

Applying a Domestic Water-cooled Air-conditioner in Subtropical Cities

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Abstract: Water-cooled air-conditioning systems (WACS) are in general more energy efficient than air-cooled air-conditioning systems (AACS), especially in subtropical climates where the outdoor air is hot and humid. Related studies focused on evaluating the energy and environmental benefits of WACS over AACS applying to commercial buildings with central air-conditioning. This paper presents an experimental study on the performance of a 3.36 kW prototype water-cooled air conditioner. The prototype is a self-assembled unit. The results show that by the use of water-cooled air-conditioner, the energy performance can be considerably improved. The study provides useful information for the wider use of WACS in residential buildings located in the hot and humid regions.

Keywords: Domestic air-conditioner; Water-cooled condenser; Coefficient of performance; Condenser water consumption

1. INTRODUCTION

As over one third of the global CO₂ emissions are attributed to the combustion of fossil fuels to meet the energy demands of buildings [1], many energy conservation projects are targeted at reducing energy consumption in this area [1-3]. Water-cooled air-conditioning systems (WACS) are in general more energy efficient than air-cooled air-conditioning systems (AACS), especially in subtropical climates where the outdoor air is hot and humid. This has led to a lot of recent investigations on widening the application of the more energy-efficient water-cooled air-conditioning systems (WACS) and district cooling systems (DCS) to buildings. There is no exception for Hong Kong. In 1998, the Energy Efficiency Office (EEO) of the Hong Kong SAR Government has started to explore the possibility of wider application of WACS and DCS, but this is restricted to non-domestic buildings.

In Hong Kong, energy statistics show that the share of the total electricity consumption of the domestic sector has increased from 22% to 25% from 1990 to 2000 [4]. This is mainly due to the increasing use of air-conditioners because air-conditioning for residential sector responsible for 9.2% of the total electricity generated and imported to the territory [5]. The figure shows that actions should also be taken to reduce electricity consumption in the domestic sector.

Nearly all air-conditioners used in residential buildings in Hong Kong, and elsewhere in the world [6], are either air-cooled window- or split-units. The electric power that an air-conditioning equipment requires to output a given rate of cooling will increase with the entering temperature of the medium for condenser cooling. For use in Hong Kong, air-cooled air-conditioners are typically rated at an outdoor temperature of 35°C, and the coefficient of performance (COP) of such units is in the range of 2.2 to 2.4 [7]. The temperature of water from the city mains is around 27°C in summer and that from a cooling tower just slightly higher but still significantly lower than the summer outdoor air temperature. Water-cooled condensers have a higher heat transfer coefficient than air-cooled condensers, which leads to a lower condensing temperature. The lower condensing temperature reduces the pressure ratio across the compressor, and thus reduces the compressor power consumption and thereby increases the COP and capacity. Hence, water-cooled air-conditioners can be much more energy efficient than air-cooled air-conditioners.

Several studies have been conducted in evaluating the energy and the environmental benefits of WACS over AACS. There include central air-conditioning plant and domestic air-conditioner, applying respectively in commercial and residential buildings.

For domestic applications, since 2002, some small manufacturers in the US and France have started producing direct expansion (DX) water-cooled air-conditioners [6, 13]. Shell and tube condensers are used in these units, which may run with either city water or water from a central cooling tower, and rated for an entering water temperature of 33°C. Performance data and retail price of such units are still not available. In the absence of performance data and considering that the rated water temperature deviates largely from the Hong Kong situation, whether the units are suitable for Hong Kong residential buildings cannot be ascertained.

Recently, Ji et al [14] has modified a heat pump system into a combined domestic air-water-cooled air-conditioner for subtropical applications. The prototype integrates a water-cooled condenser to the outdoor unit of an air-to-water heat pump, which provides space

cooling and water heating in summer and space heating in winter. This study focused on the improvement in the overall COP with the use of a combined cooling and water heating system; no investigation has been made into the overall energy performance and the operating characteristics of a simple domestic water-cooled air-conditioner.

With regard to the performance of a simple domestic water-cooled air-conditioner, Hu et al [15] has conducted an experimental investigation for the use cellulose pads as filling materials to increase the steady state COP of the cooling tower. However, little attention has been given to evaluate the impact on the overall performance of the air-conditioner and the corresponding water consumption at the cooling tower.

Reference has been made to recent studies on the application of WACS in commercial buildings. It is noted that although performance data and simulation tools are widely available, they can hardly be used in evaluating the performance of the domestic water-cooled air-conditioners [8-10]. This is due to the fact that they differ largely in the compressor design and the capacity control provisions. For the chiller units, three types of compressor are most commonly used: reciprocating, screw and centrifugal. These compressors are often provided with precise control of cooling output, whilst very simple on-off control rotary compressors are used for domestic water-cooled air-conditioners. Furthermore, unlike the chiller units, by far no mathematical model has been developed for predicting the performance and the energy use of water-cooled domestic air-conditioners.

Among various types of cooling systems for water-cooled condenser, evaporative cooling towers are a low cost and convenient option, and albeit water losses will be incurred. Nonetheless, fresh water remains a scarce resource in Hong Kong (and its availability is a serious concern worldwide) and squandered use must be avoided. Several mathematical models are available for estimation of water losses in condenser cooling applications [11-12], but the actual amount will vary with the operating conditions of the cooling system, which needs to be determined separately.

Despite the fact that water-cooled air-conditioners are more energy efficient than the air-cooled units, there lack the performance data as well as the associated water consumption rates to enable a detailed analysis on the overall benefits for wider application of WACS in the domestic sector. In this study, a prototype of 3.36KW cooling capacity was assembled for laboratory experiments. In the experiments, the dynamic operation characteristics in response to varying load conditions, the obtainable COPs, the water consumption rates and the amount of recoverable heat were evaluated. Whilst the outdoor air conditions, which is highly variable, was kept within the controlled conditions. The experimental

results will provide useful data for future studies on the performance of water-cooled air-conditioners at different load conditions.

2. EXPERIMENTAL STUDY OF THE WATER-COOLED AIR-CONDITIONER

2.1 Prototype Design

The prototype comprises of an indoor unit, an outdoor unit, a cooling tower and a circulation pump. It has 3.36KW nominal cooling capacity and the power consumption is 0.88KW, as shown in Figure 1. Refrigerant 22 (R22) is used as a working fluid. The indoor unit includes a capillary tube and a DX evaporator with copper tubes and aluminium fins. The outdoor unit includes a high performance tube-in-tube water-cooled condenser connected to a hermetic rotary compressor. The cooling tower is a self-assembled unit because such a small capacity unit is not available in the commercial market. The specifications of the unit are summarised in Table 1.

The compressor capacity is not adjustable and the cooling output is of on-off control in accordance with the indoor set point temperature. The prototype is provided with control means to adjust the condenser water temperature and flow rate so as to maintain the condensing pressure at an acceptable level for effective operation of the capillary tube. In accordance, the cooling tower capacity, overall power input and cooling output vary according to the indoor set point temperature.

Table 1 The basic specifications of the cooling tower

Component	Specification
Cooling tower fan	39.6W, air flow rate 10.8 L/min (adjustable)
Cooling water pump	132W, water flow rate 25 L/min (adjustable)
Filling specimen dimension	53cm×53cm×50cm
Physical dimension	60cm×60cm×125cm

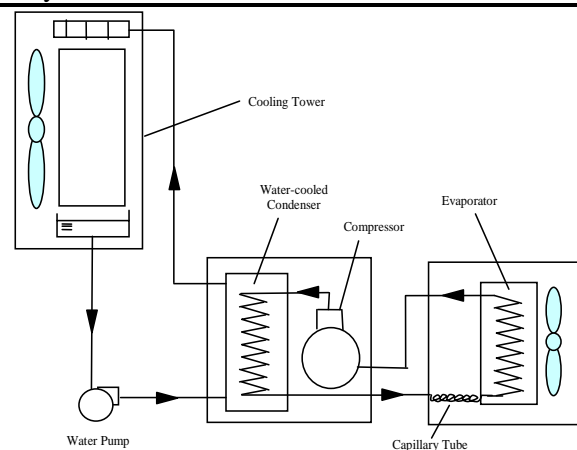


Fig. 1 The prototype system

2.2 The Experimental Set-up for the Prototype

The performance of the unit was tested in an environmental chamber, as shown in Figure 2. The indoor and the outdoor units were placed in two completely isolated and insulated chambers. One resembles the outdoor conditions whilst the other is the indoor conditions. In the indoor chamber, heat generator and moisture generator were used to simulate the varying indoor operating conditions by adjusting the sensible and the latent heat outputs. As the two generators are operating independently, the sensible heat ratio (SHR) can also be adjusted to simulate a wider range of indoor operating conditions. A set of air-handling unit was used to keep the temperature and relative humidity of the outdoor chamber at the controlled conditions. The thermal conditions during the experiments are summarized in Table 2.

A gate valve was used to regulate the cooling water flow rate at 22.6 l/min. The condenser water flow rate was measured by a turbine flow meter. For measuring the cooling output, two pairs of dry bulb and wet bulb temperature sensors were placed in the return and supply air streams of the indoor unit. Similarly, two pairs of dry bulb and wet bulb temperature sensors were placed in the supply and exhaust air streams of the cooling tower for predicting the total heat rejection and the corresponding water consumption. The air flow rates were measured by a thermal anemometer. The cooling output was determined by energy balance using the measured air flow rate, and supply and return air

enthalpy difference. The total heat rejection at the condenser side was calculated using the condenser water flow rate, and the entering and leaving water temperatures difference. Moreover, the compressor, fan and water pump power consumption were calculated using the measured running current and supply voltage. All thermometers and flow meters were connected to two data loggers. The instrumentations are summarized in Table 3.

Table 2 The thermal conditions during the experiments

Controlled air temperature(°C)	indoor chamber	outdoor chamber
Dry-bulb	22	26
Wet-bulb	15	21

3. RESULTS AND DISCUSSIONS

The total outputs from the heat and moisture generators located at the indoor chamber were adjusted in the range of 0.5 - 2.5KW (from 15% to 75% of the nominal capacity) at 0.5KW intervals, whilst SHR was in the range of 0.7 - 0.8 at 0.05 intervals. The load conditions were determined by the use of the energy simulation software HTB2 [16] and cluster analysis [17]. HTB2 was adopted to simulate the annual cooling profile of a typical bedroom in Hong Kong [18]. 2-step cluster analysis was adopted for determining the load clusters. The dynamic performance of the prototype was tested under different load conditions, as shown in Fig.3.

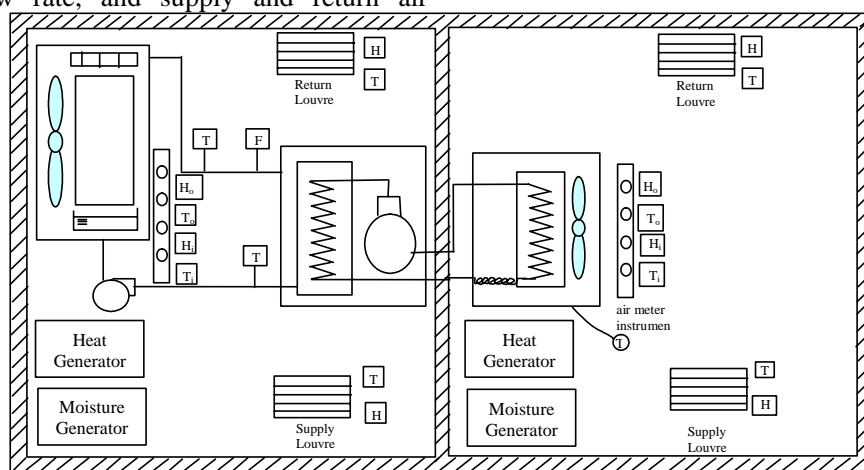
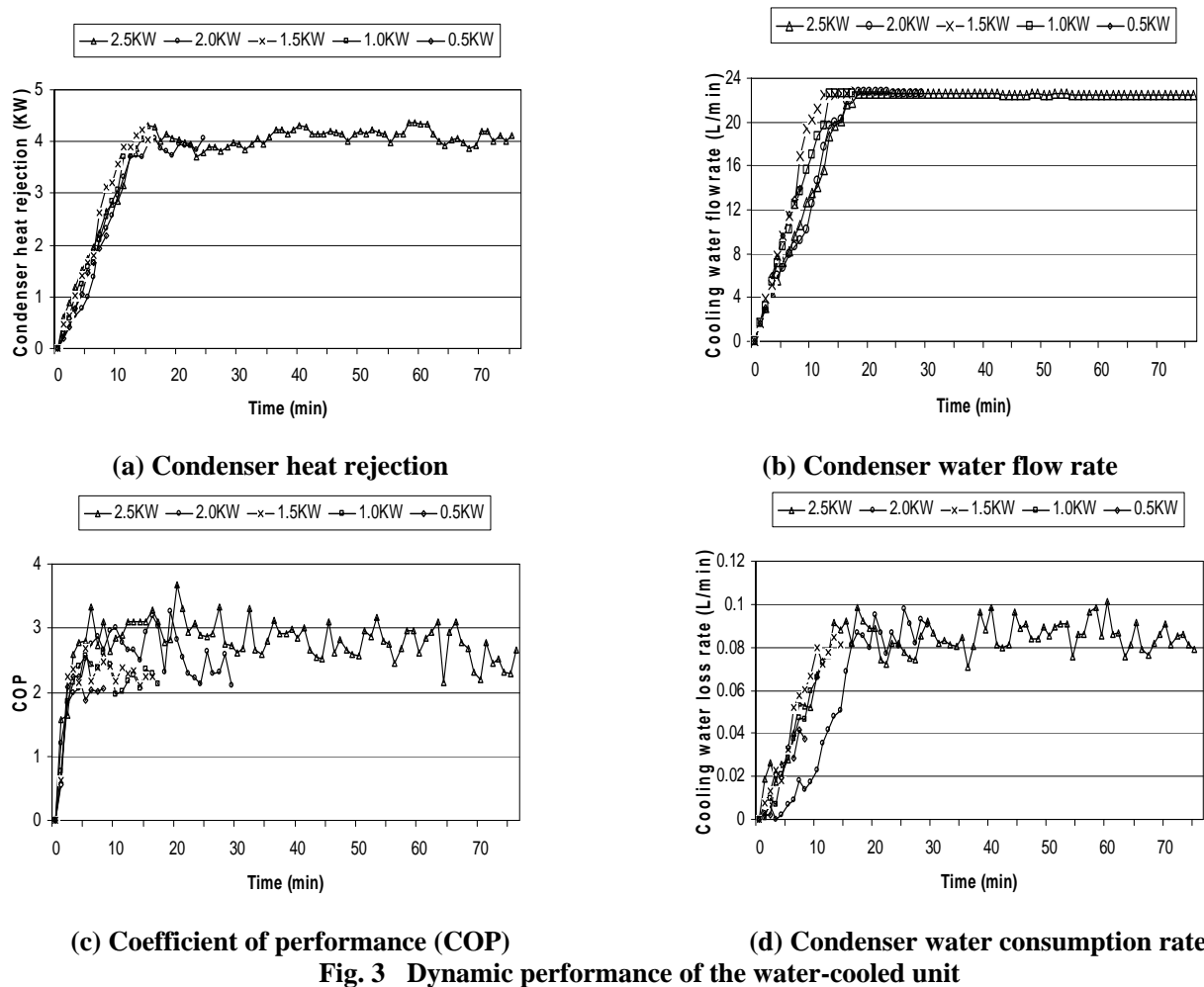


Fig. 2 The experimental set-up

Table 3 Major instrumentations

Parameters	Instruments type	Measure range	Accuracy
Temperature	Pt resistance thermometer	-50 ~100°C	±(0.05%rdg+0.5°C)
Water flow rate	Turbine flow meter	4 ~100 l/min	±2%
Air flow rate	Thermal anemometer	0~5 m/s	±2%
Power	Power meter 7330	0~ 1×10 ⁶ A a.c.	±(0.25%rdg+0.05%F.S.)
		0~ 1×10 ⁶ V a.c.	±(0.25%rdg+0.05%F.S.)



As the water-cooled unit is not equipped with capacity control, the compressor has been cycled on and off to satisfy the indoor set-point temperature requirement. Hence, it can be seen that the total operating time of the water-cooled unit changes with the load conditions.

Figure 3 shows the variation of total heat rejection, condenser water flow rate, COP and condenser water consumption rate against the operating time of the water-cooled unit under different load conditions. When the total cooling load was 2.5KW, 78 min was required to reach the indoor set point temperature. For other load conditions, the results were: 2.0KW, 32min; 1.5KW, 22min; 1.0KW, 19min; and 0.5KW, 11min. The total heat rejection increased with the increase in cooling load, likewise for the condenser water consumption rate. At steady state condition, the condenser water flow rate was 22.6 L/min. However, when the cooling load was at 0.5KW, the flow rate dropped to 14 L/min. This is to ensure the condensing pressure is maintained at an acceptable level during low load conditions. The energy performance of the unit, as represented by COPs, varied with cooling load conditions. They were in general greater than 2.0.

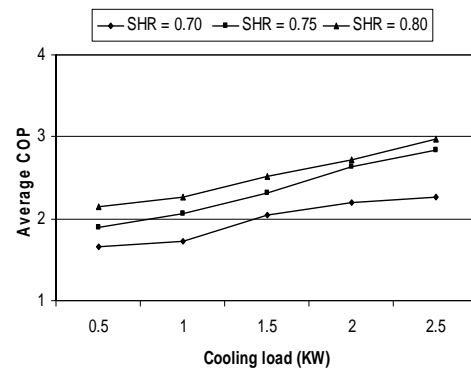


Fig. 4 Average COP at different cooling load

The measured COPs vary with the operating conditions. In this study, the average COP (COP_{ave}) was used to evaluate the overall performance of the prototype. Figure 4 shows the variation of COP_{ave} with the total cooling load at different SHR conditions. It is noted that when the outdoor air conditions and the condenser water flow rate were maintained constant, COP_{ave} increased steadily with the increase in cooling load as well as SHR. The maximum value was 2.98. However, when the cooling load was reduced to 15% of

the rated cooling capacity (i.e. 0.5KW), COP_{ave} dropped to a minimum of 1.58.

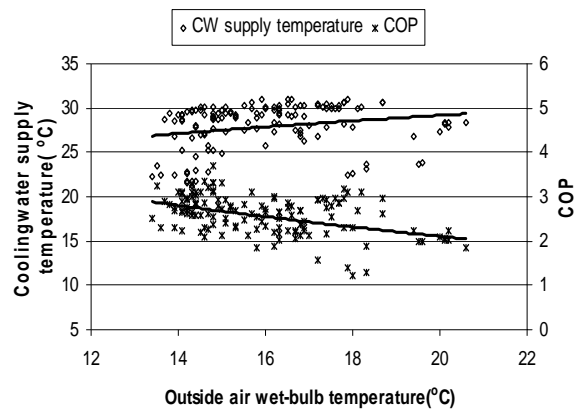


Fig. 5 Entering condenser water temperature

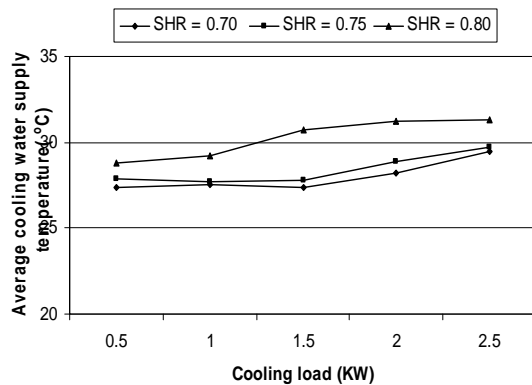


Fig. 6 Entering condenser water temperature

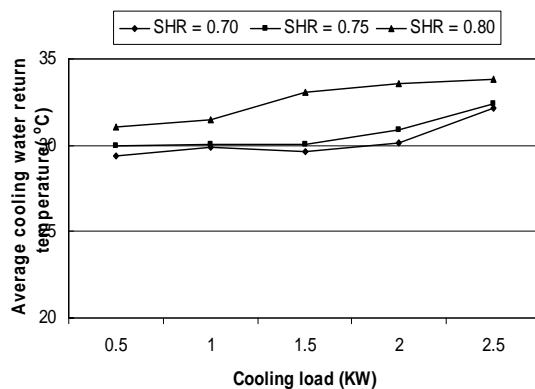


Fig. 7 Leaving condenser water temperature

Figure 5 relates the entering condenser water temperatures, operating COPs and ambient air wet-bulb temperatures. The entering condenser water temperature was ranged between 21 and 31.5°C and the ambient air wet-bulb temperature was ranged between 13 and 21°C. It is noted that although the level of variations were similar for both parameters, the operating COP was more sensitive to a change in entering water temperature than the ambient air wet-bulb temperature. It can also be

seen that the operating COP increases directly with the entering condenser water temperature. The result is consistent with the other studies indicating that the maximum COP was usually located at 70 to 80% of the nominal capacity of a unit [19]. And at particular operating conditions, the operating COP could reach the highest value of 5.

Figures 6 and 7 show the average entering and leaving condenser water temperatures at different load conditions. Higher temperatures were observed at higher SHR and cooling load conditions, and vice versa. The maximum entering temperature was no more than 31.5°C whilst the maximum leaving water temperature was lower than 34°C. The temperature difference was in the range of 2 to 3°C.

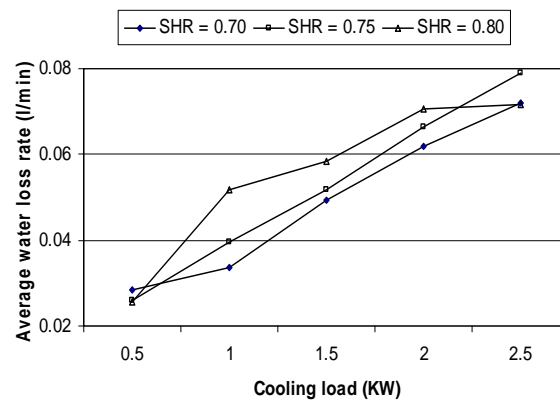


Fig. 8 Average condenser water consumption rate

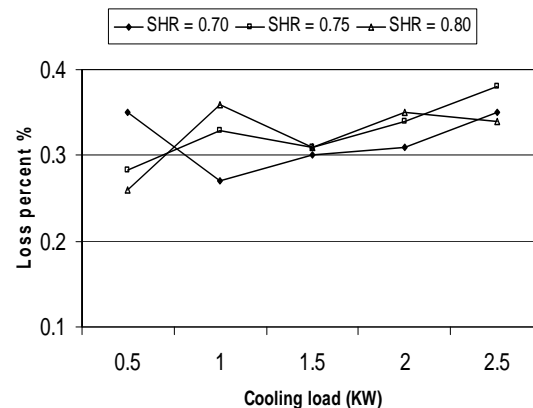


Fig. 9 Average % of water consumption

Figures 8 and 9 relate the water consumption with various load conditions. From Figure 8, it is noted that when the condenser water flow rate was maintained constant, the water consumption rate at different load conditions was in the range of 0.021 – 0.079 L/min. The rate increases with the cooling load as well as the SHR. By transforming into the percentage of water consumption, it can be seen that the figure is in the range of 0.24 to 0.38 %, as shown in Figure 9.

4. CONCLUSIONS

The overall performance of a domestic water-cooled air-conditioner which is in absence in the open literature was reported in this paper. In the experiments, the dynamic operating characteristics, the average and the obtainable COPs, and the condenser water consumption rate were evaluated. According to the experimental results, the obtainable COP at 75% nominal capacity is 2.98 and the maximum achievable COP is 5. These figures are much higher than that of the conventional air-cooled air-conditioners, which at nominal cooling capacity are in the range of 2.2 to 2.4. The results confirm the needs to promote wider application of water-cooled units in the domestic sector for energy efficiency. Water consumption which is the main obstacle for wider use of water-cooled system has been investigated. The rate, amounts to 0.38% of the condenser water flow rate, can ease the mind of most policy makers who have concern about water shortage in Hong Kong. The result of this study provides useful information for future studies on large scale application of water-cooled air-conditioners in residential buildings in Hong Kong as well as in the subtropical cities.

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