Thermal Performance Evaluation of Water Mist Assisted Air Conditioner

Najim Abid Jassim, Ph.D.
Department of Mechanical Engineering, College of Engineering, University of Baghdad

ABSTRACT
Small air conditioning units are usually used for small and medium scale residential buildings. Therefore, more energy efficiency and lower cost are needed along with reliable control for the air conditioning units. This paper considers how the thermal performance can be improved, when the water mist system is coupled with the air cooled conditioner as a pre-cool for condenser inlet air to increase the cooling capacity, and decrease the compressor power consumption. An experimental investigation has been carried out to study the thermal performance of a water mist assisted air conditioner under ambient temperatures ranging from 20℃ to 52℃. The influence of condenser and evaporator inlet air temperatures on the cooling capacity and power consumption has been investigated and presented.

The performance of the entire air conditioning system is simulated by integrated the air conditioner model and water mist model using the TRANSYS Simulation Program. The model is validated by real operating data from the system.

It has been found that due to the coupling of water mist with air cooled condenser, the cooling capacity of the air-cooled air conditioner was increased by 17.5%, and the compressor power consumption was reduced by 15.5% is achieved. It is concluded that the application of water mist condenser inlet air pre-cooling could increase the COP by up to 37%, especially when the ambient relative humidity is low. Good agreement was obtained between the experimental and simulated results for the performance of air conditioner.

Keywords
Thermal performance, water mist, air cooled condenser, air conditioner, simulation program.

1. INTRODUCTION
Refrigeration is the cooling effect of the process of extracting heat from a lower temperature heat source, a substance or cooling medium and transferring it to a higher temperature heat sink, probably atmospheric air, or water, to maintain the temperature of the heat source below that of the surroundings. The most common refrigeration systems are vapor compression systems. The use of water mist in decreasing the air temperature entering the condenser will definitely increase the efficiency of heat exchange at the condenser and so increase efficiency of the condenser and the coefficient of performance (COP) of the air conditioning unit (**ASHRAE, 2009 [1,2]**).

Cansevdi et al., 2009 [3], introduced a new water-spray mist-cooling system to assess its performance, which is based on pre-cooling the ambient air entering the condensers to decrease compressor power consumption of air-cooled chillers with a nominal capacity of 600 kW. It mainly consists of atomization nozzles, water pipe work, a filter assembly and a high pressure pump with around 70 bars. Based on the experimental data obtained from the measurements under ambient temperatures ranging from 25℃ to 39℃, the reduction in air temperature were 5 to 20℃. The energy efficiency ratio (EER) increased by a 13.5%, while an increase of 5.9% in the cooling capacity was obtained.

It is possible to improve the energy efficiency of air-cooled chillers by installing water mist system to pre-cool the outdoor air before entering condensers. The water mist pre-cooling system is not a new concept, and has been applied successfully in the industries (**Hsieh and Yao, 2006 [4]; Manske, Reindl et al., 2001[5]**). However, the application of water-mist system associated with a chiller system is not common, and a limited number of studies are found on the performance of chillers with water mist system.

Yang et al., 2009 [6], considered how the chiller performance can be improved by using water mist to pre-cool ambient air entering the condensers to decrease compressor power. A simulation analysis on an air-cooled chiller equipped with a water mist pre-cooling system under head pressure control shows that applying water mist pre cooling enables the coefficient of performance (COP) to increase. They concluded that the application of water mist pre-cooling could increase the COP in various degrees by up to 30%, especially when the relative humidity is low. Furthermore incase of using a water mist system, the chiller power could reduce by 16.2% or 15.8%.

Chan et al., 2011 [7], reported how the coefficient of performance (COP) of air-cooled chillers can be improved by adopting variable condensing set point temperature control and using mist evaporation to pre-cool ambient air entering the condensers to trigger a lower condensing temperature. Chiller models without and with water mist system were established, and the former was validated by using measured operating data of an installed screw chiller. With the validated model, the energy performance of air-cooled screw chillers with twin refrigeration circuits and water mist system serving a representative commercial building was studied. The results reveal that the chiller COP can be changed by various degrees from -0.3% up to +72% depending on the weather and load conditions, and the annual energy consumption can be reduced by 10.9% for a commercial building in subtropical climate

Yu and Chan, 2009 [8], studied how mist pre-cooling helps improve the coefficient of performance (COP) of air-cooled chillers. A modified chiller model was developed which was calibrated by using manufacturer's performance data to analyze how the COP varies in response to different condensing temperature controls and ambient conditions. The use of water mist pre-cooling could increase the COP by up to 9.8%, and could achieve an around 18% reduction in the electricity consumption.

Zhang et al., 2000 [9], indicated (practically) that the use of evaporative pre-coolers can bring about a 14.7% increase in the COP of air-cooled chillers working in a hot and dry environment. With these coolers, air-cooled chillers can operate more efficiently because the condensing temperature drops followed by any reduced outdoor temperature.

Water Mist System

When the water mist system is coupled with the air conditioner, the temperature of the air at the inlet of the air-cooled condenser will decrease compared the temperature of the ambient air, as well the condensing temperature and condensing pressure will decrease accordingly, as shown in Figure (1).

The refrigeration cycle of the air conditioner with water mist system is changed from the cycle 1-2-3-4-1 to 1'-2'-3'-4'-1'. With the decrease of the condensing pressure, the work of the compressor will decrease. However, the cooling capacity increases, so the COP of the chiller system will increase. Theoretically, air-cooled condenser coupled with a water mist system will improve the air conditioner efficiency, but it will depend on the ambient climatic conditions, cooling load, etc.

2. EXPERIMENTAL APPARATUS AND PROCDURE

A computerized laboratory air conditioner has a model of ET600 and manufactured by G.U.N.T in Germany. It was modulated in order to be used for conducting experiments. It combines the compressor, DX condenser, throttling valve, and DX evaporator. The refrigeration cycle used R134a as a refrigerant; the apparatus contains a simple duct work flow system to simulate an actual air conditioner. The system is equipped with a steam humidifier for regulating the moisture content of the air flow. There are three separate inter connected systems in this apparatus: air flow loop, refrigeration cycle and steam humidifier. The refrigeration cycle is completely separated from other except where it cools air in the evaporator.

The air conditioning system contains three stages preheater and reheater in the path of entering air to the evaporator, and another heater in the front of condenser. Each heater was connected with variable capacity transformers to control the heater power, consequently to control the air entering to the condenser and evaporator to the desired temperatures.

Air is passed through the duct work flow system by a three speeds centrifugal fan mounted at the duct intake. The fan pulls air in through an orifice which is equipped with a horizontal manometer; the air mass flow rate was modulated by varying the evaporator fan speed. An air flow schematic diagram of the ET600 system is presented in figure (2).

A typical water mist system comprises of a high pressure pump motor unit, filter unit, atomization nozzle, high and low pressure tubing was used. The high pressure pump can operate to deliver through highly specialized low flow atomization nozzle to form a water mist of very fine droplets towards the condenser. The water mist flow rate was measured by using a calibrated carafe to show the change in tank containing volume in letters.

All measuring sensors were connected to a LED digital display, enabling Temperatures and humidity to be taking during experiments. The liquid refrigerant mass flow rate was measured by a calibrated flow meter with a maximum uncertainty of ±0.5 kg/h. A digital watt meter with ±1% reading uncertainty was provided to measure the compressor consumption. The apparatus is equipped by thermocouples type T with a maximum uncertainty of ±0.2% and relative humidity sensors with a maximum uncertainty of ± 1%, were installed at the inlet and outlet of the evaporate and condenser. Also, a thermo couples type T was installed along the tube length of the evaporator and condenser to determine the condensation and evaporation temperatures.

The apparatus shown in figures (3,4) has a nominal cooling capacity of 1.2 kW, rated under the operating conditions of entering condenser air temperature, $T_{ca,,e}$ at 35°C, entering/leaving cooled air temperatures at 25°C/12°C and air flow rate at 180 m^3/h. The rated power consumption is 0.5 kW. The rated COP is, therefore, about 2.4. The air-cooled condenser contains condenser fan to deliver a airflow rate of 360 m^3/h. The flow rate of water mist supplied to the condenser was 0.017 to 0.05 l/min, depending on condenser inlet air temperature. The operating pressure of water mist pump is 70 bar.

All tests were performed in an identical manner and at steady state, during these experiments; ambient temperature was kept constant at 25°C. The experiments were repeated by varying the condenser and evaporator inlet air temperature as: 20, 25, 30, 35, 40, 46, and 52 °C, and 23, 25, and 27 °C respectively. It is worth monitoring that the room temperature was maintained around 26℃, during the experiments.

The aim of this paper is to adapt a simplified model for analyzing the thermal performance of water mist assisted air conditioner under Iraq climate. The performance of the entire air conditioning system is simulated by integrated the air conditioner model and water mist model using the TRANSYS Simulation Program., which will compare with the experimental measurements.

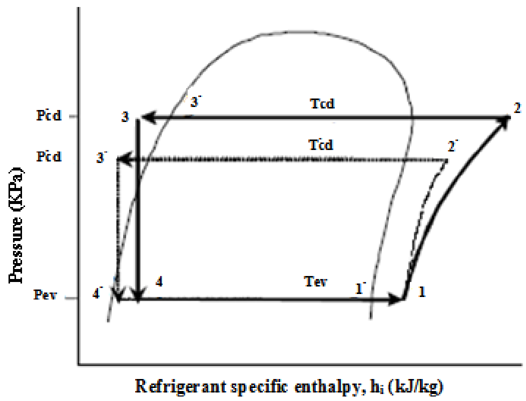


Fig 1: Vapor compression refrigeration cycle

3. MATHMATICAL MODLING

Air Conditioner Model

The measured operating data for the air-cooled air conditioner included the power of compressor, W_{CP}; the power of refrigeration cycle, W_{RP}, which equal to the power of compressor plus the power of fan, cooled air supply temperature, $T_{ea,s}$, cooled air return temperature, $T_{ea,r}$; evaporating temperature, T_{ev} and condensing temperature, T_{cd} of refrigeration cycle. The cooling capacity of the air conditioner, Q_E is:

$$Q_E = m_a \, . (h_{ea,r} - h_{ea,s}) \qquad (1)$$

Where m_a is the cooled air mass flow rate, C_a is the specific heat capacity of air, Where: $h_{ea,r}$, $h_{ea,s}$ are enthalpies of the air at evaporator inlet and outlet, respectively (kJ/kg).

Heat rejection, Q_R was calculated by Eq. (2). The heat rejection airflow, V_a was determined by Eq. (3), where $T_{ca,l}$ is the temperature of air leaving the condenser.

$$Q_R = Q_E + W_{CP} \qquad (2)$$

$$V_a = Q_R / (\rho_a\, C_a\, (T_{ca,1} - T_{ca,e})) \qquad (3)$$

The air conditioner COP is expressed as cooling capacity, Q_E over power consumption W_{CP}, as follow:

$$COP = Q_E / W_{CP} \qquad (4)$$

For any given cooling capacity, Q_E, compressor power, W_{CP} and heat rejection, Q_R will vary according to the condensing temperature, T_{cd}.

Water Mist Model

While the water mist system operates, $T_{ca,,e}$ refers to the temperature, $T_{ca,,e}^{/}$ reduced from outdoor dry-bulb temperature, T_{db}, of which the increased moisture content $W_{db}^{/}$ is dependent on air flow rate, V_a and the mist generation rate, m_{mist}. Their relationship is given by Eqs. (5) to (7) as follow:

$$\Delta W = m_{mist} / (\rho_a V_a) \qquad (5)$$

$$W'_{db} = W_{db} + \Delta W \qquad (6)$$

$$T'_{ac,e} = (h_{db} - 2501 W'_{db}) / (1.006 + 1.805 W'_{db}) \qquad (7)$$

The performance of the entire air conditioning system is simulated by integrated the air conditioner model and water mist model using the TRANSYS Simulation Program [10]. All the measured parameters taken from experimental runs, such as: condenser and evaporator air inlet dry and wet bulb temperatures, condenser and evaporator air mass rates, mist water consumption mass rate, and power consumption were fed the program as input data. All computed parameters taken from the output from the computer which are: The temperature and humidity ratio of condenser air entering, cooling capacity, and the coefficient of performance.

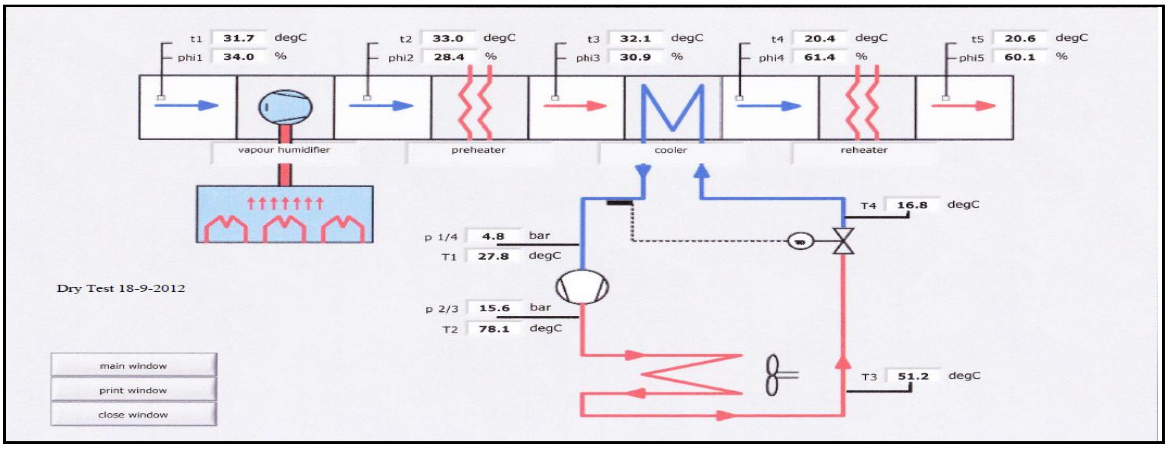
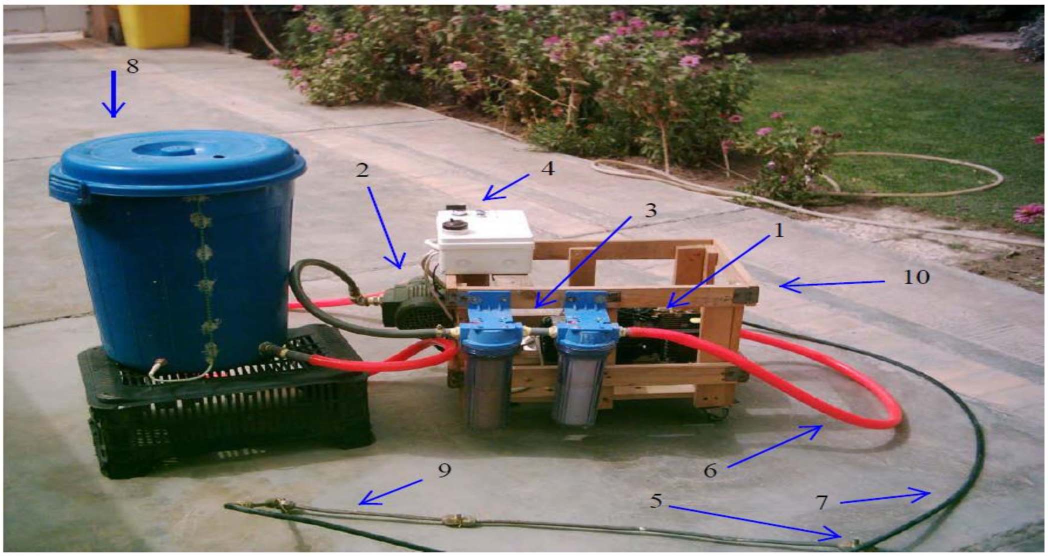


Fig 2: A schematic diagram of ET600

Fig 3: Air-conditioning system, ET600



1	High pressure pump	6	Low pressure elastic pipe
2	Low pressure pump	7	High pressure hose
3	5 microns water filter	8	Water tank
4	Operating electrical board	9	Copper mist network
5	Mist nozzle	10	Wood frame

Fig 4: A water mist system

4. RESULTS AND DISCUSSIONS

The condenser inlet air temperature affects the performance of the refrigeration cycle of air conditioner. As, mentioned, the decrease of condenser inlet air temperature, which will definitely decrease in condensing temperature, consequently the condensing pressure of the cycle was decreased.

The use of water mist in decreasing the air temperature entering the condenser will definitely decrease the condensing temperature of the refrigeration cycle.

Figures (4) to (6) show the effect of condenser inlet air temperature on the refrigeration cooling capacity of the cycle for different evaporator inlet air temperature. It is clear that the cooling capacity was increased with decreasing the condensing temperature, due to the increase in refrigeration effect and compressor volumetric efficiency.

This will definitely increase the refrigerant mass flow rate, as shown in figure (5). The cooling capacity is increased from 8.5 % to 17.5%, with decreasing the temperature of air entering the condenser from 52 ^{o}C to 20 ^{o}C.

In case of studying the effect of evaporator inlet air temperature on cooling capacity, It is found that the cooling capacity was increased by 14.6%, with increasing the temperature of air entering the evaporator from 23 ^{o}C to 27 ^{o}C, due to increase of refrigeration effect and refrigerant density, which will definitely increase of refrigerant mass flow rate that was entering the compressor.

Figures (7) to (9) show the effect of condenser inlet air temperature on power consumption for different evaporator inlet air temperature. It is clear that the power consumption was decreased with decreasing the condensing temperature, due to the decrease of condensing pressure and pressure and pressure ratio, which will definitely increase the compressor volumetric efficiency. The power consumption is increased from 5.5 % to 15.5%, with decreasing the temperature of air entering the condenser from 52 ^{o}C to 20 ^{o}C.

In case of studying the effect of evaporator inlet air temperature on power consumption, It is found that the power consumption was increased by 7.4%, with increasing the temperature of air entering the evaporator from 23 ^{o}C to 27 ^{o}C, due to increase of refrigerant density, which will definitely increase of refrigerant mass flow rate that was entering the compressor.

Figures (10) to (12) show the effect of condenser inlet air temperature on the COP of the cycle for different evaporator inlet air temperature. It is clear that the COP was increased due to the increase in refrigeration effect, which overcomes the increase of power consumption. The COP is increased from 8.5% to 17.5%, with decreasing the temperature of air entering the condenser from 52 ^{o}C to 20 ^{o}C.

Also it is found that the COP was increased by 9.6%, with increasing the temperature of air entering the evaporator from 23 ^{o}C to 27 ^{o}C. The results of present study are agreed more closely with results of Birangane and Patil, 2014[2].

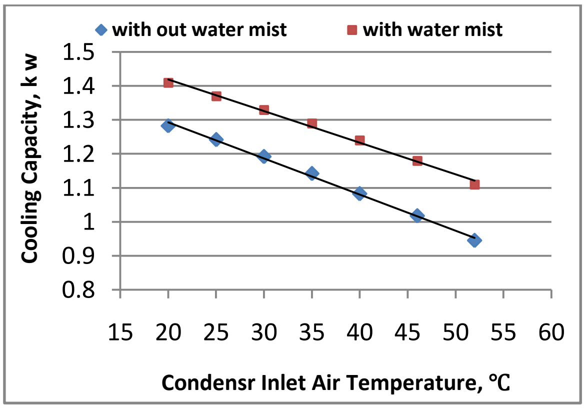


Fig 4: Influence of the condenser inlet air temperature on cooling capacity with / or without water mist pre-cooling at 23^{o}C, $T_{ea,r}$

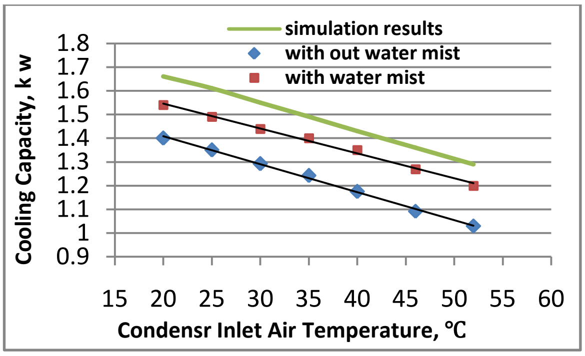


Fig 5: Influence of the condenser inlet air temperature on cooling capacity with / or without water mist pre-cooling at 25°C, $T_{ea,r}$

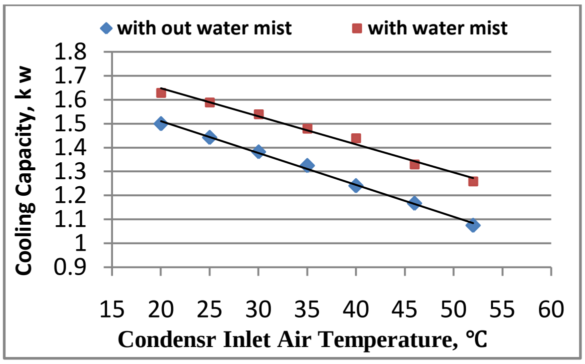


Fig 6: Influence of the condenser inlet air temperature on cooling capacity with / or without water mist pre-cooling at 27°C, $T_{ea,r}$

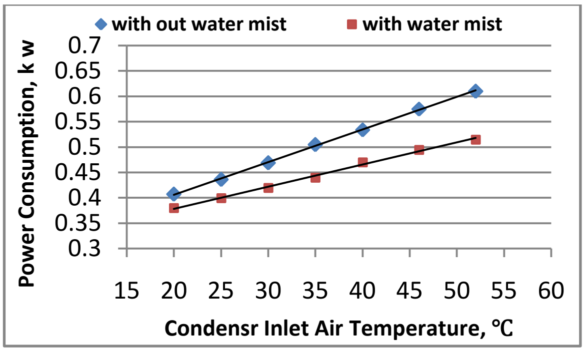


Fig 7: Influence of the condenser inlet air temperature on power consumption with/or without water mist pre-cooling at 23°C, $T_{ea,r}$

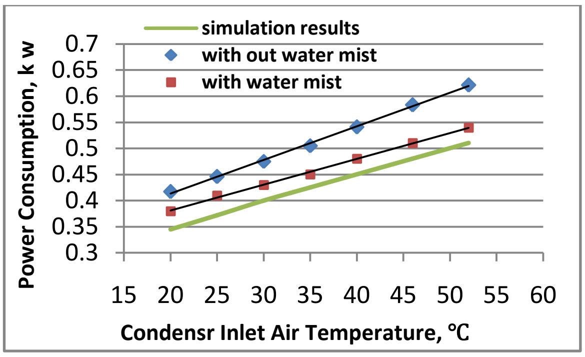


Fig 8: Influence of the condenser inlet air temperature on power consumption with/or without water mist pre-cooling at 25°C, $T_{ea,r}$

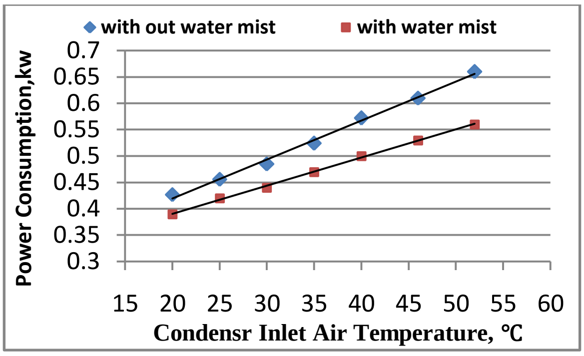


Fig 9: Influence of the condenser inlet air temperature on power consumption with/or without water mist pre-cooling at 27°C, $T_{ea,r}$

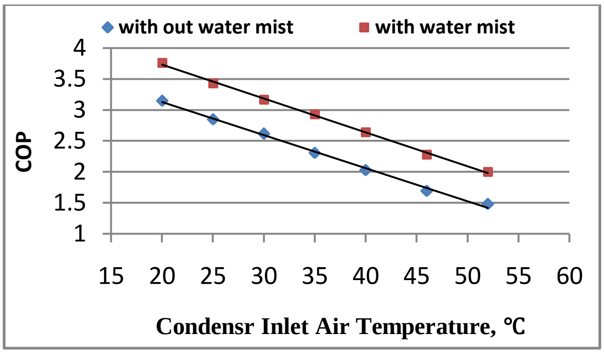


Fig 10: Influence of the condenser inlet air temperature on COP with / or without water mist pre-cooling at 23°C, $T_{ea,r}$

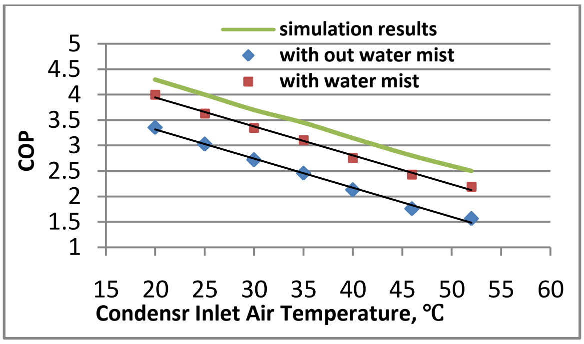


Fig 11: Influence of the condenser inlet air temperature on COP with / or without water mist pre-cooling at 23°C, $T_{ea,r}$

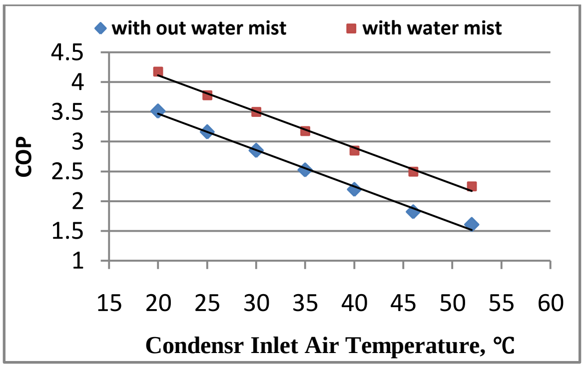


Fig 12: Influence of the condenser inlet air temperature on COP with / or without water mist pre-cooling at 23°C, $T_{ea,r}$

Figs. (5), (8), and (11) show a comparison between experimental and simulated values of cooling capacity, power consumption, and COP of the air conditioner. It is found that, when the water mist system is coupled with the air cooled condenser, the air temperature entering the condenser will decrease from the outdoor air temperature, due to the evaporation cooling process that is taken place in the water mist system. The average deviation between the experimental and simulated results of cooling capacity and COP are 8.3%, 9.7% and 11.4% respectively.

The validity of the performance of the entire air conditioning system model, which is integrated the air conditioner model and water mist model was checked by comparing the modeled results with the operating data of the air conditioner. The modeled results of the air conditioner's COP show agreed well with the corresponding measured data, the uncertainty was within ±8 %.

5. CONCLUSIONS

In this study, the potential of applying mist precooling have been investigated for air-cooled air conditioner operating in subtropical regions. The cooling effect will be better and energy savings from water mist pre-cooling would be more significant if the air conditioner operate in a hot and arid outdoor environment. The findings in this study gave an idea on how the water mist system can be used as an evaporative pre-cooler to improve the efficiency under different weather and cooling load conditions. From the above findings, it can be concluded that:

- The power consumption of the compressor was decreased by 14.6 % and the cooling capacity was decreased by 17.3%, with decreasing the temperature of air entering the condenser from 52 ^{o}C to 20 ^{o}C.

- The COP of the air conditioner was increased by 31.4 %, with decreasing the temperature of air entering the condenser from 52 ^{o}C to 20 ^{o}C.

- There is a good agreement between the experimental and simulated results.

6. NOMENCLATURE

Symbol	Definitions	Units
C_a	specific heat of air	kJ/kg ^{o}C
h	enthalpy	kJ/kg
m	mass flow rate	kg/s
T	temperature	°C
Q_E	cooling capacity	kw
Q_R	heat rejection	kw
V_a	volume rate of air	m^3/s
W	moisture content	kg/kg
W_{CP}	compressor work	kw
ρ	density	kg/m^3

Subscripts

a	air
db	dry bulb
ea,r	return air to evaporator
ea,s	supply air from evaporator
ca,e	entering air to condenser
ca,l	leaving air from condenser
cd	condensing
ev	evaporation
mist	water mist

Abbreviations

COP	coefficient of performance
CTC	condensing temperature control
DX	direct expansion
HPC	high pressure control

7. REFRERNCES

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