

An Experimental Study on Evaporative Condenser in Air Conditioning Systems Using R744

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ABSTRACT

Nowadays, the use of refrigerants has low GWP and zero ODP applying refrigeration and air conditioning systems is an important concern. There has been a lot of research taking about refrigeration systems using R744. In this study, we focus on the use of the mix of water and air for an evaporative condenser through an experiment to study the heat transfer efficiency between water and the R744. The results of this study show that it is feasible to use water to cool down R744 to a subcritical state. The data obtained show that the R744 temperature at the outlet condenser gradually decreases with each change in the number of tube layers, the condensing pressure is stable at 73 bar with a pressure drop of 0.4 bar. The water temperature is stable between 26°C and 28°C, and the air outlet temperature from the indoor unit gradually decreases from 28°C to 16.8°C. With the 3 configurations of the condenser, the coefficient of performance gradually increases from 3.6 to 4.5 respectively.

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1. Introduction

Nowadays, issues of environmental protection are becoming a great concern to countries. Scientists in the industrial refrigeration as well as air conditioning industries are constantly striving to find environmentally friendly environments. For decades, R744 has been studied to replace polluting Freons. Experimental studies and numerical simulations on transcritical and subcritical CO₂ cycles test with a variety of configurations to improve energy efficiency.

Related to refrigeration systems using CO₂ operated under the transcritical condition. Liu et al. [1] proposed a system with the replacement of the expansion valve of a traditional CO₂ transcritical refrigeration system by single vortex tube to improve the COP. They simulate the models and compare them to the conventional system to get the system performance. The results focus on energy savings, the ability to improve the COP of the system, the outlet pressure and inlet temperature of the vortex tube are studied to improve the COP of the system. Bellos et al. [2] compared 3 case studies: subcooling with one-stage refrigeration cycle using R134a, absorption cycle using Libr-H₂O and cycle without subcooling in a CO₂ transcritical system. This model is tested under a variety of conditions by selecting the most appropriate pressure and temperature. In addition, they also validated the above experiment through EES software, they discovered that the system with subcooling will have better exergy performance than without subcooling, the difference between the one-stage subcooling cycle and the absorption cycle is negligible. Zhu et al. [3], [4] investigated a transcritical CO₂ ejector-expansion system, they discussed the effects of condensing pressure, hot-water outlet temperature at the end of condenser, rotation speed of compressor, overall performance. Besides, the variations of the COP ejector expansion cycle under changing heat rejection pressures, refrigerant temperatures at outlet of the gas cooler, and the nozzle efficiencies, the diffuser efficiencies were also studied. He et al. [5] proposed an ejector refrigeration system by using the optimal quasi-cascade controller for the transcritical CO₂ cycle. They tracked the optimal gas cooler pressure with a variable nozzle throat area by the controller in real-time to improve the system performance. Yang et al. [6] studied a thermoelectric subcooled CO₂ transcritical heat pump system. They simulated the steady-state model by using lumped parameter technology and validated by experiment to define the coefficient of performance by the variety of water

flow rate and water temperature, subcooling temperature, condensing pressure. Yari et al. [7] analyzed two new CO₂ cascade refrigeration cycles as follows: high stage an ejector-expansion transcritical cycle and low stage is a subcritical CO₂ cycle. The waste heat from high stage was used to a supercritical CO₂ power. They adjust the operating parameters at each cycle to optimize the overall performance of the entire system.

Related to the subcritical CO₂ cycles, there are many configurations to study heat transfer characteristics as well as fluid characteristics used for heat pumping and low-temperature refrigeration. Zhang et al. [8] presented a detailed analysis for finding the optimal conditions of the internal heat exchanger's effect in CO₂ inverse cycles. They focused on the increasing of COP under effect of the transition condensing pressure and the transition outlet temperature of gas cooler. Sánchez et al. [9] analyzed the experimental behaviors of a subcritical CO₂ refrigeration plant by using the prototype which was designed for supercritical cycle. By the series of the steady-states, the coefficient of performance was studied based on the replacement between the heat exchanger and a gas-cooler under subcritical and supercritical conditions. Rampazzo et al. [10] discussed the performance that operated in transcritical and subcritical cycle. The results showed the effects of high pressure on the performance in the variety of operating conditions. This study also built the heat pump system in the other configuration. Lei et al. [11] evaluated experimentally of the heat transfer characteristics with the parameters which consist of mass flux, heat flux, inlet temperature effects in the R744 supercritical cycle and the R744 subcritical cycle also. Sanz-Kock [12] experimentally evaluated a cascade refrigeration plant using R134a/CO₂ in commercially applications. The prototype used two single-stage cycles with lots of specials: a semi-hermetic compressor, an electronic throttle valve, 2 parallel with 2-types of the plate heat exchanger. The experimental case-studies were based on a range of evaporating temperature condensing temperature respectively. They focused on the energy performance, the temperature difference in the cascade heat exchanger, discharge head temperatures and COP also. This objective was also investigated by Llopis et al. [13]. This study experimented on an internal heat exchanger in a CO₂ subcritical refrigeration plant. The evaluation covers the range of the evaporating temperatures and condensing temperatures with the compressor that operated at a stable speed. In addition, Zhang et al. [14] proposed a cascade system with the couple of R1270 and R744. In this article, R1270 was used to replace the traditional refrigerant for the cascade cycle such as R290 and R717. They manufactured a prototype compound of two semi-hermetic piston compressors to get the energy performance. The condensing pressure and evaporating pressure were kept constant while the evaporating pressure at R1270 side decreases from 7°C to -19°C with the increasing COP of the system. Boccardi et al. [15] investigated a small capacity R744 cascade system. The air inlet temperatures of gas cooler, and the condensing pressure were changed to evaluate the thermodynamic parameters. It's also overfed to obtain the effects of the quantity refrigerant. Wu et al. [16] performed cooling tests for the prototype CO₂ standard for liquid-to-air heat pumps, as well as extended tests at additional entering liquid temperatures. Gautam et al. [17] analyzed the thermodynamic parameters of the different adsorption cooling cycles from subcritical to supercritical cycle with a range of evaporating temperature to consider the discharge temperature. [18], [19] presented an R744/R717 cascade refrigeration system. In these studies, the thermodynamic parameters were analyzed to optimize the design. They focused on evaluating subcooling degree, superheating degree, and cascade heat exchanger temperature difference to define the maximum COP, the optimum mass flow rate for both of 2-stages. Shao et al. [20] investigated a specific cycle that used supercritical based on the principle of subcritical cycle to define the temperature at maximum constant-pressure specific heat. In this study, they developed a model to find out the relation of the optimal high pressure between the transcritical and subcritical cycle.

Most of the studies mentioned above focus on exploiting transcritical and subcritical R744 cycles in thermodynamic properties such as compressor discharge temperature, condensation temperature, evaporation temperature, cascade temperature difference, COP, etc. The efficiency of the cycles is higher when using subcritical cascade cycles. However, studies of subcritical cycles by using the evaporative condenser are quite limited. In the climatic conditions of Vietnam, it is important applying this method to decrease the inlet R744 temperature of the expansion to increase the COP of the CO₂ air conditioning system.

2. Methodology

2.1. Calculation and Design

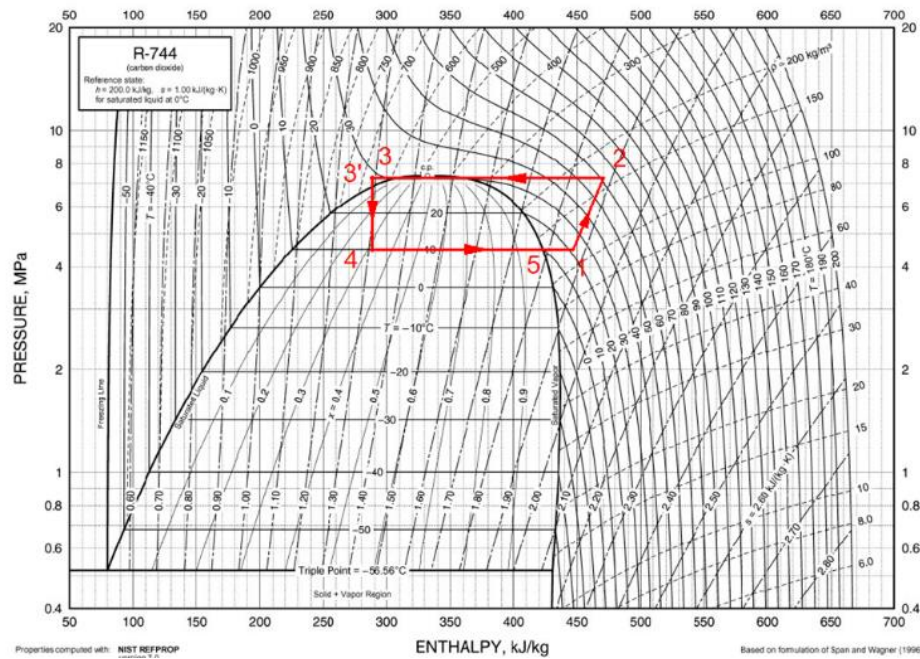


Figure 1. *p-h diagram for the testing cycle*

The experimental system was designed with a cooling capacity of 1000W, cooled by evaporative cooling method, operating in the Vietnam climatic conditions. Here are some typical calculation formulas:

The cooling capacity was calculated as:

$$Q_0 = G(h_5 - h_4) \quad (1)$$

The condensing capacity was quantified by:

$$Q_k = G(h_2 - h_3) \quad (2)$$

The energy consumption for compressor was determined by:

$$N = G(h_2 - h_1) \quad (3)$$

The Coefficient of performance of the system was expressed by:

$$COP = \frac{Q_0}{N} \quad (4)$$

The overall heat transfer rate was calculated as:

$$U = \frac{Q}{A \cdot \Delta t_{lm}} \quad (5)$$

Where:

- h is enthalpy (kJ/kg)
- N is adiabatic compressive power (kW)
- G is mass flow rate (kg/s)
- U is overall heat transfer coefficient (W.m⁻².K)
- Q is cooling/heating capacity (W)
- A is heat transfer area (m²)
- Δt_{lm} is logarithmic mean temperature difference (K)

Based on the above theory of refrigeration system, the design and calculation results of this study give the following state parameter as shown in Table 1 and Fig.1.

Table 1. The state points of the testing system

State point	t (°C)	p (bar)	h (kJ/kg)	s (kJ/kg.K)	v (m ³ /kg)
1	22	45	444	1.89	0.0086
2	64	73	474	1.85	-
3	30.5	73	309	1.28	0.0016
3'	28.5	73	289	1.28	-
4	10	45	289	1.32	-
5	10	45	422	1.78	0.007

The condenser with the design parameters is depicted in Fig. 2. The condenser has a capacity of 1.2 kW and a heat transfer area of 0.75 m². There are two tube banks arranged in parallel; each bank has four tube layers (or four passes). Each layer has 25 tubes with a diameter of 4 mm.

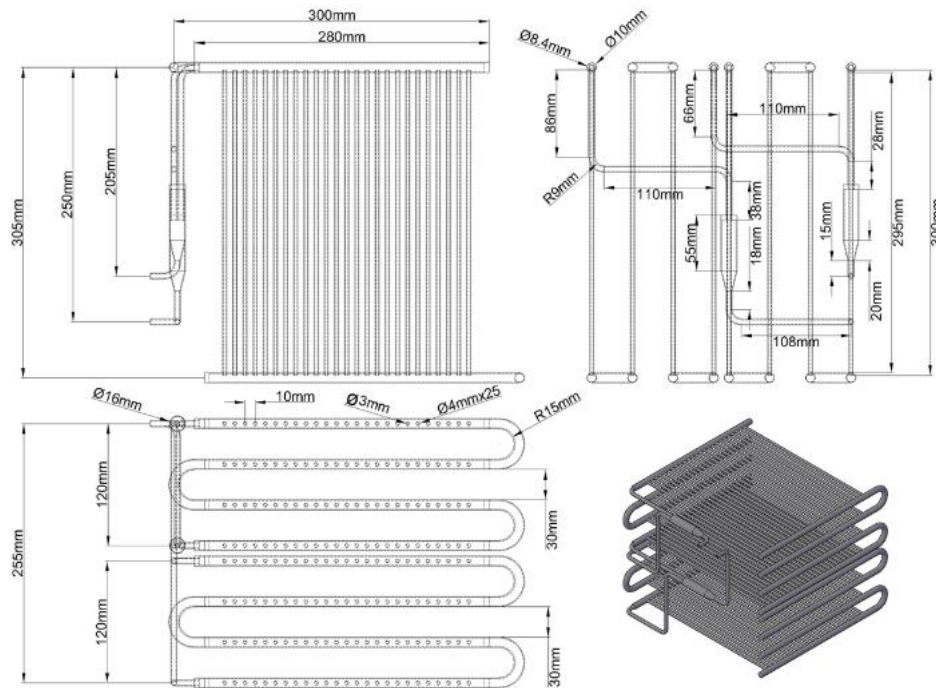
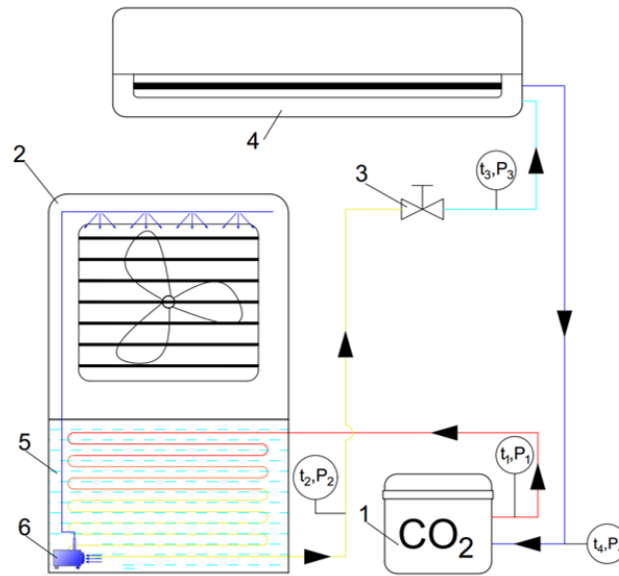


Figure 2. The design parameters of condenser

2.2. Experimental setup

The experimental system is shown in Fig. 3. Essentially, it is comprised of key equipment like the conventional refrigeration cycle. However, the research focuses on analyzing the heat exchange efficiency of condensers operating in subcritical R744 cycles. Pressure and temperature sensors were placed at the state points to collect data, combined with peripheral measuring devices to evaluate the overall performance of the system.

Fig. 4 shows the installation location of layers of copper tubes at the condenser. The rows of condensing tubes are submerged in the cooling water tank, the water is circulated by two circulation pumps, the water after releasing heat into the environment from the cooling PVC meshing film is dropped back into the cooling water tank. The amount of water will be replenished by the mechanical float when the water level is lower than the setting of the cooling device.



Description	
1	Compressor
2	Evaporative condenser
3	Hand expansion valve
4	Evaporator
5	Cooling water
6	Cooling water pump

Figure 3. Principle diagram of the testing system



Figure 4. Condenser pipe installation location

2.3. Experimental data collection

Parameters such as temperature, pressure, velocity, and current at state points are collected continuously every 10 minutes. The experimental data are collected throughout even when the temperature and humidity of the environment change during the day. The characteristic measuring devices and typical parameters are shown in Table 2.

Table 2. Accuracies and ranges of testing apparatuses

Testing apparatus	Accuracy	Range	Manufacturer
Thermometer	±0.1°C	-270 - 4000C	Extech
Clamp meter	±2% FS	0 - 600A	Hioki
Humidity meter	±3% FS	1.0 - 99.9%	Tenmars
Pressure sensor	0.05 % FS	0 - 100 bars	Sensys
Turbine mass flow rate sensor	0.5% FS	400 to 5000 kg/h	DGT

3. Results and Discussion

3.1. Experimental temperature parameters at evaporative condenser analysis

Experimental temperature parameters at evaporative condenser are shown in Fig. 5. R744 rejects heat to the cooling water and decreases the temperature and enters condensation. In this prototype, R744 discharge temperature increases gradually from the starting time to steady state; from this time, the temperature is between 61.5°C and 63.3°C. In addition, the outlet temperature of R744 at the condenser does not exceed 30°C, which shows the effective cooling ability of the evaporative cooling method. From the R744 temperature after condensing, it is easy to see that the state of R744 has completely liquefied, meeting the operating requirements under the critical point.

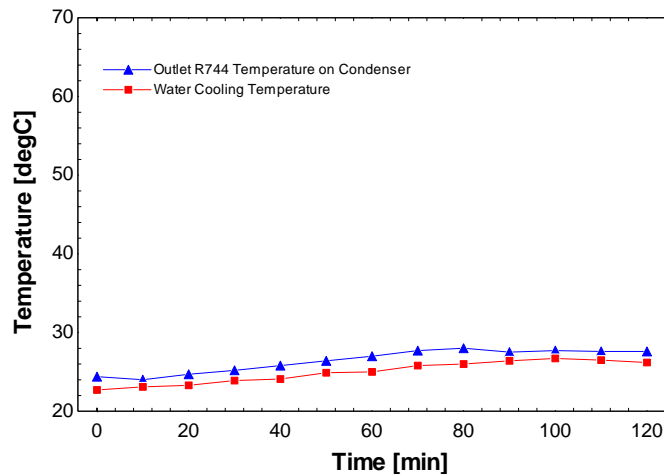


Figure 5. Experimental temperature parameters at evaporative condenser

3.2. The COP data of the testing system analysis

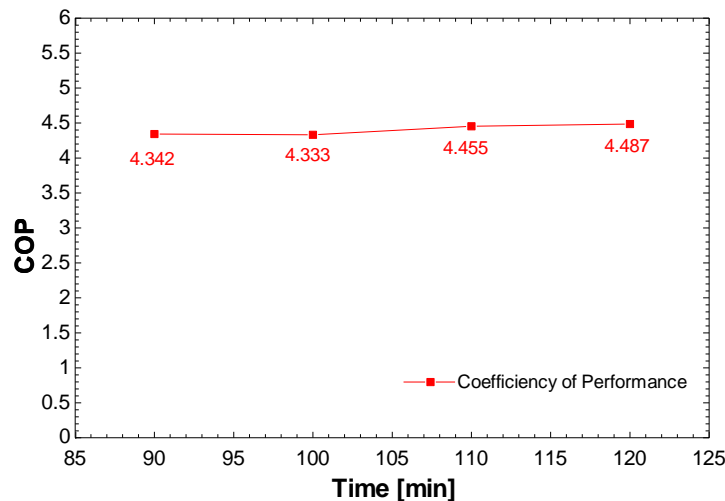


Figure 6. The COP data of the testing system versus time

Fig. 6 shows the COP data according to time running experiments for under conditions of constant evaporation temperature $t_0 = 10^\circ\text{C}$. When adjusting the throttle regime correctly, the system operates stably, the room temperature gradually decreases, the fluctuations in condensing and evaporating pressure are less frequent from 90th to 120th minutes. The COP is maintained stable from the 90th to the 120th minutes between 4.34 and 4.48. At the first stage of operation, under operating conditions at a low mass flow rate, the evaporation and condensation pressures have not reached the calculated state points. However, when operating stably at the state points such as theoretical calculations, COP reaches a high value and is stable at approximately 4.4.

3.3. The results of thermodynamic parameters of the system with three different configurations

In the same of heat transfer area, adjusting the number of layers of copper tube and tubes on each layer, three different configurations including 3, 5, and 8 layers are put to the test under the same operating condition to determine the thermodynamic parameters of the system.

Thermodynamic parameters of the system with three different configurations are shown in Table 3. At the same temperature difference between outlet temperature of condenser and water-cooling temperature of 1.4°C , the outlet temperature at the condenser decreases gradually with each change in the number of copper tube layers, the condensing pressure is stable at 73 bar, and the pressure drop is 0.5 bar. The water temperature is stable in the range of 26°C - 28°C , and the outlet air temperature in the indoor unit gradually decreases from 22°C to 16.8°C . In this study, the COP gradually increases from 3.6 to 4.48; the configuration of the number of layers of copper tube strongly affects the condensation under the critical point: the more layers of the copper tube are fabricated, the more heat exchange efficiency.

Table 3. Thermodynamic parameters of the system with 3 different configurations.

Parameters		3 layers of copper tube	5 layers of copper tube	8 layers of copper tube
Condensing pressure (bar)	Inlet of condenser	76.7	73.7	73
	Outlet of condenser	76.7	72.7	72.6
Temperature of R744 ($^\circ\text{C}$)	Inlet of condenser	65.2	63.4	63.3
	Outlet of condenser	30.3	29.7	27.5
Temperature difference between Outlet temperature of condenser and water-cooling temperature ($^\circ\text{C}$)		0.72	1.4	1.4
Thermodynamic parameters	Qo (kW)	0.72	0.86	0.886
	Qk (kW)	0.84	0.96	0.989
	L (kW)	0.2	0.21	0.197
	COP	3.6	4.09	4.48

4. Conclusions

The R744 air conditioning system with an evaporative cooling device operating in Vietnam's climatic conditions can operate under the critical point, giving very positive results as follows:

- The throttle regime plays an important role in increasing the efficiency of the refrigeration cycle.
- The average system's COP of 4.4 in conditions: the condensing pressure is stable at 73 bar with an average pressure drop of 0.4 bar in 8 layers of copper tube configuration. The cooling water temperature is stable between 26°C and 28°C , and the air outlet temperature from the indoor unit gradually decreases from 28°C to 16.8°C .
- The configuration of the number of layers of copper tubes affects the pressure drop of condenser and COP of the system. The more copper pipes in each layer and more layers, the more heat transfer efficiency.

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