# IMPROVEMENT OF PROTOTYPE OF $CO_2$ COMBINED AIR CONDITIONING AND TAP WATER HEATING PLANT

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## ABSTRACT

Research and development of a combined carbon dioxide ($CO_2$) air conditioning and tap water heating plant has been performed at Thermodynamics Laboratory, Institute Technology of Bandung. This paper discuss modification of the plant with the objective was to increase the plant cooling COP and to make the plant more compact. New heat exchangers which higher effectiveness were redesigned to increase cooling COP and to reduce overall plant dimension. The experimental results show that the new heat exchangers have improved the cooling COP of the plant. The maximum discharge pressure during experiments was 85 bar and the suction pressure was 34 bar at chilled water mass flow of 0.23 kg/s. On 85 bar discharge pressure, the cooling COP based on the evaporator load and the electrical consumption of the compressor was 2.52, compared to cooling COP 2.20 before modification. On water heating side, 210 litres tap water temperature of 60°C was reached within two hours.

## 1. INTRODUCTION

Global Warming and Ozone depleting issues force refrigeration engineers to develop alternative refrigerants for replacing CFCs and HCFCs. Since Montreal (1987) and Kyoto (1997) Protocols were signed, CFCs and, in a little longer time perspective, the HCFCs are being banned. CFCs and HCFCs must be reduced and totally banned in the end of 2030. Natural fluids such as hydrocarbon, ammonia, and carbon dioxide ($CO_2$) have been the interesting consideration for replacing CFC and HCFC refrigerants. $CO_2$ as refrigerant have advantages such as non toxic, non flammable, good thermal efficiency, and excellent availability. Considering the characteristics of $CO_2$, a combined air conditioning and tap water heating plant using transcritical $CO_2$ cycle is a promising system that should be develop continuously in tropical countries (Adriansyah, 2003).

A prototype of the combined system has been developed at Thermodynamics Laboratory, ITB, Bandung. The plant cooling COP was 2,2 and hot tap water temperature produced by the plant was 60°C (Adriansyah, 2003). All heat exchangers are of double pipe type and the plant dimension was not suitable for commercial use.

Following promising results of the plant, the research was continued with the objective was to increase cooling COP and to reduce overall plant dimension. The strategy was to change all heat exchangers with more compact ones.

## 2. PRINCIPLE DESIGN OF THE COMBINED SYSTEM

Transcritical $CO_2$ refrigeration cycle has been developed since 1988 when Professor Gustav Lorentzen (1915-1995) was proposed first draft of patent application on transcritical $CO_2$ system. Figure 1 shows schematic and process flow diagrams of transcritical $CO_2$ system.

For tropical countries, cooling of buildings sometimes are accompanied by the need of hot tap water for domestic usage. A combined air conditioning and tap water heating plant using $CO_2$ is the best system for such situation. The first prototype of a combined $CO_2$ system has been developed at Thermodynamics Laboratory, ITB, Bandung. The application areas of the combined $CO_2$ system include hotels, hospital, or other buildings that need air conditioning and hot tap water at the same time.

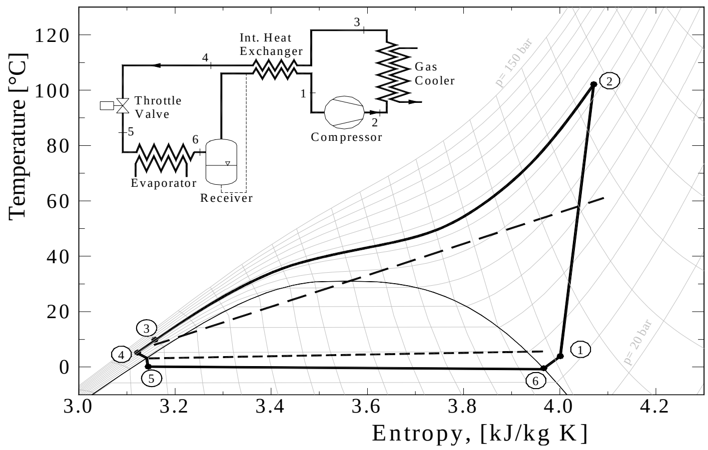



Fig. 1 $CO_2$ transcritical system with internal heat exchanger(Neksa, 2003)

Figure 2 shows schematic diagram of combined $CO_2$ system. This combined air conditioning and tap water heating system give high total efficiency due to heat recovery of the rejected heat through the gas cooler for producing hot water. Hot water temperature up to 70°C can be achieved without any difficulties. This temperature level can not be achieved without sacrificing efficiency when such combined system is applied using CFC or HCFC refrigerants.

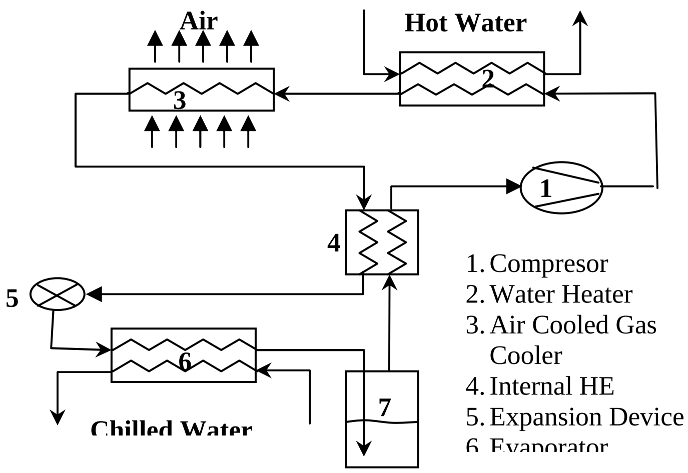



Figure 2 . $CO_2$ transcritical system for air conditioning and tap water heating.

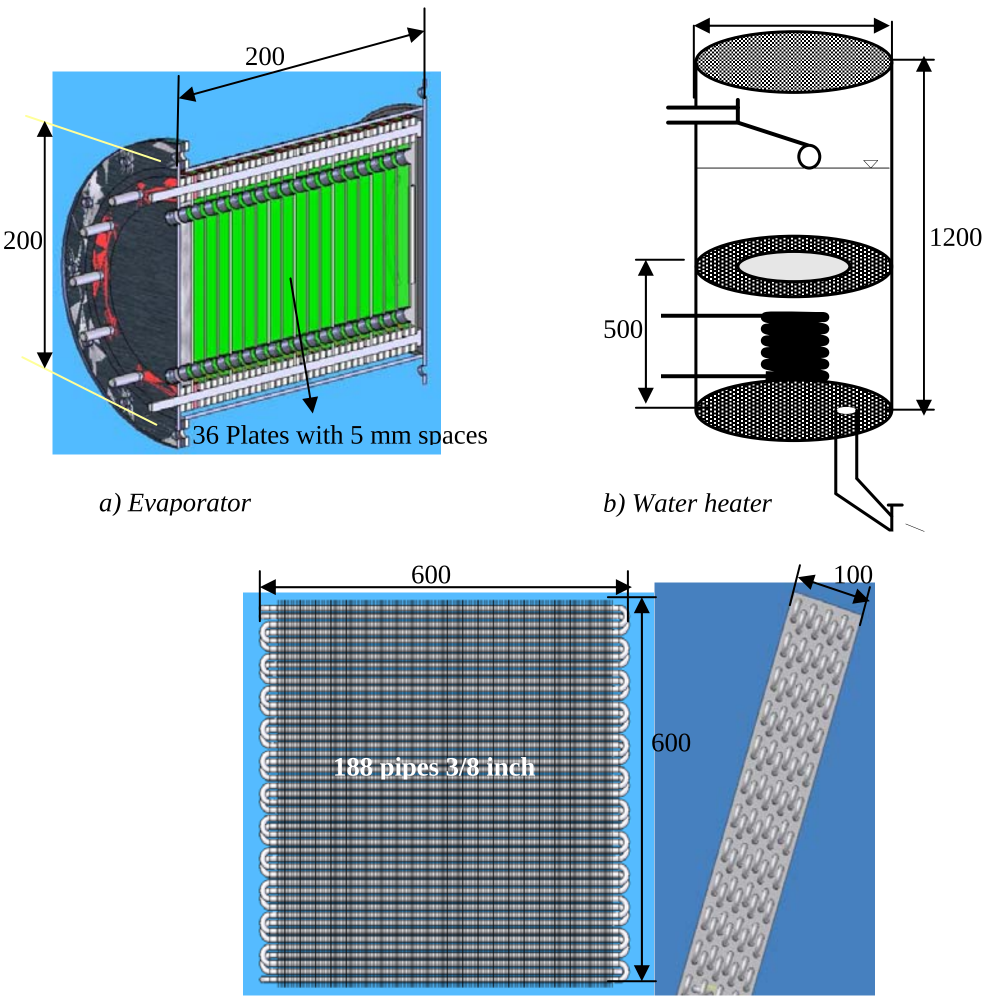
# 3. MODIFICATION OF THE COMBINED $CO_2$ PLANT

The first prototype was built successfully. All heat exchangers were of double pipe type. The experimental results showed that the optimum discharge pressure were 85 bar (Adriansyah, 2003). Cooling COP at the optimum discharge pressure was 2.2. The condition at the optimum discharge pressure is shown in Table 1.

Table 1. Optimum condition for $CO_2$ combined system (Adriansyah, 2003)

| Variable | Value | Variable | Value |
|---|---|---|---|
| Compressor Power | 2.95 kW | Isentropic Comp. efficiency | 0.7 |
| Chilled Water Flow Rate | 0.23 kg/s | Hot Water Flow Rate | 0.06 kg/s |
| Chilled water temperature different | 6.7 °C | Hot water temperature different | 35ºC |
| Evaporator Pressure | 34 bar | Water Heater Capacity | 7.3 kW |
| Evaporator Capacity | 6.5 kW | Discharge Pressure | 85 bar |
| COP base on real compressor work | 2.2 | Heat rejected through Gas Cooler | 2.2 kW |

Due to somewhat lower cooling COP of the first prototype, the development of the plant was continued with the objective were to increase cooling COP and to reduce the size of the prototype. Based on 3 kW compressor capacity, the heat exchangers were redesigned. The concept and dimension of the heat exchangers are shown in Figure 3.




*a) Evaporator* *b) Water heater*

*c) Gas cooler*

Figure 3. Component design of the heat exchangers (all dimensions in mm).

The evaporator is of shell-and-plate type. Chilled water flows inside the plate and $CO_2$ flows through the shell. The design capacity of the evaporator was 9 kW with 9.5 K temperature difference of the chilled water at 0.23 kg/s water flow rate.

Water heater together with air-cooled gas cooler could reject heat of 12 kW. The heat exchanger in the hot water tank is a helical pipe. Design temperature difference between inlet water and outlet water was 35 K at water flow rate of 0.063 kg/s.

The air-cooled gas cooler was designed with 5 K approach temperature (temperature difference between CO2 out of  the gas cooler and inlet air to the gas cooler).

Figure 4 shows the new heat exchangers installed in the prototype. All components of the prototype can be placed in one box. The dimension of the box without water heater is similar to the dimension of an outdoor unit of a HCFC-22 split type air conditioning.

a) Shell-and-plate evaporator b) Air-cooled Gas cooler

c) Water heater

Figure 4. The new heat exchangers of the combined $CO_2$ plant

# 4. EXPERIMENTAL RESULTS

The schematic diagram of the test rig and measurement points are shown in Figure 5. A data acquisition system was used for recording measured data. During experiments, discharge pressure of the compressor were varied from 75 bar to 85 bar, and the other parameters were set the same as at optimum conditions for the first prototype. The experimental results for 75 bar to 85 bar discharge pressure are shown in Table 2. The reason why the experiments were run only up to 85 bar discharge pressure is due to limitation of the hydraulic test device.

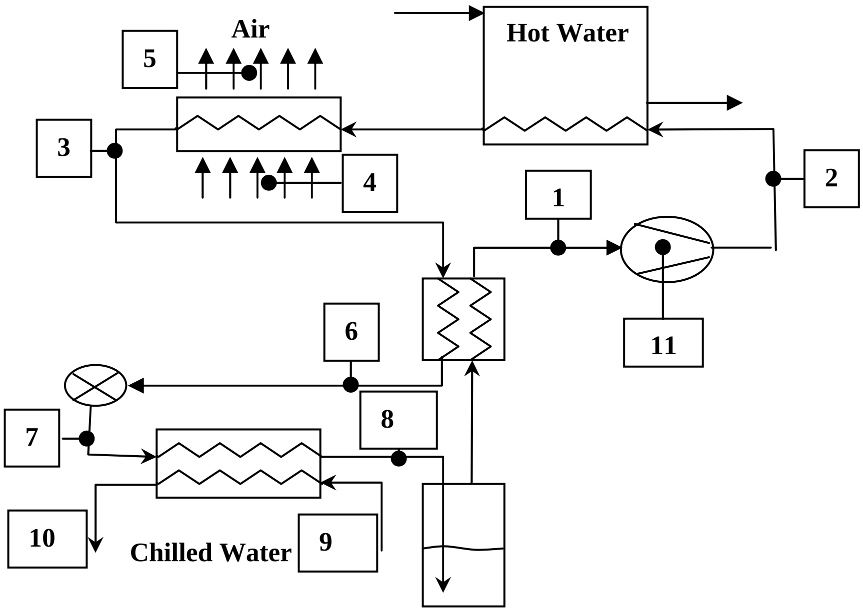



Figure 5. Schematic diagram and measurement points in the prototype.

Table 2. Some data from the experimental results

| Measurement Point | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | 2 | | 3 | 4 | 5 | 6 | 7 | 8 | 9 | | 10 | 11 |
| p | T | P | T | T | T | T | T | T | T | T | $m_{cw}$ | T | $W_{comp}$ |
| 34 | 22.5 | 75 | 93.4 | 33.2 | 28.4 | 34.5 | 32.1 | -0.3 | 1.8 | 27.3 | 0.23 | 20.6 | 2.90 |
| 34 | 19.1 | 80 | 91.9 | 32.4 | 28.7 | 34.3 | 31.6 | -1.4 | 1.9 | 27.4 | 0.23 | 20.2 | 2.97 |
| 34 | 14.0 | 85 | 90.2 | 32.3 | 29.1 | 34.4 | 30.7 | -2.9 | 2.4 | 27.8 | 0.23 | 19.8 | 3.06 |

Note: p (pressure, bar), T (temperature, °C), $m_{cw}$ (chilled water flow rates, kg/s), $w_{comp}$ (compressor power, kW).

# 5. DISCUSSIONS

Based on the experimental results, the system performance can be analysis as shown in Table 3. The cooling COP - which is defined as ratio of the evaporator load and electrical consumption of the compressor - is depicted in Figure 6.

Table 3. Performance of the new $CO_2$ combined plant.

| Pressure (bar) | Chilled Water Flow Rates (kg/s) | Refrigerant Flow Rates (kg/s*) | Evaporator Load (kW) | Compressor Power (kW) | Cooling COP |
|---|---|---|---|---|---|
| 75 | 0.23 | 0.045 | 6.51 | 2.90 | 2.24 |
| 80 | 0.23 | 0.046 | 6.95 | 2.96 | 2.35 |
| 85 | 0.23 | 0.045 | 7.72 | 3.06 | 2.52 |

*) *calculated refrigerant flow rate*

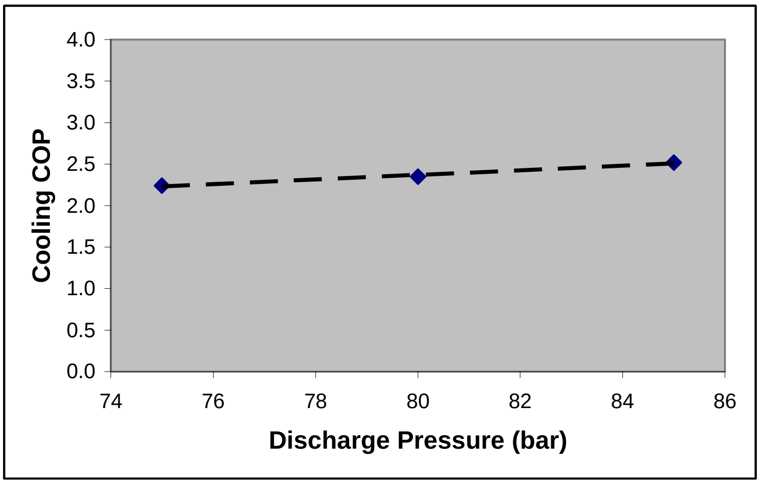



Figure 6. Influence of discharge pressure on cooling COP

Cooling COP increase from 2.24 to 2.52 for 75 bar to 85 bar discharge pressure. The cooling COP of the first prototype at 85 bar discharge pressure was only 2.2. This improvement is due to higher effectiveness of the evaporator. The evaporator of the first prototype was only able to produce 6.7 K temperature difference of chilled water while the new evaporator was 9 K. The shell-and-plate type evaporator give better heat transfer rate that could be caused by more turbulence flow in the water side. On shell side, evaporation of $CO_2$ probably enhance due to more space available where bubble can move upward easily. The shell-and-plate evaporator capacity was 18.7% higher than the previous evaporator, and the cooling COP increase by 14.5%.

Approach temperature of the air-cooled gas cooler was around 5 K as expected. This approach temperature could be reduce if contact resistance between the tubes and the fins could be reduce. It should be noted that the air-cooled gas cooler is made by hand so that better contact of the tubes and the fins can not be achieved.

The water heater can produce hot water of 210 litres at 60°C within two hours, and 98 litres at 60°C within an hour. Formerly, the water heater is designed to produce hot water in a short time by placing a moving partition. The partition splits hot water in the lower side and cold water in the upper side and will move upward as hot water volume increase. The movement of the partition was not observed during the experiment and this will be a focus for the next research.

## 6. CONCLUSIONS

Research and development of the combined air conditioning and tap water heating plant using transcritical $CO_2$ cycle has been performed for increasing its cooling COP. To reach that objective, the heat exchangers have been redesign and installed in the plant. The experimental results show that the cooling COP of the new plant is better than the previous plant. The new evaporator has 18.7% higher capacity and the cooling COP increase by 14.5%. Hot water temperature of 60°C with total volume of 210 litres can be produced within two hours.

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