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Enhancing Vapor Compression Cycle Performance Through Experimental And Numerical Insights On Water-Cooled Condensers

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Abstract
This study investigates the performance benefits of integrating a water-cooled condenser (WCC) into a laboratory vapor compression cycle (VCC) com- pared to a baseline air-cooled condenser (ACC). We combine experiments across five water flow rates (425–1050 LPH) with steady RANS CFD (SST $k-\omega$) to assess condenser outlet temperatures, compressor work, and the Coefficient of Performance (COP). The WCC reduced condenser outlet tem- perature by up to 8 °C (at 1050 LPH) relative to lower flow operation and increased COP from 0.94 to 1.17 over the tested range. CFD reproduced experimental outlet temperatures within 0.2 °C to 3.1 °C. Novel aspects in- clude: (i) paired experimental–numerical validation for a compact WCC un- der multiple water-side Reynolds numbers (6.7×10^3 to 1.7×10^4), (ii) an ex- plicit link between water-side Reynolds number and system COP, and (iii) a consolidated discussion of practical limitations (water availability, fouling, and pumping penalties). The results indicate that modest increases in water flow can yield measurable COP gains while maintaining practical pumping requirements.
Keywords: *Vapor Compression Cycle (VCC), Water-Cooled Condenser (WCC), Air-Cooled Condenser (ACC), Coefficient of Performance (COP), CFD, SST $k-\omega$*

Nomenclature Abbreviations

ACC
Air-Cooled Condenser
COP
Coefficient of Performance
CFD
Computational Fluid Dynamics
LPH
Liters per hour
VCC
Vapor Compression Cycle
WCC
Water-Cooled Condenser

Latin symbols (alphabetical)

$c_{p,w}$
Specific heat of water (kJ/kg K)
$\dot{m}_w$ Water mass flow rate (kg/s)
$\dot{m}_r$ Refrigerant mass flow rate (kg/s)
P Compressor power (W)

Q_{rej}
Condenser heat rejection (W)
Re Reynolds number (water-side)
Greek symbols
μ Dynamic viscosity (kg/m s)
ρ Density (kg/m^3)

1. INTRODUCTION

Water-cooled condensers are widely recognized for superior heat-rejection performance compared with air-cooled condensers, particularly in warm cli- mates and high heat-flux applications. However, compact laboratory systems that quantify the impact of water-side Reynolds number on COP and validate with CFD across multiple flow rates are less reported. Recent works high- light water-cooled and evaporative-condenser advances [1, 2, 3, 4]. This paper contributes an experimentally validated CFD analysis for a WCC retrofit to a standard VCC.. The increasing demand for thermal and electrical energy, particularly in the residential sector, necessitates modifications in energy systems to optimize efficiency and reduce environmental impact. House- hold appliances contribute significantly to greenhouse gas emissions, raising global temperatures and decreasing energy savings. Direct evaporative cool- ing systems, which involve direct contact between air and water, have proven effective in enhancing energy efficiency by studying variables like feed water temperature, wet-bulb temperature, and mass ratio of feed water. These pa- rameters substantially influence system performance, offering a pathway to greater sustainability in energy systems [5, 6, 7]. Split-type air conditioners, equipped with both air-cooled and water-cooled condensers, demonstrate the advantages of water-cooled systems, including reduced energy consumption and improved performance metrics [8].

Refrigeration systems utilizing low-temperature refrigerants such as R507A,
R502, and R404A have shown enhanced efficiency through exergy analysis, which evaluates energy transformation and losses within the system. While domestic refrigerators commonly use refrigerants like R134a and R152a, hy- drocarbons like R600 and R600a offer environmentally friendly alternatives, mitigating the ozone layer depletion caused by CFCs. Recent studies high- light that incorporating nanoparticles, such as CuO, in water-cooled con- densers can decrease power consumption by 11% and boost the coefficient of performance (COP) by 17% [9, 10, 11]. Additionally, comparative studies between air-cooled, water-cooled, and evaporative condensers indicate the superiority of evaporative systems, which reduce power consumption and en- hance COP by leveraging efficient liquid circulation and heat transfer mech- anisms [12, 13].

The integration of water-cooled condensers in household systems has demonstrated promising energy savings and performance improvements. Ex- periments in tropical regions revealed energy consumption reductions of 21–27% and an 8.9% increase in COP compared to air-cooled systems. Advanced configurations, such as those utilizing brazed plate heat exchangers, have achieved COP improvements of up to 75%, alongside reductions in total equivalent warming impact (TEWI) by up to 43% [5, 14]. Studies have fur- ther explored the potential of evaporative cooling systems in diverse climates, with results indicating enhanced performance in hot and dry conditions com- pared to hot and humid environments. Systems using evaporative condensers demonstrated energy savings of 20% and a performance increase of 50%, un- derscoring their applicability in high-temperature regions [6, 15].

Numerical simulations and experimental studies have refined the design and operation of condensers for better energy efficiency and environmen- tal compliance. Enhanced nozzle arrangements and optimized spray rates in water sprayer cooling systems improve heat transfer in air-cooled con- densers under high ambient temperatures [16, 17]. Computational models incorporating steady-state exergy analysis have highlighted the benefits of refrigerants like R152a for higher COP values. Moreover, research on hybrid systems, such as those integrating heat pumps with water-cooled condensers, reveals significant reductions in fuel costs, energy consumption, and green- house gas emissions [18, 19]. The development of liquid desiccant-based cooling systems and advanced heat exchangers continues to shape sustain- able and efficient refrigeration technologies for residential and commercial applications [20, 21]. [22]The experimental results showed that the COP of the WAC is 17.4The increasing demand for thermal and electrical energy in the residential sector highlights the need for efficient energy systems to reduce greenhouse gas emissions and enhance energy savings. Direct evapo- rative cooling systems and split-type air conditioners with water-cooled con- densers have shown significant potential for improving performance metrics and reducing energy consumption. Exergy analysis of refrigeration systems underscores the efficiency of low-temperature refrigerants and environmen- tally friendly alternatives like hydrocarbons. Adding nanoparticles to water- cooled condensers further enhances system efficiency. Comparative studies validate the superiority of evaporative condensers over traditional air-cooled and water-cooled systems in reducing energy consumption and improving COP. Advanced configurations, such as water-cooled condensers with brazed plate heat exchangers, have demonstrated considerable energy savings and reductions in TEWI. Evaporative cooling systems perform exceptionally well in hot and dry climates, achieving significant energy and performance im- provements. Numerical simulations and experiments reveal that optimized nozzle arrangements and hybrid systems, like heat pumps with water-cooled condensers, deliver substantial energy efficiency, cost savings, and reduced greenhouse gas emissions. Research continues to refine sustainable refrigera- tion technologies, focusing on innovative materials, refrigerants, and system designs. [23] The study examined the impact of condensation and desorption temperatures on COP, with a particular focus on the variation in solution concentration. [24]The study examined the impact of condensation and des- orption temperatures on COP, with a particular focus on the variation in solution concentration. [25] Refrigerant R134a enhances heat transfer rate, while Copper outperforms Aluminum alloy 1100 for tube material, but its weight disadvantage makes Copper an alternative. [26]The thermodynamic cycle's process paths differ from ideal cycles, particularly in isosteric heat- ing and isobaric adsorption phases, due to mass transfer resistance effects and increased adsorbent thickness. [27] The study investigated various heat sinks and flat plate heat sinks for sizing microprocessor heat using water as a coolant, revealing that water can significantly enhance heat sink perfor- mance. [28] Installing a water heater in an outdoor unit of a split type air conditioner can increase energy efficiency and reduce fuel costs, while heat pumps provide a cost-effective solution.

[29] The evaporative cooling condenser increased the saturation temper-
ature drop and refrigerant mass flow rate, leading to a 14.3% reduction in compressor power and an increase in COP. The cost-optimal applicable tem- perature was found to be 33.1 °C [30] The evaporative fluid cooler's outlet process fluid temperature has increased by 4.7%, and a parametric research is being conducted to evaluate its impact on performance metrics [21] The model's technique accurately models refrigerant mixes in chillers, with vali- dation data from single and twin screw chillers confirming agreement within
±10%. [31]Water sprayer cooling enhances air cooled condenser heat transfer in low air velocity regions. Numerical simulations and experimental results
show improved cooling performance with the right nozzle arrangement and distance, allowing for optimized spray water rate. [32]The study compares evaporative cooled and conventional air cooled condensers with a split type air conditioner system. Results show a significant reduction in power con- sumption and increased COP, making the evaporative cooled system suitable for changing climate conditions with low humidity

and high temperatures.
[33]The system uses an evaporative cooled condenser for optimal air con- ditioning performance, reducing power consumption by 20% and increasing performance by 50% in hot weather conditions up to 49°C. [34]The study re- veals that wet-cooling systems generate more power than dry ACC systems, and doubling the air-side convective heat transfer coefficient and mass flow rate can increase power production.
In accordance with the literature review, to summarize this it appears that air cooled condensers are used on a large scale in VCC as compared to WCC. Very few studies in the literature investigated the work on the WCC. The fundamental understanding of WCC and systematic arrangement were not adequately explained in the literature. Hence there is no clarification on usage of power for WCC. However, logically it is clear that water is much better than air as far as heat transfer coefficient is concerned. There is a great scope for experiments and analyses of the use of water in VCC. Inves- tigate the impact of water on COP. To check the feasibility of WCC using a non-conventional way of water cooling. To study effect of Reynolds number of water by increasing flow rates on the performance of VCC using WCC. Therefore, in the present work, the entire experiment revolves solely around the WCC to limit power usage and provide the best results for commercial applications. The suggested work is designed to be installed in commer- cial buildings and government offices for the Refrigeration System or an Air Conditioning System. There is limited understanding of the long-term envi- ronmental impacts and lifecycle costs of advanced cooling systems. There is lack of comprehensive studies comparing the performance of hybrid systems in various climate conditions. There is insufficient research on the integration of advanced materials, like nanoparticles, across diverse applications. There is minimal exploration of liquid desiccant cooling systems for residential ap- plications.
In view of this context follwoing will be the scope of our work:

- To evaluate the long-term environmental and economic impacts of ad- vanced cooling systems, including water-cooled and evaporative con- densers.
- To conduct comparative performance studies of hybrid systems, such as heat pumps with water-cooled condensers, under diverse climatic conditions.
- To investigate the integration and effectiveness of advanced materials, such as nanoparticles, in enhancing energy efficiency across various re- frigeration and cooling systems.
- To develop and assess liquid desiccant-based cooling systems tailored for residential and small-scale applications, focusing on energy savings and environmental compliance.

2. METHODOLOGY

2.1. Experimental Setup

A domestic-scale VCC test rig was instrumented with pressure transduc- ers, thermocouples/RTDs, and an energy meter. Tests were conducted at five water flow rates: 425, 625, 825, 1025, and 1050 LPH. COP was computed as the ratio of cooling effect to compressor power. The refrigerant used was R134a due to widespread availability, compressor compatibility, and mod- erate discharge pressures in the tested range (practical for educational/lab rigs).

2.2. Procedure

Experimental setup was developed to satisfy the objectives. This analysis was done on two setups, first VCCA setup and VCCW setup. First VCCA was developed and observations are taken. Then modification in VCCA setup was done for VCCW setup. The VCCW setup comprised of two cycles, one VCC with WCC which is used for getting cooling effect and second is of water circulation cycle for circulating water throughout the setup. Apart from this other measuring instruments are used and all the

components are mounted on the table. In VCC, Compressor, WCC, Capillary tube, Evaporator then water circulation cycle pump, piping, reservoir, valves are used.
Compressor is used to convert low pressure and low temperature vapour refrigerant to high pressure high temperature vapour refrigerant. Compressed refrigerant is passed through condenser where heat is transferred to the water flowing through shell. WCC is shell and tube heat exchanger. It transfers heat from refrigerant flowing through tubes to the water flowing through cell. After this heat exchange, refrigerant becomes low temperature high pressure mixed refrigerant (liquid-vapour refrigerant). Capillary tube is used to ex- pand the refrigerant where low temperature low pressure liquid-vapour refrig- erant. Evaporator is used for our motive of getting cooling effect. Where low temperature, low pressure liquid-vapour refrigerant is converted to low pres- sure low temperature vapour refrigerant. In Measuring instruments, Pressure gauges namely Suction gauge and Discharge gauge are mounted in suction and discharge lines of compressor respectively. RTD sensor are used to mea- sure temperature at 8 places namely at suction line, discharge line, after condenser, after capillary tube, in evaporator, water temperature, shell out- let, environmental temperature. All these temperature were recorded during the observation with help of temperature indicator. Energy meter is used to calculate electricity consumption. Water Rotameter is used to measure flow rate of the water flowing from pump to condenser shell inlet. 2 Toggle switches are used. Main switch is used to ON/OFF the setup and protec- tion from high voltage for temperature indicator and the pump. In WCC, tubes are mounted through which refrigerant flows. Shell is around the tubes through water flows. Shell inlet is connected to water pump via water Ro- tameter and outlet is connected to reservoir with help of pipes as shown in fig. 1. (d). The VCCA setup was made with Compressor, ACC, capil- lary tube, evaporator connected to form VCC. All measuring instruments, switches mounted on the control panel and connections were made to major components as shown in fig. 1. (b). Following component connections, all setup was flushed with nitrogen gas for removing moisture content and re- moving foreign material if present. Setup was created vacuum to remove air and fill R134a refrigerant into the system. Electrical wiring was connected to compressor, pump and temperature indicator. Toggle switches were con- nected; Main switch and energy meter were connected. The system is run and readings are taken. VCCW setup is developed with making modifica- tions in the VCCA setup. Modifications are to change ACC with WCC and assemble the water circulation cycle. WCC is MS shell of cuboidal shape with tubes inside. There are inlet and outlet holes for refrigerant and water both on shell as shown in fig. 1. (d). Water circulation cycle made of pump is connected to reservoir. Pump is connected to shell with pipe in which water Rotameter is placed. Then pipe is joined to reservoir from water outlet of shell. The pump is utilized to circulate the water which is then gathered in the 200-liter reservoir. Similarly after connections of components setup was nitrogen gas cleaned and vacuum made. Refrigerant R134a was filled inside the system. Three types of reading are taken for both VCCA and VCCW setup. First no load inside the evaporator, second load inside evaporator at ambient (room) temperature and third load inside evaporator with more than ambient temperature. All 3 types reading are taken three times to avoid errors in readings. For readings with loading the water bottles were kept in- side the evaporator. Each reading is for 1 hour to observe the variation in temperatures and pressures. Temperature at each location, suction pressure, discharge pressure, energy consumption, and water flow rate are measured in every reading. After reading, Work done by compressor, pull down time required, coefficient of performance are calculated.

2.3. Uncertainty and repeatability

Each operating point was repeated three times. Instrument uncertainties were incorporated via standard propagation: for a derived quantity $y = f(x_1, \ldots, x_n)$,

$$u \Sigma \quad \partial f \quad ^2 \qquad u_y = , \quad _i \quad \overline{\partial x_i} u_{x_i} \quad . \tag{1}$$

Representative bounds are reported in Tables where applicable. Repeatabil- ity standard deviations were within typical lab variability; methodology and data-processing scripts are available upon request.

2.4. Calculations

The setup is established by the flow of the refrigerant and water. The entire project was completed during a rainy season. The components of the single door household refrigerator are taken into account. Because the existing work is focused with performance enhancement and COP, readings were taken for several water flow rates. The measurements were done under three distinct conditions for both the air and WCCs. First, ACC observations are made, followed by WCC observations. Both condensers are operated under three circumstances. In order to study the impact of WCC on ACC we have done the experiment as per the procedure explains in the above section. Initially the setup was operated using ACC and the readings were taken to calculate the COP such as for. The results are discussed in more detail in the result and discussion section. Further the experiment was continued by using WCC. In order to calculate the COP of WCC the following readings were taken. We have calculated separately the COP by using ACC and WCC respectively.

Actual Refrigerating Effect

Actual Refrigerating Effect

$$R.E. = \frac{m_w C_{pw}(T2 - T1)}{t} \tag{2}$$

Work input

$$P = \frac{Avg.ofblinks \times Impulserate}{t} \tag{3}$$

2.5. CFD modeling

A conjugate heat-transfer domain of the WCC was meshed with unstruc- tured tetra/prism elements. Turbulence closure employed SST k−ω owing to its robustness near walls and separated regions. Inlet boundary condi- tions matched experiments: refrigerant side $\dot{m}_r$ = 0.008 kg/s, $P_{in} \approx 210$ psi; water side $\dot{m}_w$ per test (425–1050 LPH). The pressure-based SIMPLE algo- rithm was used with second-order discretization; convergence required resid- uals $< 10^{-5}$ and monitor stabilization of outlet temperatures and heat flux. A grid refinement check (coarse/medium/fine) confirmed solution changes < 2% in outlet temperature.

2.6. CFD analysis

The Computational Fluid Dynamics analysis was carried on the WCC after the experimental results were achieved. It was coupled with thermal analysis to get results of thermal changes and pattern of fluid flow. It is carried out to validate the experimental results as well as to understand the thermal patterns inside the WCC. The analysis is carried out in Ansys 2022 R1 student version.

2.7. Geometry

The model of water cooled condenser was created in the Catia V5 R21 software, having same dimensions as of the experimental model. For main domain and simplicity, only water cooled condenser was taken consideration instead of the whole setup. As shown in fig. 2. The condenser consists of the tubes, shell, inlet and outlets. The shell has dimensions as 10051× 8 cm. Water inlet and outlet holes are of 2.54 cm each. Condenser tubes are bent in zigzag shape and having 12 turns of 0.6 cm diameter. So, the refrigerant flows through tubes and the water flown around the tubes go out from outlet at bottom.

2.8. Meshing

Mesh is tria mesh with face sizing. Meshing is the process of transforming geometry into a number of small parts known as elements. The geometry is meshed using a simple mesh with linear order. To obtain a more accurate solution, a mesh with fine elements is generated here.

2.9. Boundary condition

The model used in this study is k-omega SST so that the flow around the boundary can be studied well. Also the thermal conditions at outlet are found out. This analysis shows the change in temperature patterns inside the condenser from water and refrigerant inlet to both the outlet. Also, 5 mass flow rates are varied i.e. 425, 625, 825, 1025, 1050 LPH so as to obtain optimum heat transfer from the refrigerant to water.

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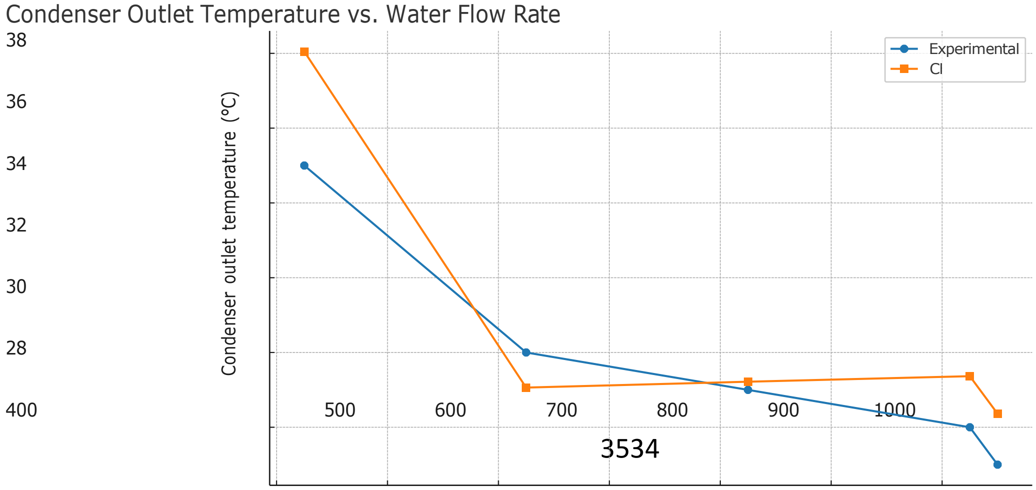
3. RESULTS AND DISCUSSION

3.1. Condenser outlet temperatures

Figure 1 shows experimental and CFD condenser outlet temperatures versus water flow rate. Agreement is within 0.2 °C to 3.1 °C across all points.

Condenser Outlet Temperature vs. Water Flow Rate



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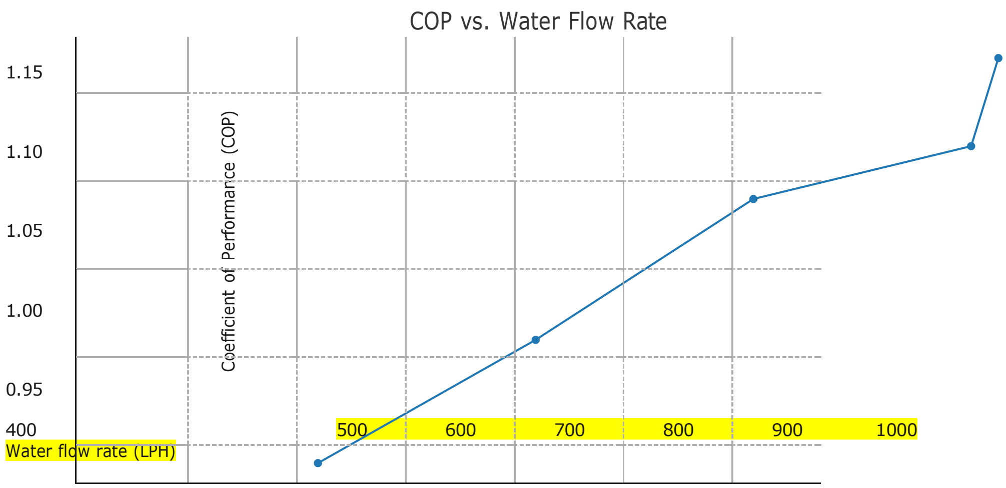
Water flow rate (LPH)

Figure 1: Condenser outlet temperature vs water flow rate (experimental and CFD).

3.2. COP trends with flow rate and Reynolds number

COP increased monotonically with flow rate and with water-side Reynolds number (Figure 2). These trends align with the expected increase in water- side h due to turbulence intensification, lowering mean condensing tempera- ture.



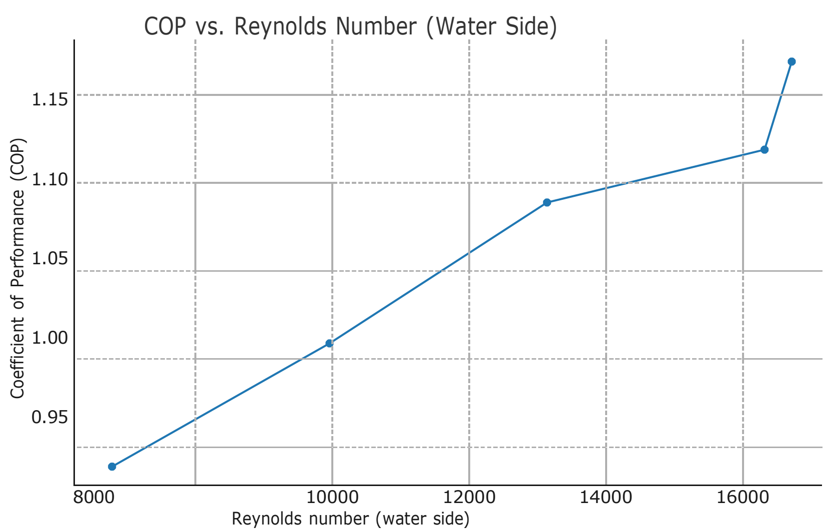
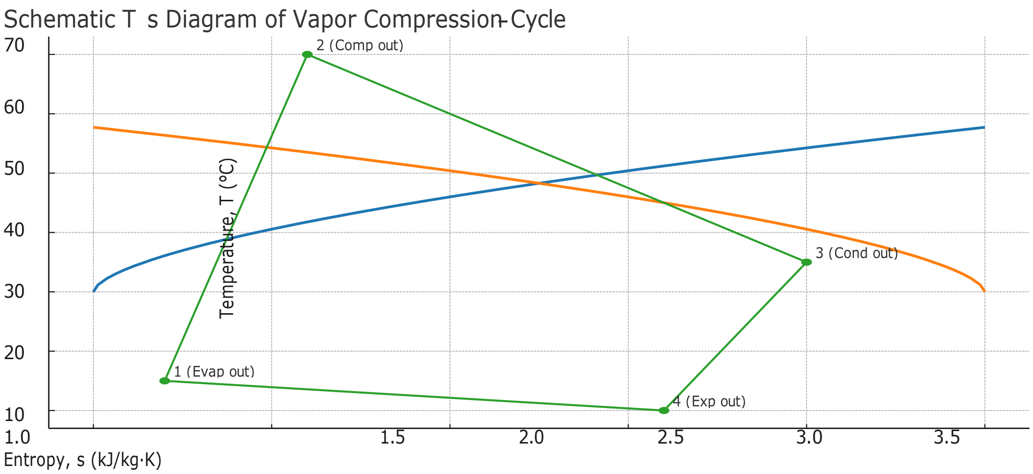


Figure 2: Top: COP vs water flow rate. Bottom: COP vs water-side Reynolds number.

3.3. Thermodynamic cycle diagrams

Schematic T–s and P–h diagrams (Figure 3) summarize the operating states and the effect of improved condensation on cycle temperatures and compressor work.



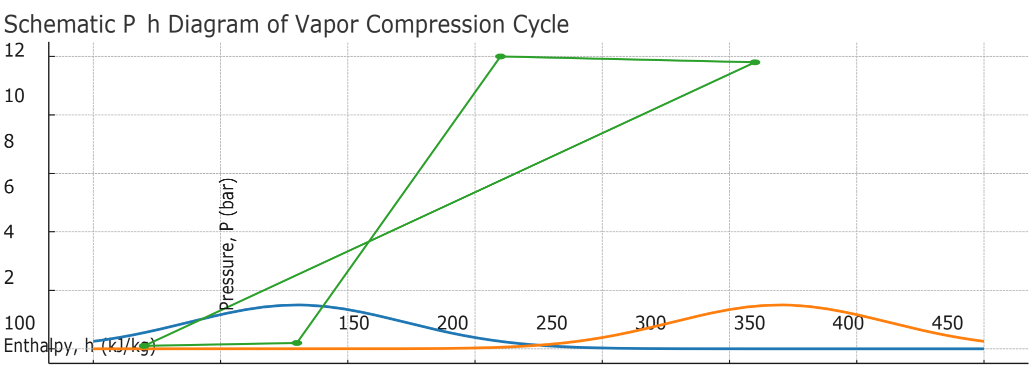


Figure 3: Schematic T–s and P–h diagrams of the VCC

3.4. Comparison with literature

Our results are consistent with recent advances in compact water-cooled condensers and numerical predictions for water-cooled CO_2 units [1, 2]. The observed COP gains with rising water-side Reynolds number align with broader findings on enhanced condenser-side heat transfer [3]. This section displays the results of several parameters in relation to one another in order to demonstrate the impact of one parameter over another. Graphs illustrate several variables such as time, temperature, COP, flow rate and Reynolds number for loading conditions.The major goal of this work is to understand the impact of a water-cooled condenser over an air-cooled condenser. For the systematic study, we first conducted experiments with ACC. So, during the duration of the experiment, the readings, calculations, and findings of the ACC are the control, which will help to determine which arrangement is bet- ter. So, for the experiment, we loaded the water bottles into the evaporator and took time vs. temperature readings. Throughout that time, the amount of time it took for the temperature to drop in both setups was recorded.

The temperature drop in both condensers is shown in Fig. 02 comparatively. In both configurations, the readings are taken for one hour. The amount of temperature drop in both setups for the same amount of working time is displayed. As it explains, the temperature drop in the WCC is greater than in the ACC which is efficient. Following that, we computed the COP. The evaluated COP of the ACC temperature is 0.7 which matched with the literature value. [2] Further we have calculated the COP water cooled con- denser. Once the COP was determined, it was discovered that the WCC has given better COP results than the ACC for the water flow rate of 425 LPH is 0.94, which improved with small scale. Thus, to see enhanced COP values, readings were obtained with increased flow rates with the impact of the Reynolds number on the COP of the particular VCC being studied. As a result, experiments were conducted on the other four alternative flow rates which were 625 LPH, 825 LPH, 1025 LPH, and 1050 LPH.

Based on the calculations, the maximum COP at the maximum flow rate of 1050 LPH is 1.27, which is also consistent with the literature value. Also, for the impact of the Reynolds number, it was determined for all flow rates. By increasing the flow rate leads to increase in the Reynolds number alternatively the COP too, which is desirable for the configuration. The increased Reynolds number shows the turbulence flow of water in the system so; it is advantageous for the system.

3.5. Limitations and practical considerations

WCC performance depends on water availability and quality; fouling and scaling may degrade U -values over time, requiring water treatment. Pumping power partially offsets gains; however, for the tested range, the net COP improvement remained positive. System-level cost-benefit depends on local tariffs, water pricing, and maintenance practices.

3.6. CFD Investigation:

As the readings are taken for five various flow rates of water to determine the COP of the system, which increases as the flow rates increase, the CFD analysis for the VCCW system is performed to analyze the temperature of the refrigerant and water at the WCC's outlet. It is carried out using ANSYS Fluent 2022. The results for the required objectives can be easily achieved by calculations and observations using analytical calculations and experimental research. However, understanding how the required parameters change from point to point and have an effect on the object or device under study is difficult for a detailed investigation. So, the CFD analysis is done to determine the effect of the water in the condenser shell, and by studying the fluid profile, the effect of the water on the refrigerant temperature can be easily studied at different temperatures at different points. The temperatures obtained for the water and refrigerant in the condenser shell at the outlet of the WCC from the experimental study match the results obtained by the CFD profiles on a small scale.

The CFD analysis is performed to investigate how the fluid moves inside the condenser shell in order to evaluate the effect on the refrigerant temper- ature by providing the refrigerant and water with the necessary parameters such as temperature, flow rate, and so on. The temperatures obtained in the simulations match the experimental values by a small margin using ANSYS Fluent. The temperatures of the water and refrigerant have an effect on the flow rate of the water as it increases or decreases. Figure 04 depicts the respected influences for water and refrigerant temperatures. Thus, we can state that the flow rates are performed vital role for the heat transfer in the condenser shell.

The study of the temperatures of the refrigerant and water at the outlet points of the condenser shell are observed and studied in the above section. Similarly, the impact of water temperature for on the refrigerant temperature is illustrated in the above table 8. For various flow rates of the water the temperature of the refrigerant is observed experimentally and numerically and having matching with the small scale.

The relationship between the Mass Flow rate and the Compressor work for a water-cooled condenser is determined. Readings are taken for varying Mass Flow rates, and the compressor work is located based on the results. According to the working, when the Mass flow Rate increases, the Power required for the work reduces. In terms of the first and last conditions, 425 LPH and 1050 LPH require compressor work of 121.04 W and 105.64 W, respectively. As a result, the condition used is clearly illustrated in Fig. 6

Assuming the setup operated for 8 hours in a day, the compressor work is computed for those 8 hours under two conditions: ambient water and hot water. Fig. 7 depicted the per-day power usage for both the Air Cooled and Water Cooled condensers. The work done for the ambient and hot water conditions are 1055.84 W, 903.84 W, and 1120.48 W, 883.2 W, respectively. It was clearly demonstrated that VCCW consumes less power than VCCA. The set of readings gives the overall COP for both previous and updated systems. Fig. 8 shows clearly the loading conditions for both. The variation in the COP of both systems and in the own COP is clearly highlighted in the works. When the Hot Water VCC is taken into account, the Hot VCCA COP is 0.7 [2] and the Hot VCCW COP is 1.09. As an outcome, we may

conclude that VCCW is more effective and beneficial than VCCA.

In terms of cost and energy, we needed some more energy for pumping and cooling the water. It is clearly stated in the objectives that such applications can be utilized for commercial applications where the COP or efficiency of the system is more significant than the work necessary for pumping water in order to decrease expenses. We can also use non-conservation energy sources such as solar energy or any other alternative source to pump and cool the water

4. CONCLUSIONS

Increasing water flow from 425 to 1050 LPH reduced condenser outlet temperature and raised COP from 0.94 to 1.17. CFD (SST k–ω) reproduced outlet temperatures within 0.2 °C to 3.1 °C. Water-side Reynolds number is a strong predictor of COP in compact WCCs. Future work: detailed exergy analysis, fouling-factor sensitivity, and optimization of pump scheduling.

1. The pull down (reduce the temperature of space) time required to attain specific temperature is less in VCCW than the VCCA.
2. The improvement in COP of setup is observed in VCCW than the VCCA. It is increased up to 20% to 25%.
3. The effect of the flow rate of water circulated in WCC is studied on the COP. The COP shown direct proportion with flow rate in VCCW setup
4. The effect of the Reynolds number on the performance of the VCCW system was examined; by increasing the flow rate. It is found that, more the Reynolds number more the COP.
5. Using CFD simulation, the influence of water on the refrigerant temper- ature in the condenser is examined, revealing that water temperature increases as refrigerant temperature decreases in the condenser shell.
6. The temperatures noted at WCC outlet experimentally and numeri- cally shown little variation for water and the refrigerant.
7. The pull down time for the temperature of -5oC the time required by VCCA is more than

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VCCW.
8. The per day power consumption by VCCW is 20% less than the VCCA.
9. COP of the VCCW setup is observed to be increased as compared to VCCA for all the three condition of the working.

Declaration of competing interest: The authors declare no competing interests.

Data availability: Data are available upon reasonable request.

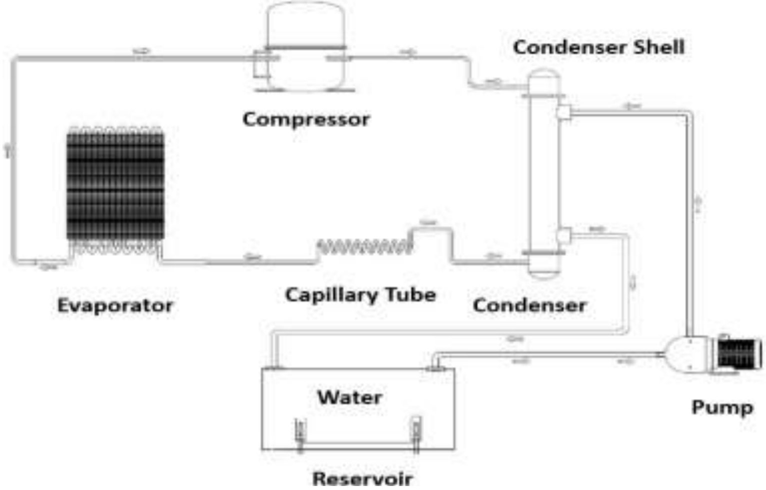

Figure 4: Schematic Diagram

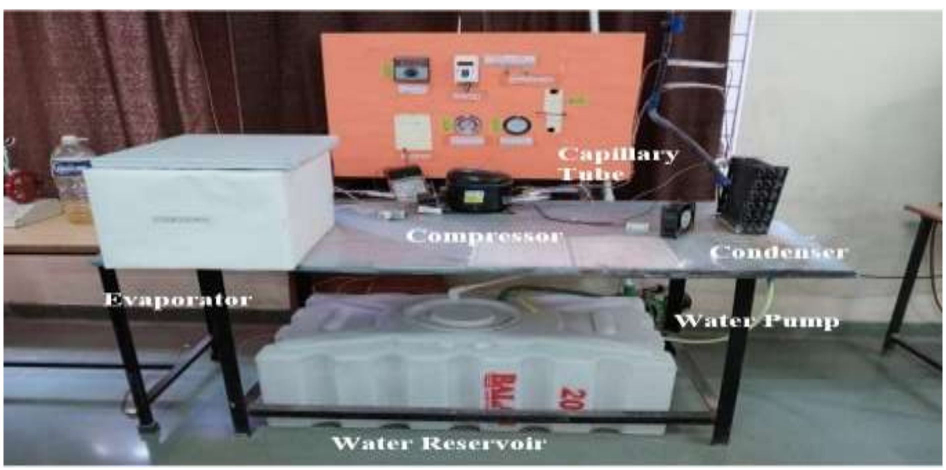

Figure 5: Actual Set Up

Figure 6: Water cooled condenser

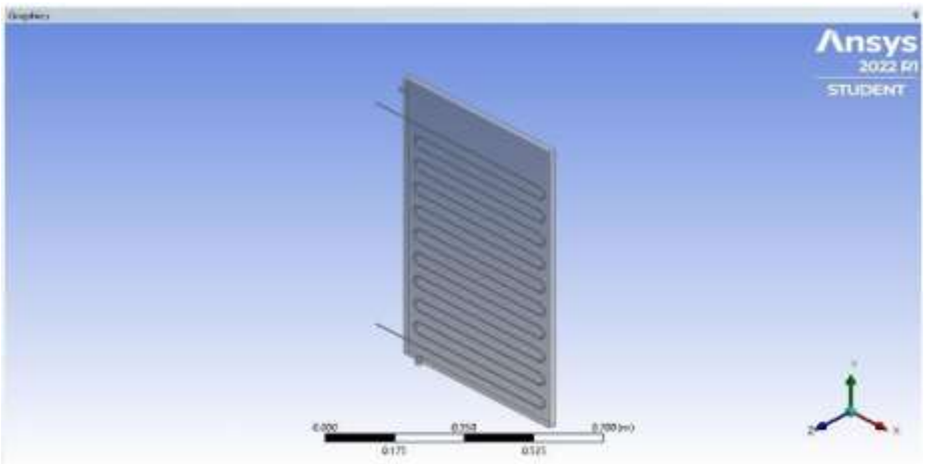

Figure 7: Imported geometry in Design mo

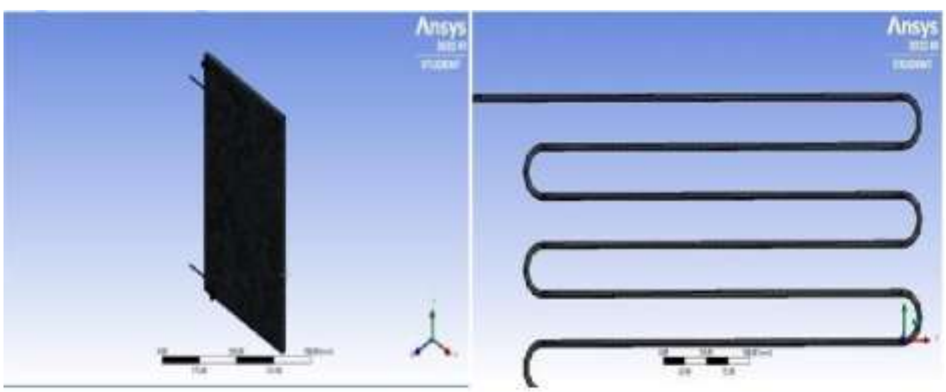

Figure 8: (a) Meshing of shell (b) Meshing shown for Tubedeler Ansys 2022 R1

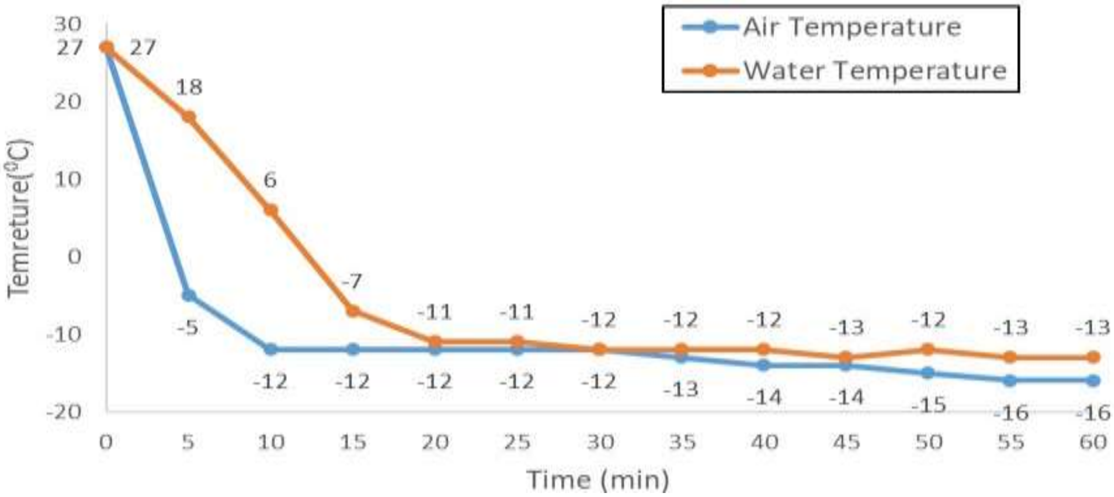

Figure 9: Temperature vs. Time (ACC and WCC

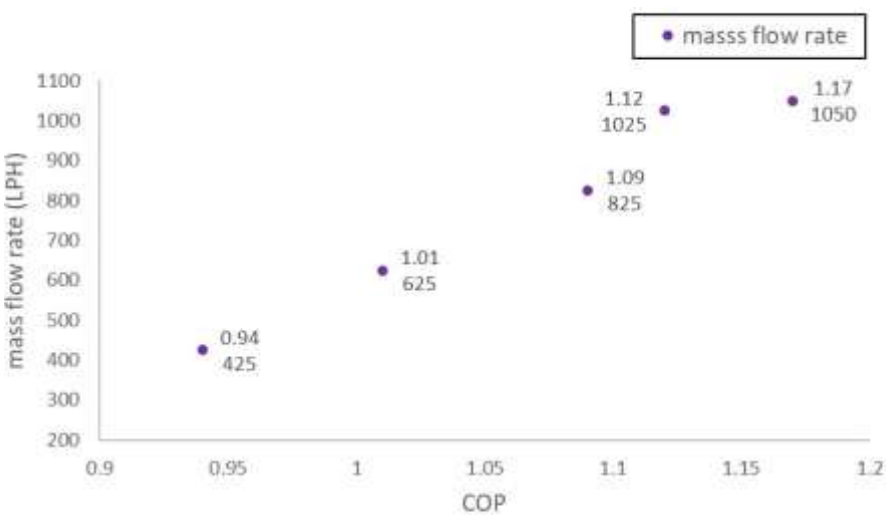

Figure 10: flow rates vs. COP (WCC))

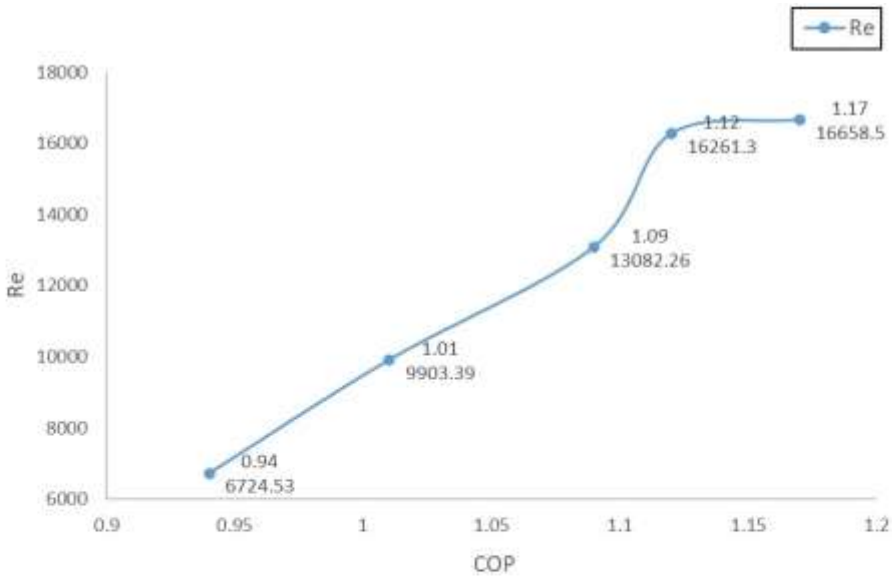

Figure 11: Reynolds number vs. COP (WCC)

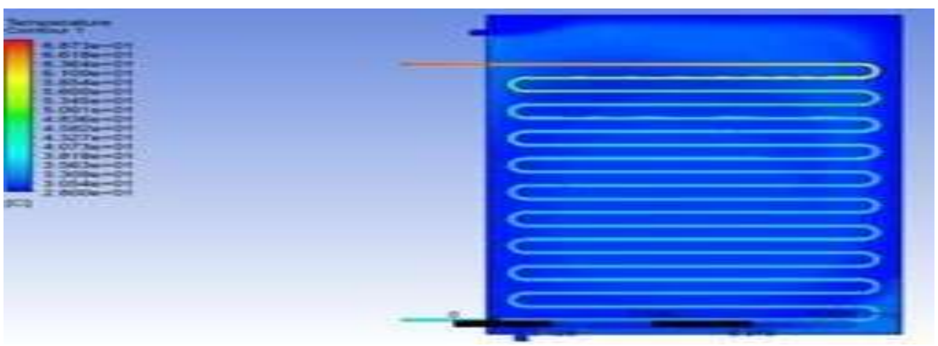

Figure 12: Flow Rate 425(LPH) CFD Temperature Profile

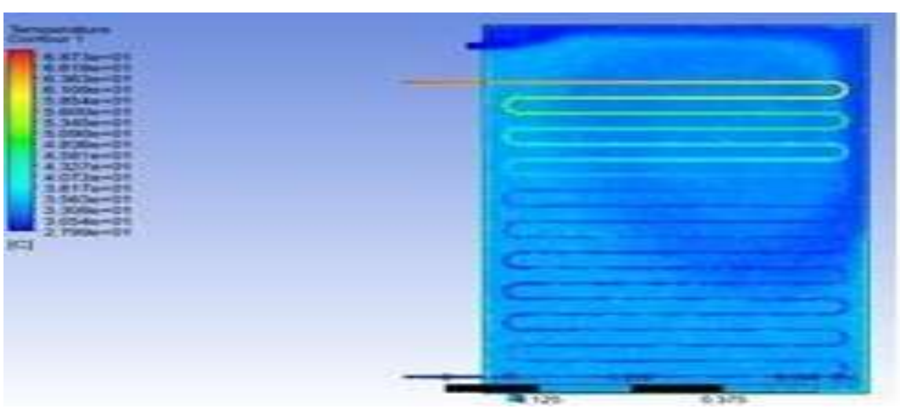

Figure 13: Flow Rate 625(LPH) CFD Temperature Profile

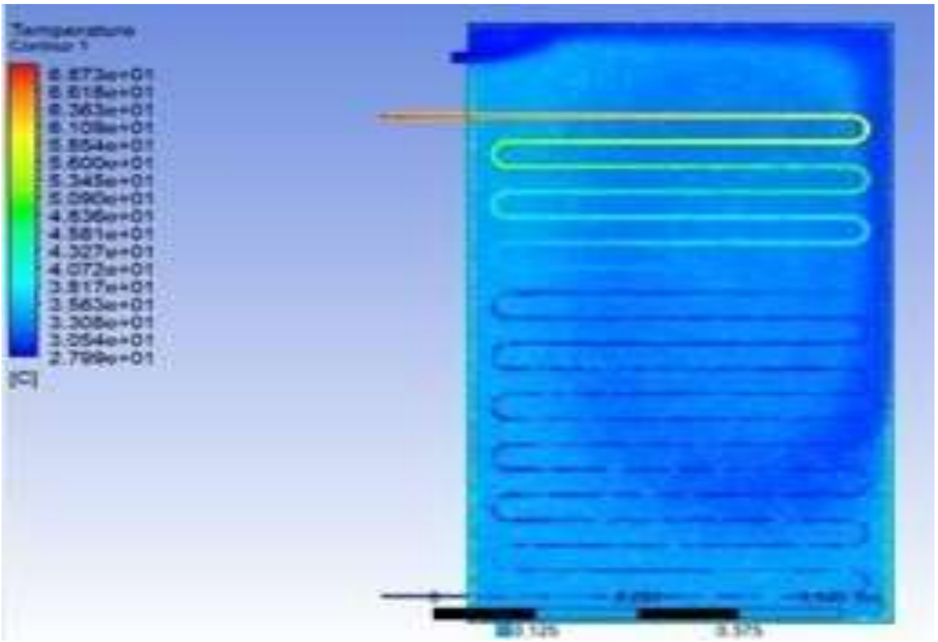

Figure 14: Flow Rate 825(LPH) CFD Temperature Profile

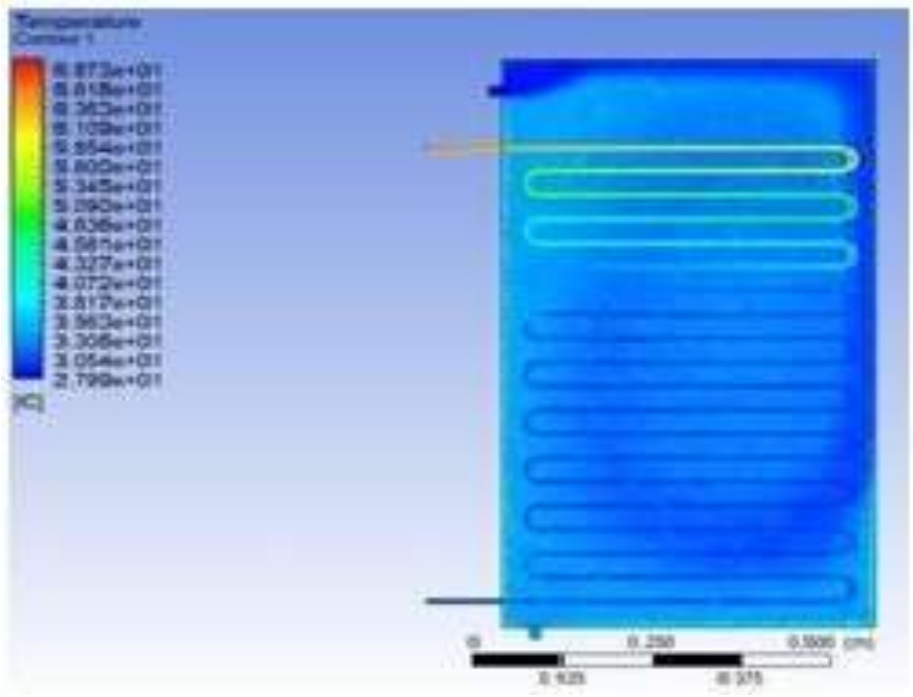

Figure 15: Flow Rate 1025(LPH) CFD Temperature Profile

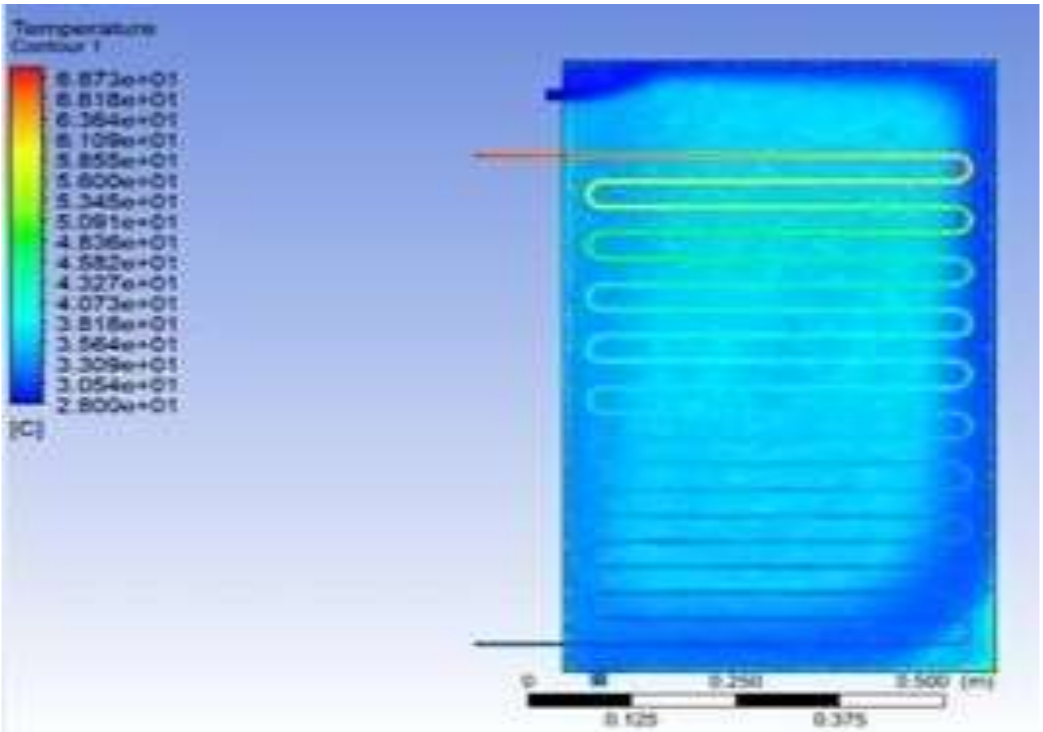

Figure 16: Flow Rate 1050(LPH) CFD Temperature Profile

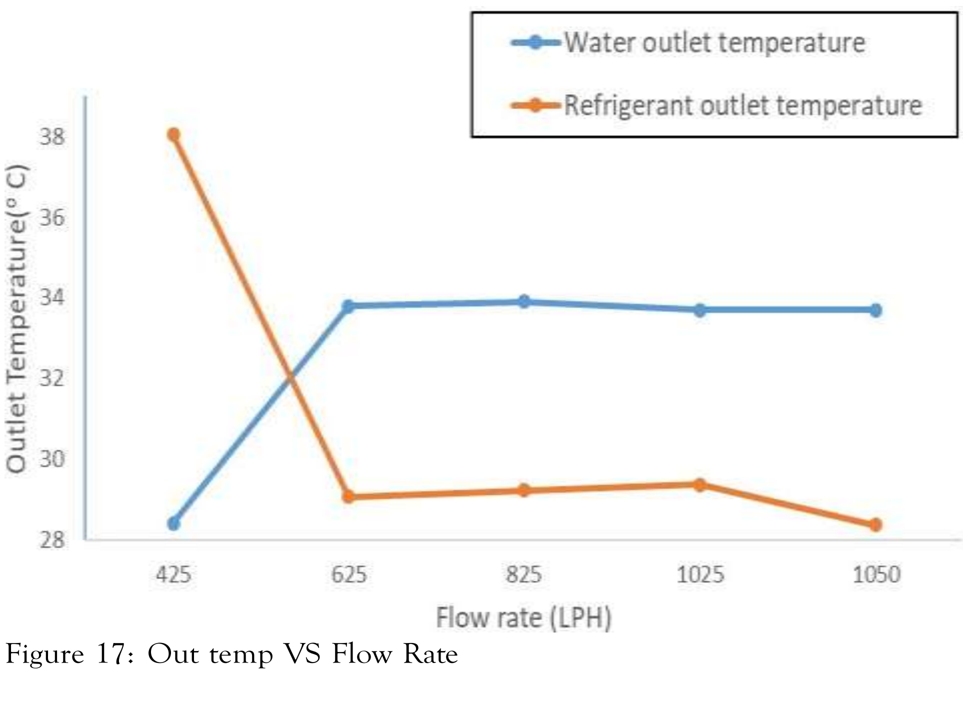

Figure 17: Out temp VS Flow Rate

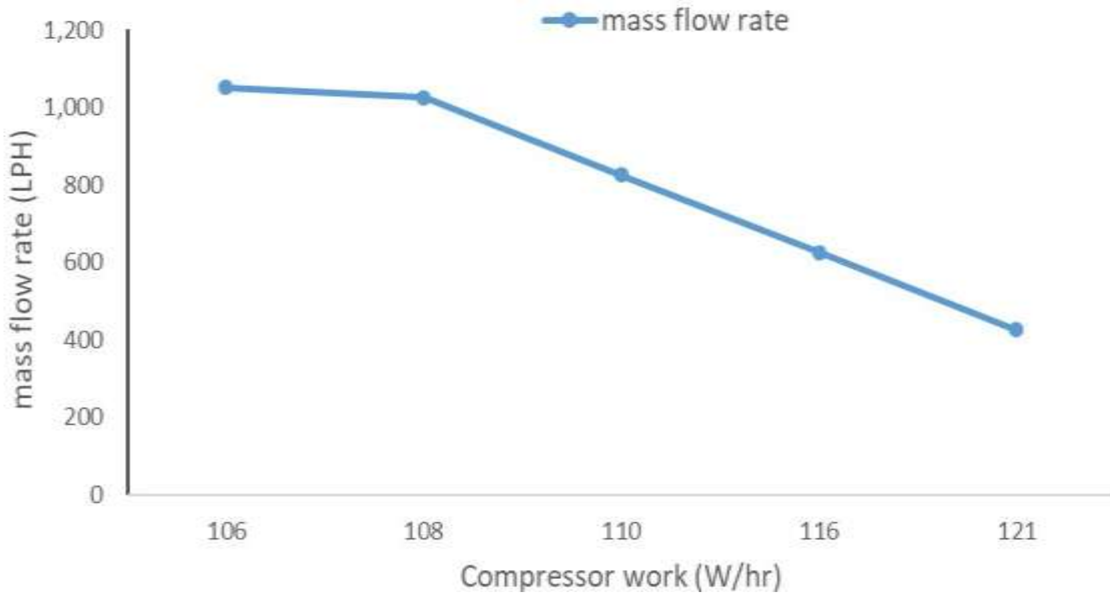

Figure 18: Flow Rate VS Comp Work

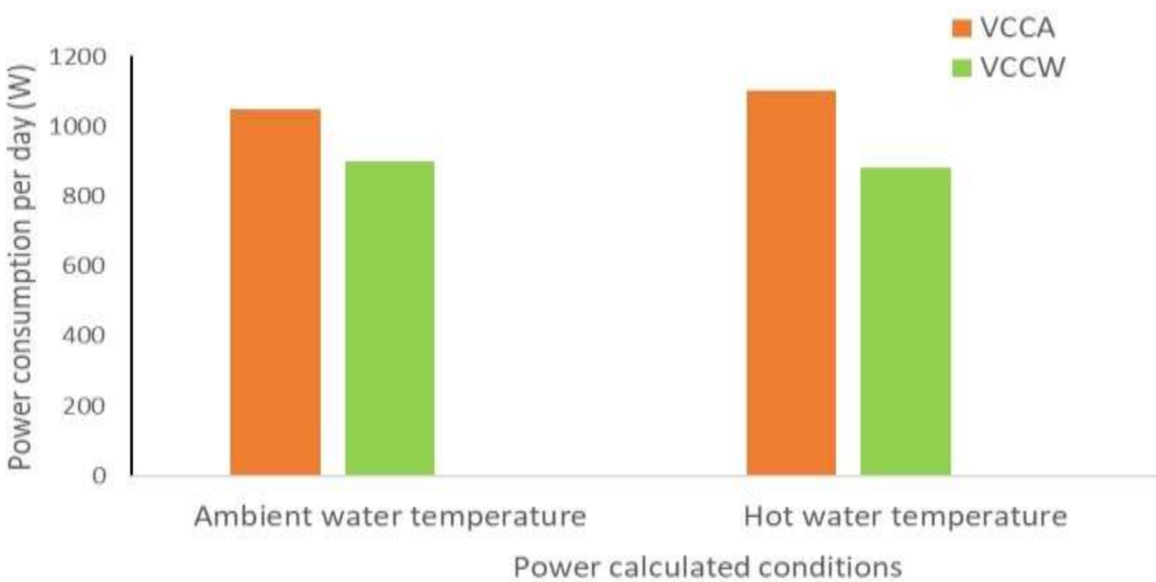

Figure 19: WCC - Per day energy consumption vs. VCCA VCCW

Figure 20: COP - VCCA VCCW

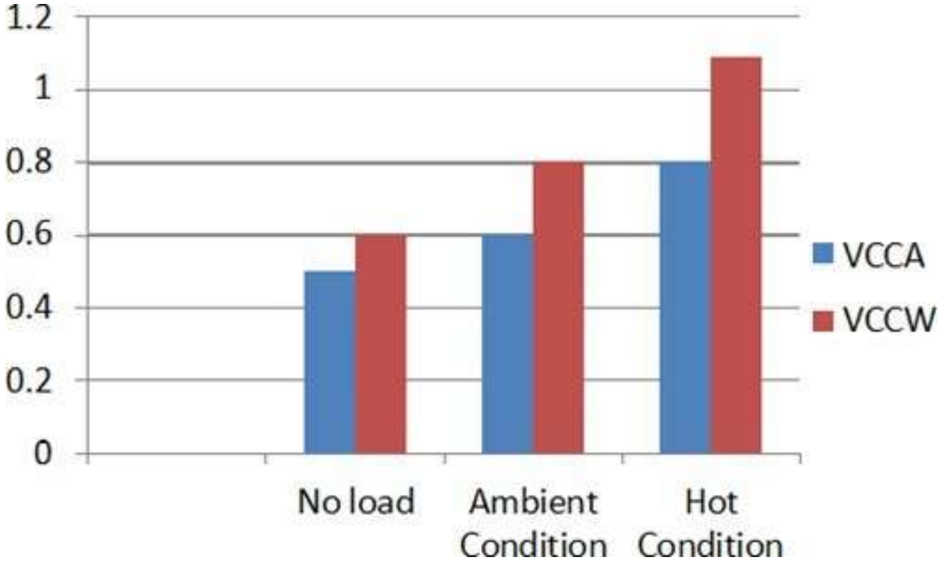

Table 1: Components and their specification used in setup

Components	Specifications
Compressor	Godrej A1 = 120 W 230V, 50Hz, 1 Phase, R134a Motor type = RSCR
WCC	No. of turns = 12, Tube Material = Copper, Shell material = Mild steel with 1.5 mm thick, Dimensions of shell = 100(L) × 51(B) × 8 (H) cm
Capillary Tube	Length (L) = 304.79 cm, Diameter (ϕ) = 0.2cm
Evaporator	Standard evaporator with refrigerant lines inside Dimensions = 47(L)× 35.8(B) × 3(H) cm
Pump	Centrifugal Pump, Power = 370 W, 220 V, 50Hz, Discharge = 1050 LPH Head = 150 cm
Water Rotameter	Make - Perfect flow Instruments, Range = 0 to 1100 LPH / 18.33 LPM
Pressure Gauge – Suction	Make – HONGSEN, Pressure range =15 to 260 psi
Pressure Gauge – Discharge	Make – SYMBOL, Pressure range = 30 to 550 psi

Temperature Indicator	8 channel, 230 V, 3Amp, Temperature range = 100 to 1000 °C Resolution =1 °C
Toggle Switch	2 Phase, 6 Amp
Main Switch	Anchor Polycarbonate DP, 32 Amp
Energy Meter	1 Phase, 2 wire, 5-30 Amp, 240 V, 50 Hz, 3200 imp/kWh
RTD – PT 100	Measuring range = 50 to 300 °C, Probe diameter (ϕ) = 0.3cm Wirelength = 300cm
Copper Tube	Dimension = 304.799× 0.6 cm
PVC Pipe and Return Hose Pipe	Dimension = 304.799× 2.54 cm, Valve – cock type
Water Tank	200 liters
Table	152.39× 121.91× 91.43 cm

Table 2: ACC and WCC Calculations Output

Sr. No.	Entity	Air Cooled Condenser	Water Cooled Condenser
1	**Actual Refrigerating Effect (R.E)**	**116. 30 W**	**116. 3 W**
2	**Work input (P)**	**141. 16 W**	**111. 16 W**
3	**COP**	**0. 7**	**1. 05**
4	**Heat rejected (Q_{rej})**	**257. 46 W**	**227. 46 W**

Table 3: Equations used for calculations

Feed water at 27 °C	**Dynamic viscosity (μ)**	**0.0008509 Kg/ ms**
	Density	**996.5 kg/m³**
Discharge	Q = AV	
Reynolds number (Re)	Re =ρV D/(μ)	

Table 4: Calculations of Reynolds Number

Discharge	Reynolds number (Re)
Q = AV	Re= ρV D/(μ)
0. 000118 =π/4D2V	996. 5 × 0. 220 × 0. 0261 / 0. 0008509
V= 0. 220 **m**/ sec	**Re** = 6724. 53

Table 5: Variation of COP with Reynolds Number

Flow rate (LPH)	COP	Reynolds number (Re)
425	0.94	6724.53
625	1.01	9903.39
825	1.09	13082.26
1025	1.12	16261.3
1050	1.17	16658.496

Table 6: Comparison of Condenser Outlet Temperatur

Condenser Outlet Temperature (°C)		
Flow Rate	**Experimental temperature**	**CFD Simulation temperature**
	Refrigerant	**Refrigerant**
425	35	38.048
625	30	29.061
825	29	29.218
1025	28	29.366
1050	27	28.362

Air Cooled Condenser						
Load Cond.	Gauge Pressure		tini(°C)	tfin(°C)	tref(°C)	tevap(°C)
	Suction	Discharge				
Without load	0	120	-	-	55	-18
With load (amb.)	170	10	26	15	49	-11
With load (Hot)	200	15	44	22	58	-5

Table 7: Air Cooled Condenser Readings

Table 8: Water Cooled Condenser Readings

Water Cooled Condenser						
Load Cond.	Gauge Pressure		tini(°C)	tfin(°C)	tref(°C)	tevap(°C)
	Suction	Discharge				
Without load	90	15	-	-	38	-24
With load (amb.)	110	0	27	12	51	-16
With load (Hot)	115	3.81	46	21	65	-6

Table 9: Loading conditions used in Experiment

Air Cooled Setup			**Water Cooled Setup**		
Loading Condition		W.B.T.	**Loading Condition**		W.B.T.
Without load		-	Without load		-
2*4 Kg	With load	26°C (ambient)	2*4 Kg	With load	27°C (ambient)
	With load	44°C		With load	45°C

Table Declaration

Condition	**Value**
Fluid	Refrigerant: R-134a
Condenser tubes material	Water Copper
Condenser shell material	Mild steel
Model	k- omega SST
Solution method	Simple
Refrigerant	Pressure =210 psi, mass flow rate () = 0.008 Kg/s
Inlet Water Inlet	Pressure =14.69 psi, mass flow rate() =0.118 Kg/s
Refrigerant outlet Water Outlet Outlet	Mass flow rate() = 0.008 Kg/s Mass flow rate() = 0.118 Kg/s

1. ‘Clinical trial number: not applicable.’
2. ‘Ethics, Consent to Participate, and Consent to Publish declarations: not applicable.
3. Author Contribution:

i. Mr. Amol Bhalerao: conducted the experiments And collected the data, wrote the initial manuscript draft, prepared the figures, ta- bles, and data presentations, Designed the methods or models, respon- sible for software tools and simulation.

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10: Conditions And Their Values

ii. Dr. Nilesh Totala: contributed to the conceptualization of the study, including the development of the research framework and ob- jectives. ensuring the appropriate techniques and approaches were ap- plied.
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iii Dr.Pramod Kothmire: Developed the idea and research goals, responsible for software tools and simulations, verified the results, , managed and organized the data for analysis and sharing, revised, re- viewed, and edited the manuscript. performed the CFD analysis.
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iv Dr.Yogesh Bhalerao: Supervised the project and the research team, managed the overall progress and coordination of the project, provided materials, data, lab space and other resources.
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4. About Funding: Not Applicable

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