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Chiller Performance Study with Refrigerant R290

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Abstract. The purpose of this paper is to examine energy efficiency through the study of performance in vapour compression cycle for auditorium in University of Indonesia using natural refrigerant R290. The installation of the chiller system which is the first in Indonesia within academic institution is particularly relevant in light of the gaining interest and research regarding the implementation of refrigeration system utilizing relatively low ODP and GWP refrigerant as alternative to replace the refrigerant HCFC-22. It is found that the highest COP during 64% partial cooling load is 4.27 at temperature water inlet is 8.9ºC. The maximum COP during 75% partial load is 5.25 at temperature water inlet is 6,8 ºC. The cooling capacity are 125.93 kW and 148.39 kW during 64% and 75% load, respectively.

INTRODUCTION

According to the Green Policy Paper released by the Finance Ministry Republic of Indonesia, total energy demand is growing around seven percent per year. One of the largest sectors that consume a large number of energy in Indonesia is cooling [2]. Cooling demands in a building could rack up a percentage of 30% of the total energy needs [1]. In the discipline of air conditioning, after Montreal Protocol 1987, the use of different types of HCFC-based refrigerants has been decided to phase out by 2030 in all developed countries and by 2040 in developing countries [3,4]. University of Indonesia as the oldest tertiary-level educational level in Indonesia has been encouraging all of its civitas academics to contribute and participate through Green Campus Movement. As part of its strategy to comply regarding this movement, University of Indonesia initiated The UI Green Metric World University Ranking on sustainability issues based on their self-assessed input for the criteria set and extensive independent research and survey responses conducted for the UI Green Metric World University Ranking. One of the UI efforts is by initiating the use of environmental friendly air conditioning system for its building.

Amongst HCs, propane is gaining interest for chillers and heat pumps, due to its benign environmental properties and because its behaviour is considered to be almost neutral with respect to baseline refrigerant R22. Several recent researches have been reported on the HCFC refrigerant properties in AC system [5-7]. Chang et al. [5] experimented slightly improved COP and decreased capacity when R22 was substituted by R290. Heat transfer coefficients of hydrocarbons are much greater than that of R22 at the same mass flux condition due to low liquid viscosity, high liquid thermal conductivity, and high density ratio. It can be concluded that propane's heat transfer performance is comparable to R22 [5].

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SYSTEM DESIGN AND DESCRIPTION

The air-cooled reciprocating chiller is installed at the Auditorium Art Center in University of Indonesia for the purpose of air conditioning the indoor of the Auditorium which is built for art performance and educational activities. The building, particularly the auditorium, is functionally designed to cope with the incoming and outgoing of audience whenever there is on event being held. Outside the hours, the auditorium is closed to the public. The auditorium is able to house 400 people.

The cooling system utilizing natural refrigerant within academic institution is the first in Indonesia. The system is designed with a typical one-stage refrigeration cycle. The main components of the system under consideration include two compressors, two expansion valves, two condensers, one shell-and-tube evaporator, and two plate heat exchanger sub-coolers. The components are connected in a closed loop with refrigerant HC290 flowing through the copper piping system. The usage of dual circuit for the refrigerant system is to support the cooling effect that is desired to achieve and the additional of dedicated sub-cooler heat exchangers is to accommodate the cooling down of refrigerant below saturated liquid at a constant pressure before entering expansion device.

Refrigerant HCFC22 (R22), the most estimated currently, despite its low ODP, has a 1,810 GWP which is considered high. The limit on the use of R22 is 2030 for developed countries, and 2040 for developing countries. Therefore, R22 needs to be replaced with other environmentally friendly refrigerants [4,10,11].

Many studies have been dedicated to alternative refrigerant HC290 (R290) and several other refrigerant mixtures [4, 12, 13, 15]. R290 has zero ODP with very low GWP, which is 3.3. The disadvantage of this refrigerant, especially in refrigerants with HC base is the level of flammability [15]. Based on ISO 5149 Standards [16], R290 is assigned to A3 classification, with explosion range for R290 at 2.1% volume up to 9.5% volume.

TABLE 1. Specification of system chiller

Cooling Capacity	56 TR 197.6 kW
Total Power Consumption	55.9 kW (dual compressors)
Refrigerant	Propane HC290 (R-290)
Charging	2 x 16.6 kg
Total Rated Ampere	101 A
Refrigerant Charge	2 x 14 kg
Nominal Fluid Flow	33.8 m^3/h
Pressure Drop @ Nominal Flow	30.0 kPa
Refrigerant Flow Control	Thermostatic Expansion Valve with External Equalizer
Quantity (Circuit)	1 (2)
Complementary Measurement Tools	Refrigerant Side & Water Side Measurement, Pressure Transducer, Temperature Transducer, Refrigerant Flow Meter, Water Flow Meter, Water Temperature Inlet & Outlet Chiller, kWh Energy Monitoring.

TABLE 2. Comparison of refrigerants [18]

No.	Refrigeran	Boiling Point (°C)	Critical Pressure (Mpa)	Critical Temperature (K)	ODP	GWP (in 100 years)
1	R22	-40.81	4.99	369.3	0.055	1760
2	R290	-42.11	4.2512	369.89	0	3

Many studies indicate that propane systems have a heating capacity, when used as a heat pump, which is about 8% lower than R-22, while the COP is 5-7% higher. It was also shown that the refrigeration charge of a propane system is reduced by about 50%, when compared with R-22, for the same geometry. This is due to its smaller molar mass. When R-22 is to be substituted by propane, the costs of the necessary changes (expansion valve, lubricant) are negligible when compared with the costs of the substitution by hydrofluorocarbon [18].

EXPERIMENTAL SETUP

The chiller system was operated in partial load. The capacity of the auditorium itself is 400 seat and was occupied by around 120 people during an art performance. The data was acquired and recorded in real-time using LABVIEW which are consisting of temperature and pressure at refrigerant and water side, refrigerant and water flow rate, water temperature inlet & outlet chiller, and energy consumption monitoring system (kWh). However, in this study, the variables that were taken into account are the ones that contributed directly for calculating the performance of the chiller.

Specific heat capacity of water $C_{p_{water}}$ is calculated from the average value between water temperature at the inlet and outlet side [17]. The obtained value will be taken into account utilizing linear interpolation in accordance to the thermodynamic properties of water at 2 bar of pressure. The equation is given by:

$$f_n(x) = \sum_{n=0}^{n} L_i(x) f(x_i) \quad (1)$$

Since we want the value of specific heat capacity of water at T water, we need to choose the data points that are closest to it hence,

$$C_p(T) = \sum_{i=0}^{1} L_i(T)\, C_p(T_i) \quad (2)$$

$$C_p(T) = \frac{T - T_1}{T_0 - T_1} C_p(T_0) + \frac{T - T_0}{T_1 - T_0} C_p(T_1) \quad (3)$$

The obtained value of specific heat capacity of water can be used to calculate the capacity

$$\dot{Q}_{chiller} = (\dot{m}_{water}) \left(C_{p_{water}}\right) (T_{water\ in} - T_{water\ out}) \quad (4)$$

Energy consumption is acquired and recorded in real-time utilizing LABVIEW that is the consumption of the whole plant.

$$COP = \frac{\dot{Q}_{chiller}}{W_{plant}} \quad (5)$$

Table 3 shows error calculations using standard deviations from chiller data samples without loading when the maximum chiller under test conditions. The standard deviation value on energy consumption for both compressors in which the average performance does not vary. This can be seen from the pressure of suction and discharge are almost uniform. While the value of the deviation at high cooling load in addition to the set temperature, this is because the movement of the Sun when the operation of the chiller from the day and affects the temperature of the water flow in and out. The large variance at the value of the cooling capacity is not something undesirable because the chiller is trying to keep cooling from the auditorium.

TABLE 3. Standard deviation of chiller during freeload testing condition.

	***Power Consumption* (kW)**	**T water in (°C)**	**T water out (°C)**	**$\dot{m}$ water (kg/s)**
$\bar{x}$	54.36	14.42	9.52	9.4
σ	0.3	1.93	2.12	0.14
	Cooling Capacity (kW)	COP	$P_{discharge}$ (bar)	$P_{suction}$ (bar)
$\bar{x}$	193.42	3.56	14.5	3.6
σ	20.63	0.38	0.045	0.043

RESULTS AND DISCUSSION

Figure 1 shows a significant increase in the beginning to produce a cooling effect resulting in a large compressor performance. At 24,5ºC and 14,1ºC the estimated cooling effect was reached and the performance of the chiller and heat transfer system was not significant.

The highest cooling effect was obtained when the temperature water inlet at an average of 14.1ºC as shown in Figure 1. This is influenced by ambient temperature. When temperature water inlet was at an average of 24,5ºC the highest cooling capacity is obtained.

The condition of free load of this test required 28.25 - 34.62 kW of power for two compressors in a refrigerant circuit with a cooling capacity of 113.68 - 135.33 kW.

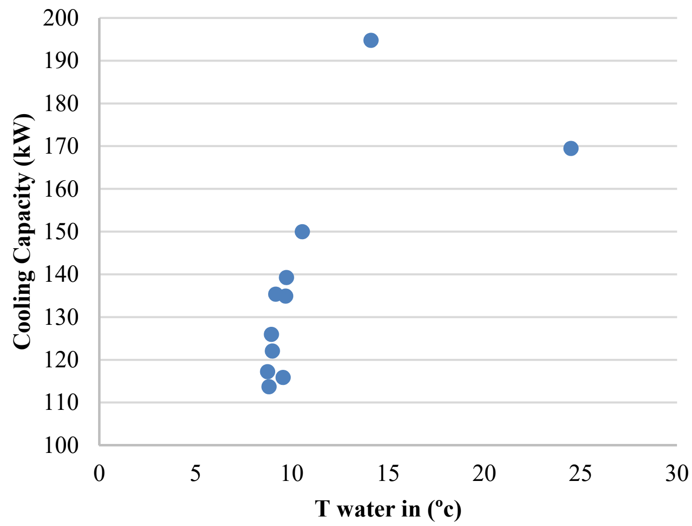

FIGURE 1. Cooling capacity as the function of Temperature water inlet.

The comparison of cooling capacity to energy consumption is shown in Figure 2. When first turned on, the temperature of the chiller water flow high entry produced great heat transfer giving rise to a surge in the performance of the compressor. But after the cooling effect, and the ambient temperature for the daytime temperature, the temperature difference of inlet and outlet decreases so that the heat transferred and the compressor work down.

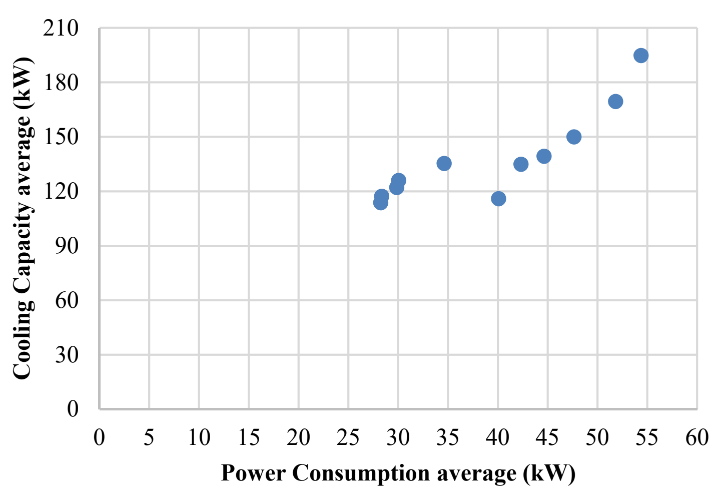

FIGURE 2. Comparison between cooling capacity and power consumption.

Figure 4 shows the value of COP that increases power consumption. High compressor power when the chiller was first turned on and higher ambient temperature conditions due to daylight results in low COP values. After the cooling effect was obtained, the compressor decrease power because the energy of heat transfer had been reached where the value of capacity was declining due to the reduced value of the temperature difference between the water flow. This resulted in an increase COP.

The highest COP values were obtained when the water temperature conditions at 8.9ºC. And the COP averaged maximum of 4.27 (Figure 4) was with cooling capacity 125.93 kW and compressor performance of 30.06 kW. If at this time the cooling effect is obtained from the first operation of the chiller, then the start-up time of the chiller system look approximately one hour.

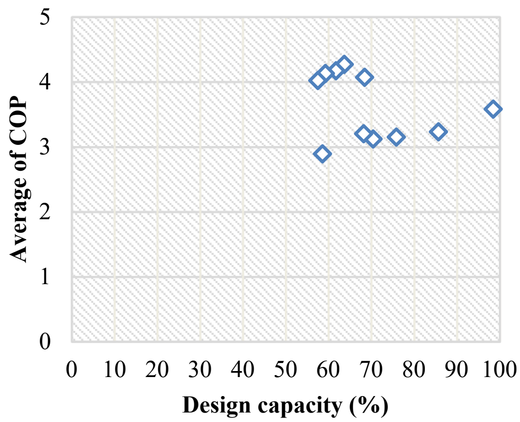

FIGURE 3. The mapping of chiller performance during 64% load.

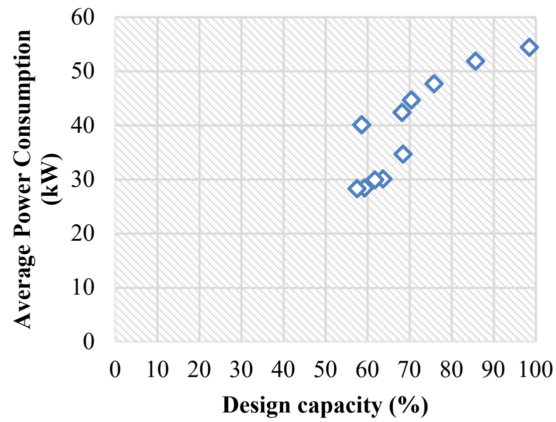

FIGURE 4. Comparison between chiller power consumption and design capacity.

The optimum system was obtained at 64% cooling load and the inlet water flow temperature of 8.9 ºC as shown in Figure 3. At this point, the power consumption for the compressor is lower than the loading above 80% of the initial design. At the time of loading near 100% obtained the largest cooling effect but with the performance of the compressor close to the maximum will affect the life-time compressor components. Therefore, the best operation for the compressor at loading is about 64% of the design. It can be concluded that the chiller specification can satisfy partial loading test conditions with a comparable COP value ratio.

TABLE 4. Comparison of design capacity and power consumption of the chiller.

	Freeload (kW)
Q design	197.6
Q calculated average	137.57
Energy consumption design	55.9
Energy consumption in actual	39.13

The compressor works according to the demand for cooling effect as shown in Figure 5. Chiller power consumption increases as the cooling capacity increases but when the enthalpy brought by circulated water is satisfied at a certain pressure, the compressor component may decrease so that the inlet water flow value decreases as the pressure and the temperature on the compressor suction decreases.

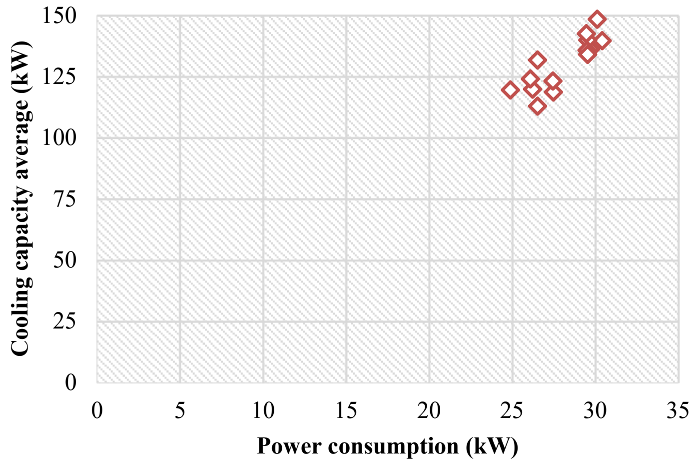

FIGURE 5. Comparison between cooling effect and power consumption.

The optimum cooling effect occurs at an inlet temperature of 7.8ºC as in Figure 6. The data processing distribution for the cooling capacity is more uniform so that the optimum COP averages are more consistent in the range of the inlet temperature.

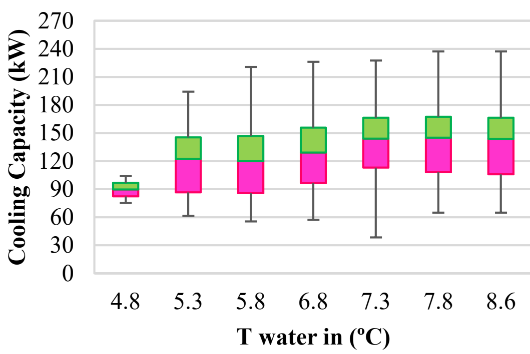

FIGURE 6. Water temperature at inlet side as the function of cooling effect.

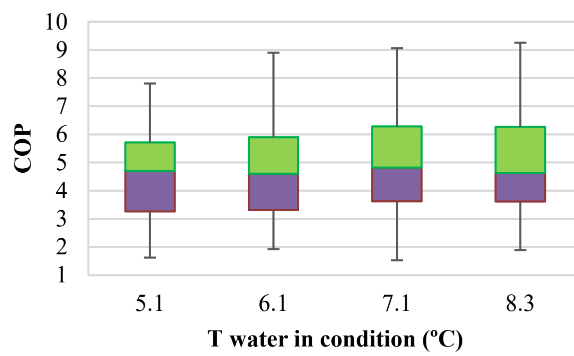

FIGURE 7. Water temperature at inlet side as the function of COP.

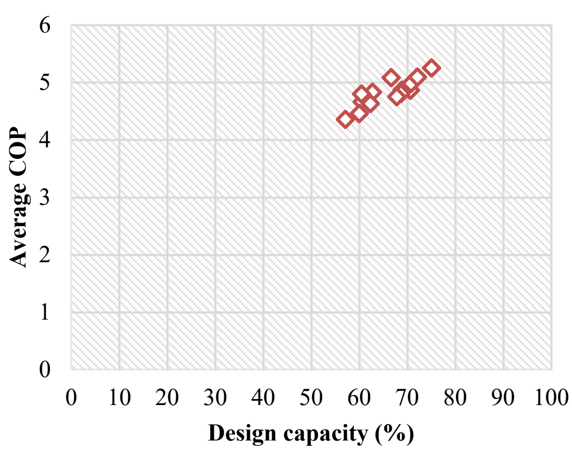

FIGURE 8. The mapping of chiller performance during partial load.

Figure 7 shows the highest COP when the inlet temperature is in the range of 7.1ºC but the average tends to be below 5. This is still the same as the initial design of the chiller system. The partial load COP value is greater than the chiller system design due to the operating time at night when the ambient temperature is low so that the flow temperature difference is not high which makes the compressor performance decreases.

The optimum chiller in the range of 75% loading on the evaporator of the system design during partial loading as shown in Figure 8. In this condition, the compressor power consumption is in the range of 30 kW to maintain the cooling effect inside the auditorium during the event. From the test conditions, the partial loading COP value is still in accordance with the chiller specification design.

CONCLUSIONS

From the performance investigation, the following conclusions can be drawn, the maximum cooling effect at freeload condition is reached at 135.33 kW with energy consumption of 34.62 kW when the water temperature at inlet side is within 15.1ºC. At partial load during testing condition the obtained cooling capacity is 148.39 kW with power consumption for compressor work is 30.12 kW when the water temperature at inlet side is within 7.8ºC. The highest COP value during freeload is obtained when the water temperature at inlet side is within 8.9ºC. The maximum value of COP is 4.27 with cooling effect generated around 125.93 kW and compressor work of 30.06 kW. The optimum system at 64% cooling load from the chiller specification design. The maximum value of COP during partial load is reached at the value of 5.25 with cooling capacity obtained is 148.39 kW and the compressor work of 30.12 kW when the water temperature at inlet side is within 7.8ºC and the optimum chiller in the range of 75% loading. Comparison of reading values on the thermocouple sensor corresponds to data retrieval under test conditions. But sometimes inconsistencies occur in some sensor components or disconnected during testing so that temperature data cannot be used. The design specifications of the air-cooled reciprocating water chiller XB 2.80 PE-H series from AICOOL are able to meet the needs of operating the auditorium in testing conditions.

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