency. The paper examined the impact of ambient temperature on the cooling system performance in mining plants and data centres using a sample size of 60 observations (30 observations each in both settings) and ambient temperature ranged between 18.3 C and 42.8 C. The statistical analysis was performed using SPSS, which involved descriptive statistics, testing of normality, Pearson correlation, simple linear regression, one way ANOVA with post hoc comparisons using the Tukey HSD, and independent samples t tests. Coefficient of performance ($r = -.987$, $p < .001$) and cooling capacity ($r = -.972$, $p < .001$) exhibited strong negative correlation with ambient temperature, and compressor electrical power ($r = .993$, $p < .001$). It was demonstrated that ambient temperature explained 97.3, 98.6 and 94.4 percent of the variation in COP, compressor power, and cooling capacity, respectively. There was a significant difference between low, moderate and high temperature groups on all four performance indicators ($p < .001$) and no difference between environment type on any of the performance indicators ($p > .05$). Compressor energy demand increases with ambient temperature and cooling capacity and efficiency in both environments decrease to support its application as a key variable in energy optimization and cooling system design of critical infrastructure.

Keywords: ambient temperature, cooling systems, coefficient of performance, energy efficiency, mining facilities, data centers

1. Introduction

All types of energy intensive infrastructure in the modern economy are supported by cooling systems. There are two industries that are more reliant on continuous and reliable cooling than others. Artificial cooling of underground mining facilities is necessary to maintain the working conditions and make them safe, as the depth and temperature of the rocks grow. The operation of data centres needs continuous cooling to secure servers and to uphold uptime. The cooling system in both environments is not an ancillary one. It is an inherent factor of safety of operations, life of equipment and cost of energy. Demand of data centre cooling in the world is rapidly increasing. As noted by the International Energy Agency [1], the electricity demand of data centres in 2025 increased drastically as a result of artificial intelligence load and is projected to approximately grow by 2030. This electricity consumption is usually a significant portion of cooling systems since servers produce continuous heat that has to be thrown away to the environment.

One of the most powerful external cooling load drivers is ambient temperature. As the air temperature outdoors or locally increases, the temperature difference to reject heat is reduced and the mechanical cooling system must exert more effort to keep the conditions the same indoors [2]. A systematic review of data centre-free cooling, air and liquid cooling technologies identified that cooling strategy is a key factor that affects

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overall facility electricity consumption with increasing server heat loads [3]. The same trend is true underground. With the continued digging of deeper mines, the temperature of rocks and the airflow situation create significant heat loads, which need to be extracted to ensure the safety of workers and the performance of their equipment [4]. These loads are usually controlled by underground and spot cooling systems with their performance highly reliant on ambient conditions where they are used [5]. Mining is also one of the more energy intensive industrial sectors and ventilation and cooling are often cited as some of the greatest users of energy in a mine [6].

The two environments are based on the same thermodynamic cycle. The majority of mechanical cooling systems employed in mining and data centre applications are vapour compression cycle based where a compressor increases the pressure and temperature of a refrigerant to allow heat to be rejected to ambient environment [7]. The most energy consuming part of this cycle is the compressor. The amount of power it draws, and the overall system coefficient of performance (COP) is directly related to the temperature difference between the refrigerant and the air surrounding the refrigerant [8]. As ambient temperature rises, condensing pressure generally rises as well, increasing compressor work and decreasing COP at constant cooling output [9]. This temperature sensitivity has gained significance due to the changing climatic trends across the world. Increasing average temperatures and the increasing number of high temperature periods are projected to raise cooling requirements in most parts of the globe but reduce heating requirements in the same parts of the globe [10]. An international study of cooling degree days revealed that even a second half degree of warming, between 1.5C and 2.0C above preindustrial temperatures, would cause cooling demand to soar in most populated areas, with the biggest proportional changes predicted in those countries that are least equipped to endure heat [11]. In facilities which cannot afford downtime, including data centers, or which need to safeguard the safety of workers, including underground mines, this tendency increases the practical significance of comprehending precisely the impact of ambient temperature on the functioning of cooling systems.

Although both mining and data centre cooling systems have a common thermodynamic basis, they are seldom addressed in a similar statistical framework. Much of the available literature may consider data centre cooling and mine cooling to be distinct research topics, each with its performance metrics and modelling conventions. There is no well established, combined, quantitative comparison of the effect of ambient temperature on cooling performance in both environments. This gap is filled in the current research. On a sample size of 60 observations of cooling system, which are a result of mining facility and data centre operating condition, this study uses descriptive statistics, correlation analysis, linear regression and analysis of variance to estimate the relationship between ambient temperature and coefficient of performance, compressor electrical power, cooling capacity, thermal effectiveness and specific energy consumption. The research also determines whether cooling-system performance differed between mining facility and data centre observations. The results will be used to inform decisions on energy optimization and give a statistical foundation to evaluate the cooling system in critical infrastructure.

This study has threefold specific objectives. The first will be to measure the statistical dependence between ambient temperature and five major performance indicators of thermodynamics using correlation and regression analysis. The second objective is to examine whether there is a significant difference in performance of cooling systems in low ambient temperature conditions, moderate ambient temperature conditions and high ambient temperature conditions. The third objective is to examine whether cooling-system performance differs between mining facility and data centre operating conditions. Section 2 examines literature on the thermodynamics of cooling systems, ambient effects, and cooling in the mining and data center settings. Section 3 outlines the data set, variables, and statistical procedures. The results are presented in section 4. Section 5 addresses the findings in comparison to the previous studies and in practice. Section 6 discusses limitations and Section 7 is the end of the paper.

2. Literature Review

2.1 Thermodynamic Principles of Vapour Compression Cooling Systems

A majority of industrial and commercial cooling systems use the vapour compression refrigeration cycle. This is a cycle where a refrigerant takes up heat in the space or process that is being cooled at low pressure and low temperature and then expels it into the ambient environment at higher pressure and higher temperature. This cycle is performed by four elements, the evaporator, the compressor, the condenser, and the expansion device [7]. The only in this cycle that requires a lot of mechanical or electrical work is the compressor. It increases the pressure and temperature of the refrigerant vapour and in such a way that heat is rejected to a warmer ambient temperature than would otherwise be achievable.

The common measure of cooling system efficiency is the coefficient of performance (COP). It can be described as the proportion of useful cooling to electrical or mechanical work input needed to generate the cooling. An increase in COP means that it is an efficient system that generates more cooling than the amount of energy used. Since a compressor does almost all the work input in a vapour compression system, COP is very sensitive to any condition that raises the compressor workload; this is an increase in condensing temperature, increase in compression ratio, and decrease in compression efficiency [9].

A calculation method of power input of the helical screw compressor, a type of compressor, is proposed by Petrilean [8], and is used in industrial and mining refrigeration due to its ability to work continuously with continuous load. The technique is a combination of a graphical analytical technique with a mathematical model of the gas flow in the compressor. It demonstrates that a few operating parameters (e.g., pressure ratio, rotor speed, volumetric and adiabatic efficiencies) can determine compressor power input. The present study relies on this calculation framework to give the thermodynamic knowledge in understanding how electrical power of compressor reacts to changing operating conditions, such as ambient temperature. More recent analysis of twin screw compressor rotor geometry has confirmed that shaft power draw increases proportional to the operating pressure ratio that the compressor has to overcome, and that pressure ratio is the dominant mechanical connection between the condenser side conditions and compressor electrical requirement [12].

The second thermodynamic process that is applicable to the performance of cooling systems is heat transfer between the air and surrounding environment. Petrilean and Popescu [13] examined temperature determination of hydrotechnical works with respect to the energy exchange between the air and the adjacent rock or structure. Their observation proved that air temperature in an enclosed/underground space is determined by the amount of heat generated by the surrounding material and the humidity of the air stream. Petrilean [14] further elaborated this thermodynamic model in a specific discussion of heat transmission, the conduction, convection, and radiation processes that determine the flow of heat between a cooling system, its refrigerant, and the outside world. Collectively, these works define that ambient temperature is not merely a background variable, but a boundary condition to the whole cooling cycle. Vapour compression systems with low global warming potential refrigerants have also been analysed using exergy-based analysis, which has demonstrated that cooling capacity, compressor power, and second law efficiency all change together with the compressor operating conditions, highlighting that COP cannot be used independently of compressor workload [15].

2.2 Ambient Temperature Effects on Compressor Power, COP, and Cooling Capacity

Numerous studies affirm that ambient temperature can be considered one of the most powerful external factors influencing the performance of vapour compression systems. The review on residential air conditioning systems vibrated under high ambient temperature conditions by Alawadhi and Phelan [9] showed that the ambient temperature steadily decreases cooling capacity, COP and increases compressor power consumption. Their review found that condenser side improvements on their own resulted in 18 percent to 50 percent higher COP, and 8 percent to 30 percent higher cooling capacity when systems were designed to operate at high ambient temperatures, a fact that reflects the level of performance loss that is caused by operating systems in non-adapted high ambient temperature environments. Experimental work under controlled conditions on a hydrocarbon refrigerant vapour compression system also determined that the coefficient of performance was maximum at a moderate ambient temperature, and decreased with ambient conditions moving outwards, confirming that ambient temperature dominates the efficiency of a cycle even at the scale of one compressor and condenser pair [16].

This trend has a physical account that is a direct result of the refrigeration cycle. An increase in ambient temperature causes the condenser to reject heat to warmer air and increases the condensing pressure at a constant evaporator temperature. This increases pressure ratio that compressor has to work against and consumes more power in compressor to handle a given refrigerant mass flow. Simultaneously, the smaller temperature difference to be used in rejection of heat decreases the heat transfer rate between the refrigerant and the ambient air. The overall consequence is that this system uses more energy and less cooling capacity as ambient temperature rises.

The results of this relationship are directly pertinent to data centre design. A model of the global energy effects of increasing the internal space temperature of data centres by Zhang et al. [2] revealed that COP of cooling systems depends on the operating mode of the cooling system drastically with changes in the ambient conditions. The cooling system COP dropped to about 3 to 5 in their analysis with mechanical cooling modes, which must occur at higher ambient temperatures, versus a COP of about 11 under free cooling modes, which can only occur when ambient temperatures are low enough to reject heat without mechanical compression.

This result demonstrates that ambient temperature does not merely induce a tiny linear penalty on efficiency. It can establish which cooling mode thermodynamically can exist at all, and with large implications on total energy consumption. Empirical support of this sensitivity is provided by experimental studies which pre cooled air cooled condensers, using evaporative and mist based methods, which increased average COP, by approximately half a factor, by reducing the effective temperature difference between the condenser and the surrounding air, a direct demonstration of the mechanism behind the temperature performance relationship studied in this paper [17].

The current research expands on this known relationship through the quantification of the same in one amalgamated dataset, which comprises two distinct critical infrastructure settings. Instead of assuming the relationship between temperature performance is a general law, the analysis in Section 4 estimates particular regression coefficients, which quantify the magnitude of the change in COP, compressor power, cooling capacity and thermal effectiveness with each degree Celsius rise in ambient temperature, over a range of ambient temperature, between 18.3 °C and 42.8 °C.

2.3 Cooling in Data Centre Environments

One of the most rapidly expanding types of electricity demand in the world has now turned into data centres. According to the International Energy Agency, the world electricity demand of data centres increased by 17 percent in 2025 alone, and was significantly caused by artificial intelligence loads, and is expected to approximately increase by about 2030 [1]. Since servers produce a steady amount of heat no matter the external conditions, cooling is not a non-essential load. It must ensure equipment security and reliability, and it usually constitutes a significant portion of the overall electricity usage in data centres. An in-depth analysis of internet data center cooling technologies also found that traditional mechanical cooling systems use a disproportionate amount of building energy when compared to information technology equipment, and that the energy savings realized by other cooling technologies varies greatly based on local climatic conditions and geography [18].

Conservative internal temperatures (between 20°C and 25°C) in conventional data centres have partially been due to the fact that this lowers the equipment failure probability and makes it easier to design cooling systems [2]. Yet, it takes more mechanical cooling effort to maintain such lower internal temperatures under warm conditions in the ambient environment, as a larger temperature difference would have to be overcome between the ambient condition and the desired indoor condition. Zhang et al. [2] suggested that by increasing the temperature of the internal space of data centres, as well as hardware engineered to operate at higher temperatures, it would be possible to have much more hours of free cooling operations globally where only natural air would be sufficient to cool the equipment without mechanical cooling. They calculated that a global temperature rise of space to about 41 °C would enable almost all terrestrial regions to use free cooling throughout the year, which would help significantly cut cooling energy use.

Such research proves that the connection between ambient temperature and cooling system performance is not merely a question of efficiency at the edges. One of the key design considerations that dictate the need of mechanical compression is the requirement of mechanical compression at all. In data centres that are in warmer climates or are used over a season where the ambient temperature is high, a quantitative relationship between ambient temperature and cooling system performance measures e.g. COP and compressor power is required to ensure correct energy projections and infrastructure planning. A computer-based test of the usefulness of power usage in more than one climate zone validated that the amount of energy saved by economizer based free cooling significantly depends on the local ambient conditions and that the performance of facility level cooling is not generalizable between climates [19].

The dataset used in this research comprises 30 observations that are based on the data centre operating conditions, covering the similar ambient temperatures range as the mining facility observations. This design will enable the temperature performance relationship developed in the data centre cooling literature to be directly tested on similar mining facility conditions that will be discussed further in Section 4.6.

2.4 Cooling in Underground Mining Environments

There is a different yet related cooling problem in underground mining. As mining activities are drilled to deeper levels, the temperature of the rock increases because of the geothermal gradient and the ventilation air picks up the heat of the surrounding rock mass, machinery, and man. The working conditions at depth may go beyond the safe limits in both the health of the workers and the equipment without active cooling [4]. Xu et al. [4] conducted a review of heat damage prevention in deep mines and found that the traditional mechanical cooling of refrigeration is the most common method, although there are limitations that are well known such as high energy usage, incomplete dehumidification and cooling losses along the distribution path between the refrigeration plant and the working face. A significant source of this energy load is ventilation. A study of

ventilation on demand systems in an underground coal mine established that active fan speed control and airflow minimization could save the yearly ventilation electrical energy usage by over one million kilowatt hours at one location, demonstrating the extent of energy saving that could be achieved when air and cooling delivery are dynamically controlled based on actual working conditions, instead of operating in a fixed capacity mode.

The efficiency of such underground cooling systems highly depends on ambient conditions at the point of use. Dosa et al. [5] investigated the role of ambient temperature in determining the effectiveness of an underground spot cooling system to control localized heat in mine workings due to the declining ventilation as a larger mining operation shift to the mine closure stage. They found that the thermal efficiency of the spot cooling system under various ambient temperature conditions was significantly different and this supported the idea that ambient temperature is an operating condition that cannot be afforded a fixed design parameter. The observation is similar to the trend in data centre cooling literature and warrants the ambient temperature to be considered as one of the explanatory variables in the current analysis. Mobile refrigeration Field trials of a mobile refrigeration system deployed at a high temperature metal mine working face also found that cooling operation was highly dependent on the temperature and speed of delivered air, and that the system was capable of reducing the wet bulb temperature at the target zone to safe regulatory levels only when the supply conditions were within a specified range, highlighting that the efficacy of spot cooling in mines is extremely sensitive to the thermal environment.

Integrated engineering problems have also been investigated in ventilation and cooling system design. In a deep mine ventilation and cooling system was optimally realized at a depth of over 1,100 meters, Nie et al. [20] reported that mine water of a naturally lower temperature was utilized as a cooling source with a reconfigured ventilation network. Their case study revealed that ventilation redesign coupled with dedicated cooling source delivered quantifiable temperature and humidity decreases at the working face, indicating that performance of cooling in mines is a product of interaction between airflow, humidity and the cooling source available, rather than refrigeration capacity alone.

One of the key limitations to the design of underground cooling systems is their energy consumption. Mining is one of the highest energy-intensive branches of industry, and ventilation, along with related cooling systems is often cited as a major energy user in a mine, along with the transport of materials and comminution [6, 21]. Since underground cooling systems are required to be running 24 hours in order to ensure safety of workers, any increment in compressor power demand necessitated by rise in ambient temperature directly translates into increment in operating cost and site energy consumption. This will encourage these observations of a mining facility to be included in the current dataset with data centre observations in order to test the relationship in two operationally different and thermodynamically similar environments.

Previous studies by Petrilean and Popescu [13] on temperature measurement in hydrotechnical and underground structures are another source of support to this method. They found that the air temperature in enclosed underground spaces is determined by the joint effect of heat emitted by the rock mass around the space plus the humidity of the ventilating air stream, which depends on the depth and season. This is one reason that ambient temperature, even in one underground facility, can range enough to form a range that can be statistically analysed, which is also in line with the range that is present in the current dataset.

2.5 Climate Change and Rising Cooling Energy Demand

In addition to facility level engineering, there are larger climate trends that are enhancing the practical significance of ambient temperature as an inductor of cooling energy demand. A study by Deroubaix et al. [10] of thirty climate model simulations across the globe discovered that climate driven trends in cooling energy demand were much stronger after 1990 than it had been in the last four decades. Their results revealed that the growth in cooling energy demand was stronger than the growth in heating demand in most densely populated mid latitude areas and that the growth in cooling demand was highly diverse, ranging a few percent to a few hundred percent, depending on the location and climate model.

Both mining and data centre operations are directly relevant to this trend. Plants in areas with forecasted greater cooling degree days gains would anticipate a similar increment in the ambient temperature levels that their cooling systems will have to cope with. As it is shown that ambient temperature and cooling system performance have a strong, measurable relationship in the current study, the regression models created in Section 4 can be used as a useful tool to estimate how future warming trends, as simulated by Deroubaix et al. [10], can be transformed into future higher compressor energy demand at the facility level. This demand adds to an already existing escalating worldwide electricity demand linked with the increasing use of data centres [1], which is why the value of a quantitative, temperature-based model of cooling system performance of the type provided in this study is practical.

2.6 Statistical Approaches to Thermal Performance Analysis

Thermodynamic performance data are typically statistically developed based on a systematic order. Descriptive statistics determine the range and central tendency of each variable and normality test whether to use parametric statistics like Pearson correlation, linear regression and analysis of variance. Correlation analysis establishes the nature and direction of the relationship between variables prior to regression modelling and is therefore a measure of the functional relationship between a predictor (ambient temperature) and an outcome (COP). Analysis of variance is the generalization of this technique to group comparisons, and post hoc tests such as Tukey honestly significant difference tests are used to identify the pairs of groups that are different in the event an overall difference was found. Recent assessment of normality testing tests with a variety of sample sizes, skew and kurtosis values discovered that the Shapiro-Wilk test is still among the most dependable options with a moderate sample size, which justifies its use along with the Kolmogorov-Smirnov test in the normality test reported in Section 4.2 [22].

This ranking is suitable to the data of cooling system performance because the underlying thermodynamic correlations, e.g. the dependence of compressor power on the condensing temperature, are most likely to be approximately linear with moderate operation ranges. Past mining cooling research like ambient temperature experiment of Dosa et al. [5], has been anchored on direct calculation of thermal efficiency under various ambient conditions to explain the behaviour of the system. The present article expands on this approach by applying a complete inferential statistical model, which entails a test of significance and the presentation of the effect size, to a pooled dataset in two critical infrastructure environments.

2.7 Research Gap and Study Objectives

Collectively, the literature reviewed develops three points. First, a well-known and strong driver of vapour compression cooling system performance is ambient temperature, which influences COP, compressor power, and cooling capacity via known thermodynamic processes [7, 8, 9, 14]. Second, this relationship has been shown singly in research on data centre cooling [1, 2] and in underground mining cooling research [4, 5, 20]. Third, the conditions of the ambient temperature which are controlled by cooling systems in both industries are likely to be more widespread due to broader climate trends with time [10]. What has not yet been developed is a direct, statistically based comparison of performance of cooling systems in these two settings within a single dataset and analytical framework because most existing research analyses data centre cooling or mining cooling in isolation, with different metrics that are hard to directly compare.

This research fills this gap. It uses a standardized set of descriptive, correlation, regression, and analysis of variance processes to a mixed collection of 60 cooling system observations, half of which were under mining facility and data centre conditions, with an ambient temperature range of 18.3C to 42.8C. The objectives will be to measure the strength and shape of the relationship between ambient temperature and five performance indices, to test the hypothesis that performance varies significantly between low, moderate, and high ambient temperature conditions and to test the hypothesis that performance varies between the two types of environments when ambient temperature is considered as the primary explanatory variable and to test whether cooling-system performance differs between the two types of operating environments.

3. Materials and Methods

3.1 Research Design and Data Source

The present study involved a quantitative, cross-sectional design, which was based on the analysis of a structured dataset of the operating observations of the cooling system. The dataset represented 60 individual observations each of which was an operating condition of a vapour compression cooling system. The observations were sampled to thirty based on the conditions of mining facilities operation and thirty based on data center operation. Ambient temperature was recorded with each observation, along with a collection of measures of thermodynamic performance of the cooling system in that condition.

Data used in this analysis came in the form of structured data sets of cooling system observations, which represented operating condition of the mining facilities and data centres. The data were collected over an ambient temperature range of 18.3 o C to 42.8 o C with that range being comparable to the ambient temperature range of seasonal and geographic variation reported in previous mining and data centre cooling research [2, 5]. This range enabled the analysis to include the cooling system performance at low, moderate, and high ambient temperatures in the same dataset.

In case of grouped comparisons, ambient temperature was recoded into three categories. A temperature of 25o C and below was considered low temperature. The temperatures that were observed to be above 25C and below 35C were categorized as moderate temperatures. Any observations beyond 35 C were considered

as high temperature. This resulted in a total of 19 low temperature observations, 25 moderate temperature observations and 16 high temperature observations.

3.2 Study Variables

The primary statistical analysis involved eight continuous variables and one grouping variable (categorical). The main independent variable during the analysis was ambient temperature measured in degrees Celsius. Cooling capacity, which is in kilowatts, was the rate at which the cooling system achieved the heat removal. Electrical energy consumption of the compressor was in the form of compressor electrical power expressed in kilowatts. The dimensionless ratio was called co-efficient of performance; and was the cooling capacity divided by the compressor electrical power and was the main indicator of efficiency. The thermal effectiveness was measured as a percentage of how effective the cooling system was in regard to its theoretical maximum. The inverse measure of efficiency, how much energy input was needed per unit of cooling output, was expressed as specific energy consumption, in kilowatt hours per kilowatt of cooling produced. The secondary environmental and operational variables included the relative humidity as a percentage and airflow rate in cubic meters per second. The operating environment of each observation was determined by the environment type which is a categorical variable that has two levels, mining facility and data centre. These variables along with their units and purpose in the analysis are presented in Table 1.

Table 1. Study variables and definitions. Temperature Group was derived from Ambient Temperature as follows:
Low = $\leq 25^{\circ}\text{C}$, Moderate = $25\text{--}35^{\circ}\text{C}$, High = $>35^{\circ}\text{C}$

Variable	Type	Unit	Description
Ambient Temperature	Continuous, independent	$^{\circ}\text{C}$	Air temperature surrounding the cooling system at the time of observation
Cooling Capacity	Continuous, dependent	kW	Rate of heat removed by the cooling system
Compressor Electrical Power	Continuous, dependent	kW	Electrical power consumed by the compressor
Coefficient of Performance (COP)	Continuous, dependent	Dimensionless	Ratio of cooling capacity to compressor electrical power
Thermal Effectiveness	Continuous, dependent	%	Efficiency of heat exchange relative to the theoretical maximum
Specific Energy Consumption	Continuous, dependent	kWh/kW cooling	Energy input required per unit of cooling output
Relative Humidity	Continuous, secondary	%	Moisture content of the ambient air
Airflow Rate	Continuous, secondary	m^3/s	Volumetric flow rate of cooling air

3.3 Statistical Analysis Procedures

IBM SPSS Statistics Version 29 was used to conduct a statistical analysis. All continuous study variables were calculated as descriptive statistics (minimum, maximum, mean, and standard deviation) to describe the sample. The Kolmogorov-Smirnov test with the Lilliefors significance correction and the Shapiro-Wilk test were used to determine the normality of the major performance variables along with skew and kurtosis. The visual analysis of normal quantile plots of each variable was also done.

The correlation coefficients of the linear relationship between ambient temperature and each of the performance indicators and the correlation between the performance indicators themselves were determined using Pearson product moment correlation coefficients with two tailed significance tests.

Five dependent variables, COP, compressor electrical power, cooling capacity, thermal effectiveness, and specific energy consumption were analysed by simple linear regression analysis and ambient temperature was the only predictor in each model. Each model the unstandardized regression coefficient, the standard error, the standardized coefficient, t-value, R^2 , adjusted R^2 and an overall analysis of variance F test were recorded.

The one-way analysis of variance was employed to determine the difference in the performance of cooling systems between the three ambient temperature conditions low, moderate, and high, when using each of four performance indicators, namely, COP, compressor electrical power, cooling capacity, and thermal effectiveness. Each ANOVA was preceded by a test of the assumption of homogeneity of variance with Levene. In the cases where a large overall F test was found, Tukey honestly significant difference postdoc tests were performed, to determine which particular pairs of temperature groups differed significantly. A different

one way ANOVA was made to determine whether the thermal effectiveness was different in the two types of environments, again Levene test was used to determine the homogeneity of the variance.

Independent samples t tests were used to determine whether COP, compressor electrical power, cooling capacity and thermal effectiveness between mining facility and data centre environments was significantly different. The test of equality of variances by Levene was applied to report the result of equal and unequal variances in each comparison. Each comparison had ninety five percent confidence intervals of the difference in the means and Cohen d effect sizes. To maintain complete consistency with the primary analysis output, these post hoc and group comparison procedures were calculated using the recorded values of the dataset directly using the same statistical logic and equations as used by IBM SPSS Statistics.

All tests were to be statistically significant ($p < .05$). R^2 was used as the effect-size measure for the regression models, η^2 for the one-way ANOVA models, and Cohen's d for the independent-samples t-tests. Since the relationships between ambient temperature and vapour compression cycle thermodynamics were expected to be strong and consistent a two tailed alpha level of .05 was always deemed suitable.

4. Results

4.1 Descriptive Statistics

Table 2 presents descriptive statistics for the eight continuous variables included in the analysis, based on 60 observations. Ambient temperature ranged from 18.30°C to 42.80°C, with a mean of 29.88°C (SD = 7.13°C). Cooling capacity ranged from 736.60 to 963.70 kW (M = 852.13, SD = 61.35), and compressor electrical power ranged from 218.00 to 350.20 kW (M = 281.95, SD = 38.11). Coefficient of performance ranged from 2.13 to 4.36 (M = 3.11, SD = 0.64), and thermal effectiveness ranged from 75.70% to 88.00% (M = 82.48%, SD = 3.27%). Specific energy consumption ranged from 0.229 to 0.471 kWh per kW of cooling (M = 0.336), relative humidity ranged from 35.50% to 69.70% (M = 54.25%), and airflow rate ranged from 8.24 to 24.59 m³/s (M = 15.76).

Table 2. Descriptive statistics for study variables (N = 60). M = mean, SD = standard deviation

Variable	N	Minimum	Maximum	M	SD
Ambient Temperature (°C)	60	18.30	42.80	29.88	7.13
Cooling Capacity (kW)	60	736.60	963.70	852.13	61.35
Compressor Electrical Power (kW)	60	218.00	350.20	281.95	38.11
COP	60	2.13	4.36	3.11	0.64
Thermal Effectiveness (%)	60	75.70	88.00	82.48	3.27
Specific Energy Consumption (kWh/kW)	60	0.229	0.471	0.336	0.069
Relative Humidity (%)	60	35.50	69.70	54.25	10.53
Airflow Rate (m ³ /s)	60	8.24	24.59	15.76	4.67

The diffusion of the values of each performance variable on a relative scale of the mean of the variable signifies that there is a significant variation in the operating conditions sampled. This is reasonable as the ambient temperature range represented by the dataset is fairly large and offers enough variability to run the correlation and regression analysis in the sections that follow.

4.2 Normality Assessment

Table 3 shows the findings of the normality test of the ambient temperature and the four main performance indicators. Lilliefors corrected Kolmogorov-Smirnov tests showed that ambient temperature, compressor electrical power, and cooling capacity did not differ significantly ($p = .200$ each, which is the lower end of the true level of significance). Other tests that were not significant under the Kolmogorov-Smirnov test were thermal effectiveness ($p = .093$) and COP ($p = .091$).

Shapiro-Wilk tests which are more sensitive to non-normality in smaller samples showed statistically significant non-normality in ambient temperature ($p = .022$), COP ($p = .018$), and compressor electrical power ($p = .033$). Thermal effectiveness ($p = .097$) and cooling capacity ($p = .129$) did not significantly violate the assumption of normality as demonstrated in the Shapiro-Wilk test. All five variables had skew values that were less than 0.30 in absolute value and kurtosis values that were less than 1.20 in absolute value meaning that any deviation in normality was not great but rather small. Fig. 1 shows the plots of normal quantile quantile at a glance. The values of all five variables were observed to be close to the expected normal line throughout the central range of all distributions, with a small difference observed at extreme low and high ends.

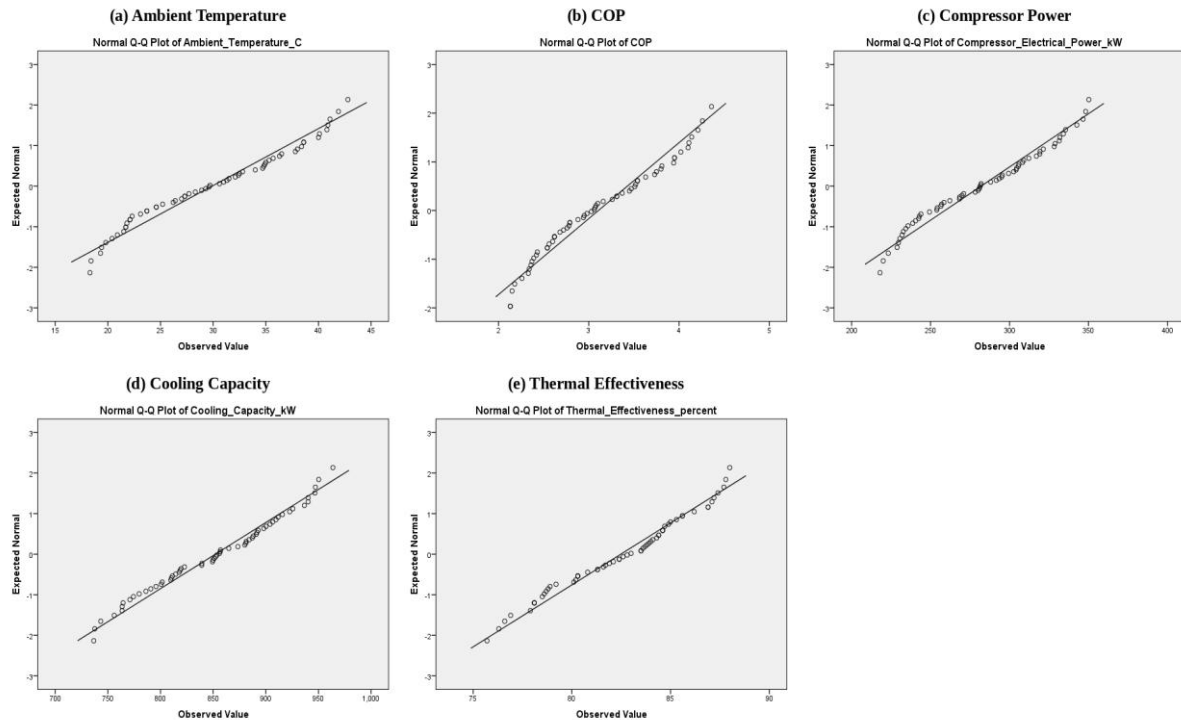


Fig. 1. Normal quantile-quantile plots for ambient temperature (a), COP (b), compressor electrical power (c), cooling capacity (d) and thermal effectiveness (e)

Table 3. Tests of normality for ambient temperature and primary performance indicators. KS = Kolmogorov-Smirnov test with Lilliefors correction, SW = Shapiro-Wilk test

Variable	KS Stat.	df	KS Sig.	SW Stat.	df	SW Sig.	Skew.	Kurt.
Ambient Temperature	.090	60	.200*	.953	60	.022	0.08	-1.20
COP	.106	60	.091	.951	60	.018	0.27	-1.09
Compressor Power	.091	60	.200*	.957	60	.033	0.05	-1.16
Cooling Capacity	.092	60	.200*	.969	60	.129	-0.13	-0.97
Thermal Effectiveness	.106	60	.093	.966	60	.097	-0.22	-0.87

Given the large sample size relative to the number of predictors, the modest magnitude of skewness and kurtosis, and the close visual fit to normality shown in the quantile quantile plots, parametric procedures including Pearson correlation, linear regression, and analysis of variance were considered appropriate for the primary analysis.

4.3 Correlation Analysis

Table 4 shows the Pearson correlation between ambient temperature and the five main performance indicators. All p values were found to be statistically significant at $p < .001$. Ambient temperature was significantly negatively correlated with COP ($r = -.987$) and positively correlated with compressor electrical power ($r = .993$). There was also a very strong negative relationship between ambient temperature and cooling capacity ($r = -.972$) and strong positive relationship between ambient temperature and specific energy consumption ($r = .992$). The association between ambient temperature and thermal effectiveness was significant and negative yet not so strong as the rest of the associations ($r = -.884$).

Table 4. Pearson correlation matrix for ambient temperature and cooling system performance indicators. All correlations significant at $p < .001$, two-tailed, $N = 60$

Variable	1	2	3	4	5	6
1. Ambient Temperature	1.000	-.987	.993	-.972	-.884	.992
2. COP	-.987	1.000	-.989	.974	.864	-.982
3. Compressor Power	.993	-.989	1.000	-.961	-.862	.992
4. Cooling Capacity	-.972	.974	-.961	1.000	.878	-.983
5. Thermal Effectiveness	-.884	.864	-.862	.878	1.000	-.878
6. Specific Energy Consumption	.992	-.982	.992	-.983	-.878	1.000

Correlations among the performance indicators themselves were also strong and consistent with the expected thermodynamic relationships. COP and compressor electrical power showed a strong negative correlation ($r = -.989$), consistent with the definition of COP as cooling output divided by power input. COP and cooling capacity showed a strong positive correlation ($r = .974$). Specific energy consumption, as the approximate inverse of COP, showed strong correlations in the opposite direction from COP across every comparison, including a strong positive correlation with compressor electrical power ($r = .992$) and a strong negative correlation with cooling capacity ($r = -.983$).

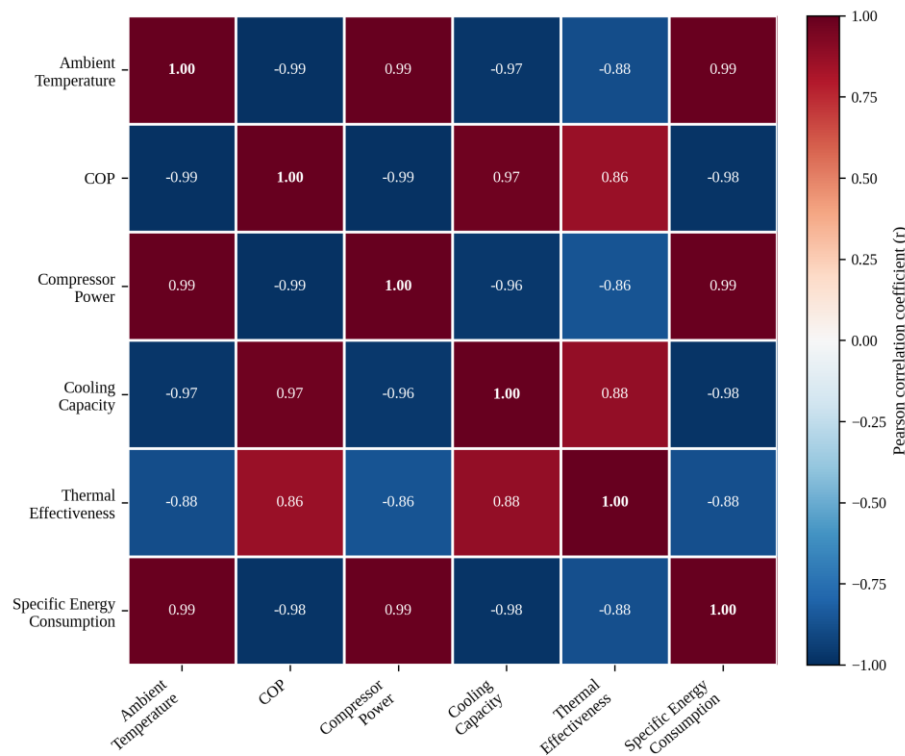


Fig. 2. Correlation heat map of ambient temperature and cooling system performance indicators.
Cell values are Pearson correlation coefficients, all significant at $p < .001$

Fig. 2 presents these relationships as a correlation heat map. The consistently strong correlations suggest a common pattern of variation that is consistent with the thermodynamic response of the vapour-compression cycle to ambient temperature.

4.4 Regression Analysis

Each of the five performance indicators was estimated using simple linear regression models with ambient temperature (T , in °C) as the only predictor. The five fitted equations are provided below and the complete results, including standard errors, standardized coefficients and t values of each model is summarized in Table 5.

$$COP = 5.757 - 0.089T \quad (1)$$

$$P_{comp} = 123.379 + 5.307T \quad (2)$$

$$Q_{cool} = 1101.924 - 8.361T \quad (3)$$

$$\eta_{th} = 94.618 - 0.406T \quad (4)$$

$$SEC = 0.048 + 0.0096T \quad (5)$$

All the five models had a significant value at $p < .001$. The two strongest relationships between ambient temperature and compressor electrical power were equation (1) ($R^2 = .973$) and equation (2) ($R^2 = .986$), which explained 97.3 and 98.6 percent of the variance in COP and compressor electrical power, respectively. Equation (1) shows that COP declined by 0.089 at every 1°C rise in ambient temperature whereas equation (2) shows that compressor power rose by 5.307 kW/degree. Equation (3) ($R^2 = .944$) and equation (5) ($R^2 = .984$) (resulting in 94.4 and 98.4 percent respectively) explained the difference in cooling capacity and specific energy consumption respectively, decreasing by 8.361 kW per degree and increasing by 0.0096 kWh per kW of cooling per degree respectively.

The weakest, but still strong, correlation was between thermal effectiveness, equation (4) and ambient temperature, $R^2=.782$, $F(1, 58)=208.39$, $p<.001$. Each 1 o C rise in ambient temperature led to a loss in thermal effectiveness of 0.406 percentage points. This relatively small R^2 , in the range of 94 to 99% of the other four indicators, indicates that there are other significant factors to thermal effectiveness, as discussed in more detail in Section 5.1.

Table 5. Summary of simple linear regression models predicting cooling system performance from ambient temperature. Predictor in every model is ambient temperature (°C). All models significant at $p < .001$

Dependent Variable	Eq.	Intercept	B (slope)	SE B	β	t	R^2	Adjusted R^2	F(1,58)
COP	(1)	5.757	-0.089	0.002	-.987	-46.01	.973	.973	2117.14
Compressor Power (kW)	(2)	123.379	5.307	0.083	.993	63.57	.986	.986	4040.76
Cooling Capacity (kW)	(3)	1101.924	-8.361	0.267	-.972	-31.29	.944	.943	979.03
Thermal Effectiveness (%)	(4)	94.618	-0.406	0.028	-.884	-14.44	.782	.779	208.39
Specific Energy Consumption	(5)	0.048	0.0096	<0.001	.992	60.56	.984	.984	3667.63

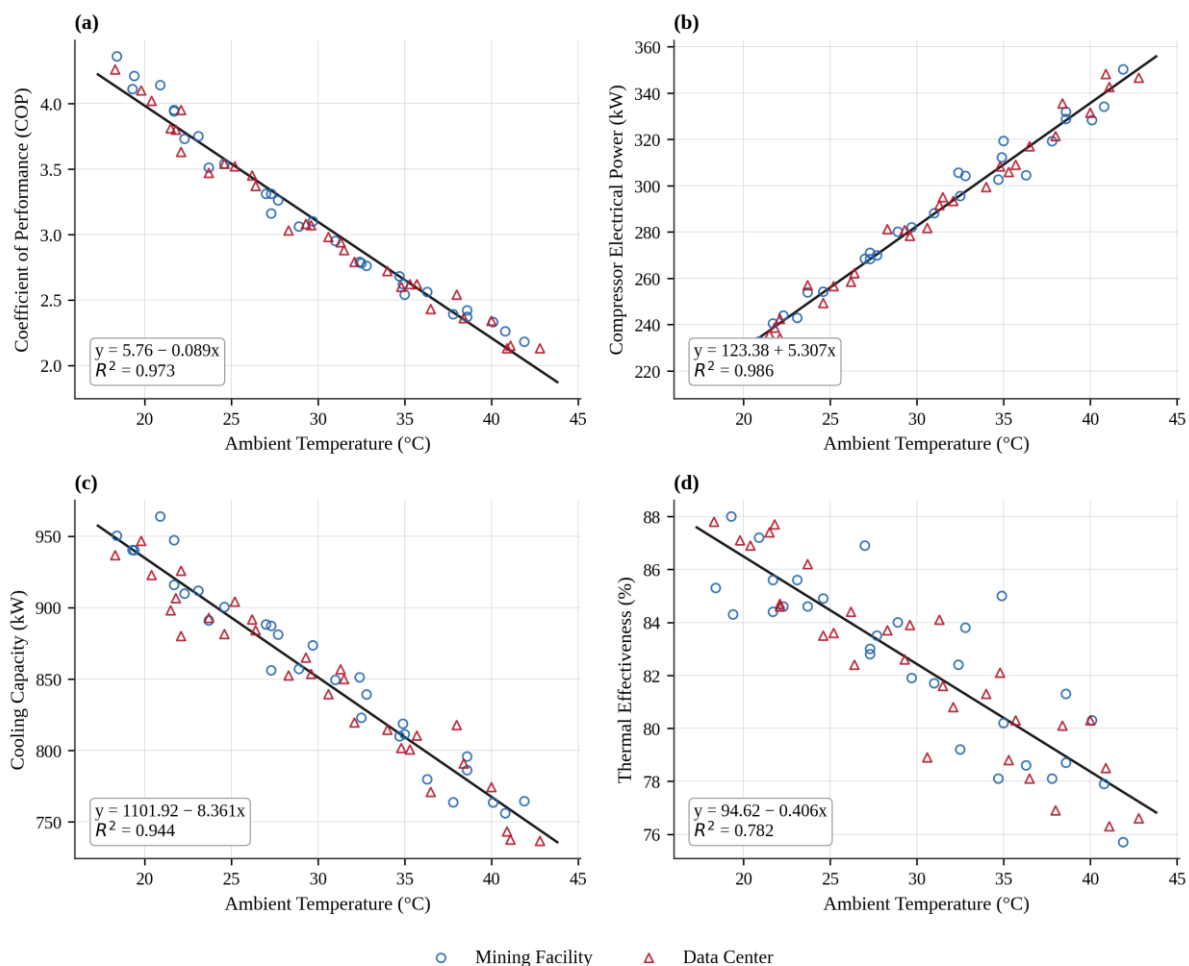


Fig. 3. Coefficient of performance (a), compressor electrical power (b), cooling capacity (c) and thermal effectiveness (d) plotted against ambient temperature, with fitted regression line. Circles: mining facility. Triangles: data centre

These five relationships, as shown in Fig. 3, are graphically displayed, with fitted regression lines overlaid onto the observed data of the four main performance indicators. In all panels, the observations of mining facilities and data centres were close to the regression line, and the ambient temperature axis does not visually show any separation between the environment types. This tendency agrees with the null finding of the comparisons of the environment types in the Section 4.6.

4.5 Comparison Across Ambient Temperature Groups

The COP, compressor electrical power, cooling capacity, and thermal effectiveness were compared between the three ambient temperature conditions, low ($n = 19$), moderate ($n = 25$), and high ($n = 16$). Table 6 presents descriptive statistics and results of ANOVA.

All four ANOVA models were statistically significant ($p < .001$) with temperature group explaining a substantial amount of variance in each indicator, with a maximum of 72.7% of the variance in thermal effectiveness and 85.3% of the variance in COP. Mean COP of the low temperature group declined to 2.36 in the high temperature group. The mean compressor power increased from 237.26 kW in the low-temperature group to 328.42 kW in the high-temperature group. Mean cooling capacity decreased from 918.94 kW to 774.43 kW, while mean thermal effectiveness decreased from 85.81% to 78.53%. According to the test of Levene, the possible violation of the equal variance assumption was only in COP, $F(2, 57) = 3.26$, $p = .046$. The rest of the three indicators had homogeneous variances, with all $p > .10$.

Table 6. One-way ANOVA comparing cooling system performance across ambient temperature groups.
Low = $\leq 25^{\circ}\text{C}$ ($n=19$), Moderate = $25-35^{\circ}\text{C}$ ($n=25$), High = $>35^{\circ}\text{C}$ ($n=16$)

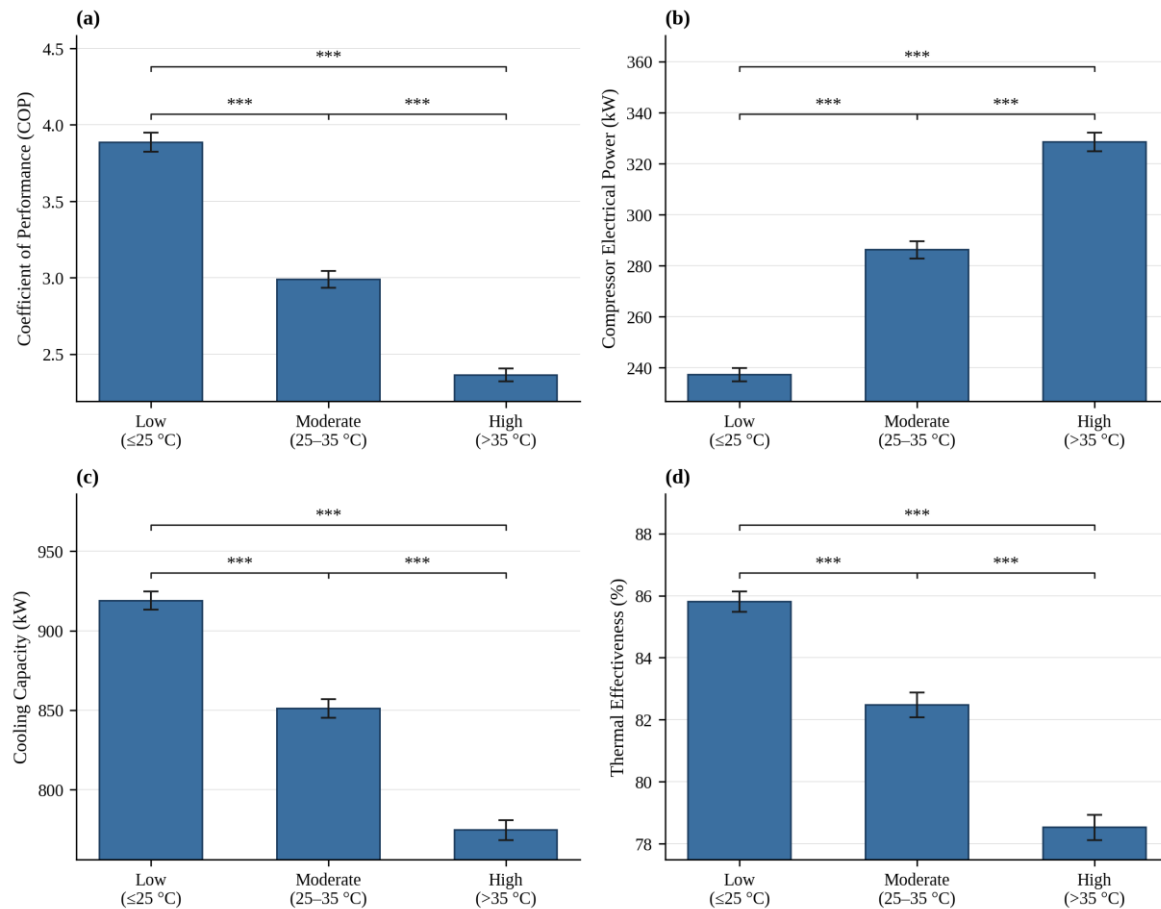
Performance Indicator	Low M (SD)	Moderate M (SD)	High M (SD)	Levene F	F(2,57)	p	η^2
COP	3.89 (0.27)	2.99 (0.28)	2.36 (0.17)	3.26	164.80	<.001	.853
Compressor Power (kW)	237.26 (11.34)	286.17 (17.32)	328.42 (14.66)	2.36	163.27	<.001	.851
Cooling Capacity (kW)	918.94 (25.05)	851.07 (28.95)	774.43 (24.75)	0.19	127.35	<.001	.817
Thermal Effectiveness (%)	85.81 (1.42)	82.48 (2.01)	78.53 (1.63)	0.53	76.06	<.001	.727

Tukey HSD post hoc tests, presented in Table 7, showed that every pairwise comparison among the three temperature groups was statistically significant at $p < .001$ for all four performance indicators. This indicates that low, moderate, and high ambient temperature conditions each produced a distinct and significantly different level of cooling system performance, rather than only the extreme groups differing from one another.

Table 7. Tukey HSD post hoc comparisons among ambient temperature groups. Mean difference is the first listed group minus the second. All comparisons significant at $p < .001$

Performance Indicator	Comparison	Mean Diff.	95% CI Lower	95% CI Upper	p
COP	Low vs. Moderate	0.895	0.712	1.079	<.001
COP	Low vs. High	1.521	1.316	1.725	<.001
COP	Moderate vs. High	0.626	0.433	0.819	<.001
Compressor Power (kW)	Low vs. Moderate	-48.910	-59.857	-37.963	<.001
Compressor Power (kW)	Low vs. High	-91.161	-103.365	-78.957	<.001
Compressor Power (kW)	Moderate vs. High	-42.251	-53.766	-30.736	<.001
Cooling Capacity (kW)	Low vs. Moderate	67.874	48.326	87.422	<.001
Cooling Capacity (kW)	Low vs. High	144.511	122.718	166.304	<.001
Cooling Capacity (kW)	Moderate vs. High	76.637	56.074	97.200	<.001
Thermal Effectiveness (%)	Low vs. Moderate	3.335	2.061	4.609	<.001
Thermal Effectiveness (%)	Low vs. High	7.279	5.859	8.700	<.001
Thermal Effectiveness (%)	Moderate vs. High	3.945	2.605	5.285	<.001

Fig. 4 presents these group comparisons graphically, with error bars representing the standard error of the mean and significance brackets indicating the Tukey HSD results.



*** Tukey HSD pairwise comparison significant at $p < .001$

Fig. 4. Mean coefficient of performance (a), compressor electrical power (b), cooling capacity (c) and thermal effectiveness (d) across low, moderate and high ambient temperature groups, with Tukey HSD comparisons

4.6 Comparison Between Environment Types

Independent samples t tests were applied to determine the difference in COP, compressor electrical power, cooling capacity and thermal effectiveness in the mining facility ($n = 30$) and the data centre ($n = 30$) setups. Table 8 gives the results.

The test that Levene used showed that equal variances could be assumed in all four comparisons, with $p > .50$. The four independent samples t tests were not statistically significant. COP did not differ significantly between mining facility ($M = 3.14$, $SD = 0.66$) and data center ($M = 3.08$, $SD = 0.63$) environments, $t(58) = 0.35$, $p = .729$, Cohen's $d = 0.09$. Compressor power, $M = 281.14$ kW versus $M = 282.75$ kW, cooling capacity, $M = 857.45$ kW versus $M = 846.80$ kW, and thermal effectiveness, $M = 82.59\%$ versus $M = 82.37\%$, likewise showed no significant difference between environments, all $p > .50$, with Cohen's d ranging from -0.04 to 0.17 . This thermal effectiveness outcome was matching a different one-way ANOVA performed by type of environment, $F(1, 58) = 0.06$, $p = .803$, $\eta^2 = .001$.

Table 8. Independent samples t test comparing cooling system performance between mining facility and data centre environments. $n = 30$ per group. Equal variances assumed for all comparisons (Levene's $p > .05$)

Performance Indicator	Mining Facility M (SD)	Data Centre M (SD)	Levene F	$t(58)$	p	Mean Diff.	Cohen's d
COP	3.14 (0.66)	3.08 (0.63)	0.09	0.35	.729	0.058	0.09
Compressor Power (kW)	281.14 (38.18)	282.75 (38.67)	0.00	-0.16	.872	-1.607	-0.04
Cooling Capacity (kW)	857.45 (63.07)	846.80 (60.17)	0.12	0.67	.506	10.643	0.17
Thermal Effectiveness (%)	82.59 (3.17)	82.37 (3.43)	0.21	0.25	.803	0.213	0.06

In all four performance indicators, the effect sizes of the environment type comparison were small with the Cohen d values of 0.04 to 0.17 at the absolute (compared to very large effect sizes of the ambient temperature group comparisons at Section 4.5). This trend shows that the ambient temperature, but not the operational category of mining facility and data centre, was the most dominant element related to the cooling system performance in this dataset.

5. Discussion

5.1 Interpretation of the Temperature-Performance Relationship

The findings of this paper indicate that there is a strong and consistent correlation between ambient temperature and all of the measures of cooling system performance investigated. Ambient temperature alone explained between 78.2% and 98.6% of the variance across five different performance indicators. This is an unusually large amount of explanatory power of a single predictor in applied engineering data, and indicates the direct thermodynamic relationship between ambient temperature and the vapour compression refrigeration cycle of Section 2.1. When ambient temperature increases, the condenser will be forced to reject heat to successively warmer air, increasing the condensing pressure and increasing the pressure ratio the compressor must overcome. This adds compressor electrical power, and decreases coefficient of performance, which is precisely what is seen in the regression results in Section 4.4.

The relatively lower R^2 with thermal effectiveness (78.2) than with COP (97.3) and compressor power (98.6) indicates that thermal effectiveness, which is not directly proportional to ambient temperature but instead a contributor of heat exchange efficiency within the system, is affected by other factors that are not sufficiently reflected by ambient temperature alone. Candidates that are plausible in this extra variation are both relative humidity and airflow rate, which are also in the dataset as secondary variables as both are known to influence the rate of heat and mass transfer in heat exchangers in cooling systems [13].

This is supported by the ambient temperature group comparisons. All four indicators of performance were found to be statistically significant in every pair-wise comparison between low, moderate and high temperature groups with large effect sizes as indicated by η^2 values ranging from .727 to .853. This shows that the relationship between temperature performance is not restrained in a few conditions. It is consistent over the entire temperature range surveyed in this data set, 18.3 C to 42.8 C, and gives meaningfully different operating conditions at the three temperature levels which have been tested.

5.2 Comparison With Prior Thermodynamic and Compressor Research

These are the same results as those obtained in previous thermodynamic studies of compressor performance and ambient temperature sensitivity. The calculation framework of the helical screw compressor power input by Petrilean [8] recognizes the pressure ratio and compression efficiency as the major determinants of power draw by compressors both of which are directly influenced by the condensing temperature and consequently by ambient temperature. The positive correlation between ambient temperature and compressor electrical power found in this study ($R^2 = .986$) fits well in that framework and empirically, data driven analogy to the analytical calculation method Petrilean [8] suggested.

They also agree well with the review conducted by Alawadhi and Phelan [9] that indicated significant losses in COP and cooling capacity of vapour compression air conditioning systems with high ambient temperatures and with the data centre focused results of Zhang et al. [2] that indicated that ambient and space temperature conditions can predetermine which cooling mode, free cooling or mechanical cooling, can be at all offered to a facility. The current study gives a complementary, continuous determination of the same underlying relationship, but as a regression coefficient, which quantifies the exact change in COP and compressor power per degree Celsius of ambient temperature.

In the case of the mining industry, the findings are in line with the findings of Dosa et al. [5] who established that the thermal efficiency of a spot cooling system underground was dependent on the ambient temperature conditions at the point of use. The current research builds on this observation by demonstrating that the relationship is statistically significant in a composite dataset comprising of both mining facility and data center conditions and does not rely on a case specific calculation to demonstrate it.

5.3 Implications for Mining and Data Centre Operations

The fact that there is no statistically significant difference between the environment of mining facilities and data centres, as reported in Section 4.6, is a practically significant finding. No statistically significant differences were observed between the mining facility and data centre groups for COP, compressor power, cooling capacity, or thermal effectiveness. The effect sizes associated with the environment-type comparisons

were very small, with absolute Cohen's d values below 0.20 for all four indicators, whereas the effects associated with ambient-temperature groups were substantially larger. This implies that it is ambient temperature rather than the operational type of the facility that is the major determinant of the cooling system performance as was recorded in this dataset.

This implies directly to energy management in the two sectors. To data centre operators, the regression models in Section 4.4 can be used to model compressor energy demand as a function of local or seasonal ambient temperature, which is applicable since the data centre electricity demand is increasing rapidly due to artificial intelligence workloads [1]. The compressor power regression equation could help a facility operator estimate the amount of additional electrical demand that would be caused by a forecasted rise in local ambient temperature, to help in better capacity planning and energy budgeting. This aligns with the current bibliometric review findings that classification, control optimization and standardized energy metrics are the unanswered questions in data centre cooling research, and that the decision to use either air or liquid cooling as a default option should be based on the ambient operating environment that the facility is located in and not on some default configuration [23].

In the case of mining, the regression relations can be used to the underground and spot cooling systems of the type investigated by Dosa et al. [5] and Nie et al. [20]. Since mining ventilation and cooling already constitute a significant portion of total site energy demand [6], a moderate increase in effective ambient temperature either seasonally or in response to deeper mining or the decrease in natural ventilation during mine closure transitions would result in a measurable and predictable increase in compressor energy demand, which is consistent with the regression coefficients in Section 4.4.

These two implications are particularly important when considering the larger climate trend recorded by Deroubaix et al. [10], which demonstrates that climate driven cooling energy demand has been rising at a faster rate since 1990 than in the previous decades. The fact that the relationship between temperature performance and the environment of the mining facility and data centre was constant in this study implies that this climate induced pressure will impact the two sectors in a similar and predictable manner and not necessarily impact one sector more than the other.

5.4 Theoretical and Practical Significance

Theoretically, this research shows that a common vapour compression thermodynamic model is analytically characterized by Petrilean (2009, 2010, 2016) to generate a statistically consistent empirical signature of two operationally different critical infrastructure settings. This justifies the inclusion of mining facility and data centre cooling systems under a common thermodynamic category to analyse ambient temperature, despite the fact that they vary in size, use and regulatory framework.

Practically, the regression equations derived in Section 4.4 provide a straightforward, ready to apply tool. These equations allow facility engineers and energy managers to compute the anticipated COP, compressor power, cooling capacity, or thermal effectiveness of a particular ambient temperature, even without a detailed thermodynamic model of the particular compressor or refrigerant employed. This can be used in early-stage energy planning, retrofit analysis and climate adaptation analysis, where it is often more helpful to have a quick, approximate estimate than a detailed simulation that needs a great deal of equipment specific input data.

The correlation coefficients found to be statistically significant in this paper, with the R^2 of three out of five performance indicators being above 94 percent, show that ambient temperature is a strong predictor of cooling system performance in both mining and data centres setting, which is why it is suggested to use it as a predictor variable in future energy optimization and system design decisions.

6. Limitations

There are various limitations of this study that must be considered when interpreting the results. To begin with, the dataset was small (60 observations) and was based on one combined sample of mining facility and data centre conditions. The regression coefficients, which were reported in Section 4.4, would be more confident in terms of the generalizability of the regression coefficients due to a larger and more geographically diverse sample.

Second, the analysis was based on simple linear regression analysis with one predictor, ambient temperature, of every performance indicator. Although this method yielded high explanatory power, secondary variables in the dataset (relative humidity and airflow rate) were not fit into a joint predictive model. Further studies might use multiple regression to find out whether these variables account to more variance than ambient temperature, especially to thermal effectiveness, which had a relatively low R^2 in the current study.

Third, the cross-sectional design only recorded performance of the cooling system at one time points of each observation, as opposed to recording the performance of one system over a changing ambient environment over time. A longitudinal or repeated measures study, of the same cooling system through an entire seasonal temperature cycle, might serve to establish whether the cross-sectional relations found here are stable across time within individual systems.

Fourth, the data lacked details about the type of refrigerant, compressor model, or system age, which are known to affect cooling system performance without dependence on ambient temperature. Since these factors were not controllable statistically, some of the unexplained variance in the regression models especially the thermal effectiveness can be due to differences in the levels of equipment used and not the ambient temperature alone.

7. Conclusions

This paper has studied the impact of ambient temperature difference on thermodynamic performance and energy efficiency of cooling systems in mining plant and data centres. The analysis of a combined dataset of 60 observations over an ambient temperature range of 18.3 C to 42.8 C had statistically significant and strong relationships between ambient temperature and all performance indicators studied. Between 78.2% and 98.6% of the variance in the coefficient of performance, compressor electrical power, cooling capacity and thermal effectiveness and specific energy consumption was explained by ambient temperature. An increase in ambient temperature was always correlated with increased compressor power requirement, reduced cooling potential, reduced coefficient of performance and reduced thermal effectiveness, a trend that was completely in line with known vapour compression refrigeration theory.

The cross-ambient temperature comparisons (low, moderate, and high ambient temperature groups) established that these relationships were present in the entire spectrum of the conditions examined, with all the pairwise group comparisons being statistically significant across all four primary performance indicators. Comparisons, in contrast, between mining facility and data centre environments indicated no statistically significant differences in any performance indicator with small effect sizes across the board. These findings suggest that ambient temperature was more strongly associated with cooling-system performance than the operational environment type within the present dataset.

These results have practical implications to the two industries. As the electricity demand of data centres around the world is escalating and as mines are being excavated to increasingly greater depths, the regression equations presented in the present paper provide a direct and quantitative means of estimating how the changes in ambient temperature, whether seasonal, or due to long term climate changes, are expected to impact the overall cooling system energy demand and efficiency of compressors. Together with the larger body of literature on increasing climate induced cooling demand, these findings suggest the explicit inclusion of ambient temperature in energy planning, system design, and climate adaptation strategies of critical infrastructure cooling systems.

Future studies based on this work might extend the data set to larger more geographically representative sample, use multiple regression models that would explain the relationship between relative humidity and airflow rate and ambient temperature in addition to following individual cooling systems through the complete seasonal cycles to verify that the relationships found here persist through time within individual facilities.

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