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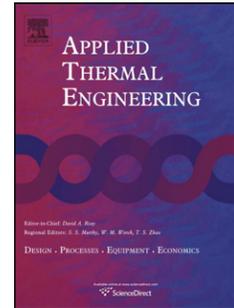
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Abstract

In this work, indirect evaporative air-conditioning was thermally designed in order to reduce energy consumption without negatively affecting the thermal comfort and in order to lower the imported oil bill on the national level and reducing the emission of harmful gasses to the environment on the international level. Moreover, the economic impact of such system was studied. The outcomes show that indirect evaporative air-conditioning can be covered most of the total annual load at 1100 ls-1. Furthermore, once indirect evaporative air-conditioning in 500,000 Mediterranean residential buildings are used instead of traditional one, the annual estimated energy saving is about 1,084 GWh/a and the annual total avoided CO₂ emission is estimated to be 637,873 Ton. The payback period for such system from the saving that occurred is less than two years.

Keywords: **Evaporative; Environment; CO₂; Energy**

I. INTRODUCTION

The energy demand in Jordan has doubled during the last 20 years, and is expected to continue at the same rate, or even higher. Hence all recent energy forecast scenarios have shown that national energy consumption might double between 2015 and 2020 (GEGEO, 2005). Such a rapid increase in demand is due to the fact that industrialization of the country did not reach saturation of high energy consuming sectors, the high population growth rate and the expansion of economical activities in various fields. The estimated investment for increasing the capacity of the energy supply by 2015 is about US\$ 2.5 billion, or even more depending on actual capacities and prices in the international market (MEMR, 2005).

The climate of Jordan is predominantly of the Mediterranean type. It is marked by sharp seasonal variations in both temperature and precipitation. Warm to hot, dry summers and mild, wet winters characterizes it. Summer starts around mid of May and winter starts around mid of November, with two short transitional periods in between (autumn and spring).

Using traditional air-conditionings during summer period in Jordan are becoming very popular last in the last two years due to climate change. These systems consume huge amount of electrical energy that is largely dependent upon fossil fuel which leads to increase the amount of CO₂ emissions. The air-conditioning can be used in all climate but it is expensive as well as its running cost. Thus, this type of air-conditioning is neither sustainable nor environment-friendly.

As the harmful environmental effects of increased concentration of greenhouse gases in the atmosphere, interest has grown in environmentally friendly cooling technologies. The ventilation (indoor quality) can be reached up to 100% from outside air. The advantages of using evaporative air-conditioning are (ASHRAE, 2008):

- Substantial energy and cost savings
- No chlorofluorocarbon (CFC) usage
- Reduced peak power demand
- Reduced pollution emissions
- Improved indoor air quality
- Life-cycle cost effectiveness
- Easily integrated into built-up systems
- Wide variety of packages available
- Provide humidification and dehumidification when needed

Direct evaporative air-conditioning is the simplest, the oldest, and the most widespread form of

air-conditioning. This system typically consists of large porous wetted pads, a sump at the bottom, an electric motor driven fan, a water pump and a water distribution.

In this system, air is drawn through porous wetted pads and its sensible heat evaporates some water; the heat and mass transfer between the air and water lowers the air dry-bulb temperature and increases the humidity at a constant wet-bulb temperature. The heat and mass transfer stop when the dry-bulb temperature of the nearly saturated air approaches the ambient air's wet-bulb temperature (ASHRAE, 2008). The amount of cooling provided is determined by efficiency of the wetting medium, the fan, and the overall design and construction of the unit. The disadvantages of such system are the noise, difficult in controlling the interior temperature, and the quality of conditioned air due to adding moisture to the air. Moreover, if the ambient wet-bulb temperature is higher than 21°C, the cooling effect is not sufficient for indoor comfort cooling [4]. Thus, this system is well suited for climates where the air is hot and humidity is low. To improve the comfort level of conditioned air, the indirect evaporative air-conditioning is introduced.

The Indirect evaporative air-conditioning is similar to direct evaporative air-conditioning, but uses heat exchanger. The cooled moist air never comes in direct contact with the conditioned air. The indirect process is a sensible cooling process on the psychometric chart. This process follows a line along a constant humidity ratio since no moisture is introduced in the indirect evaporative air-conditioning.

The performance of indirect evaporative air-conditioning is measured by Wet-Bulb Depression Efficiency (WBDE). This is calculated as follows (ASHRAE, 2008):

$$WBDE = 100 \frac{t_1 - t_2}{t_1 - t'_s} \quad (1)$$

where;

WBDE = Wet-Bulb Depression Efficiency, %

t_1 = dry-bulb temperature of entering primary air, °C

t_2 = dry-bulb temperature of leaving primary air, °C

t'_s = wet-bulb temperature of entering secondary air, °C

The dynamic performance of a novel dew point evaporative cooling for air conditioning of buildings in different UK regions was analyzed by Zhao *et al.* (2009). Lower humidity results in a higher difference between the dry bulb and dew point of the air, which benefits the system by enhancing its cooling performance. Zhao *et al.* (2009) mentioned that to retain a comfortable indoor air condition, the supply air should be maintained at a humidity level of 70% and below. Thus, it was concluded that the dew point system is suitable for most regions of the UK. Furthermore, it is found that the tap water consumption rate was ranged between 2.1–2.4 l kWh⁻¹ outputs where the cooling output of the system ranged from 3.1 to 4.2 W. m⁻³.h air flow rate, depending on the region. Also, Zhao *et al.* (2009) mentioned that the dew point system could be made as a stand-alone unit, which is suitable for being fitted in a room space (Zhao *et al.*, 2009).

A new type of polygonal counter-flow heat exchanger used in the indirect evaporative dew point cooling systems has been recently developed by Zhao *et al.* (2008). In this paper Numeric

simulations were carried out to optimize the geometrical sizes and operating conditions of the heat exchanger in order to enhance cooling effectiveness. The results of the simulations indicated that cooling effectiveness energy efficiency are largely dependent on the dimensions of the airflow passages, air velocity and working-to-intake-air ratio, and less dependent on the temperature of the feed water (Zhao *et al.*, 2008).

Steeman *et al.* (2009) presented a simulation methodology focusing on the interaction between the thermal performance of an indirect evaporative cooling system and the heat and moisture balance of the building where the return air is used as secondary air. The thermal effectiveness of an IEC system is first studied by measurements. It was found that the effectiveness is independent of the air inlet conditions. In the second part the influence of the ventilation rate and the indoor moisture production on the thermal performance were evaluated using dynamic calculations with the multi-zone building simulation program TRNSYS. It was concluded that increasing the indoor moisture production and lowering the ventilation rate both reduced the thermal performance of the system (Steeman *et al.*, 2009).

Maheshwari *et al.* (2001) developed a technology of an 1180 l s^{-1} indirect evaporative cooler, accounting for reduction in cooling capacity, peak power requirement and seasonal energy savings in coastal and interior locations in Kuwait. The power requirements of a conventional packaged unit air-conditioner in these respective areas were 4.93 and 3.85 kW, respectively compared with only 1.11 kW needed by the indirect evaporative cooler. Also, the seasonal energy savings of the indirect evaporative cooler were 12,418 and 6,320 kWh, for the interior and coastal areas, respectively (Maheshwari *et al.*, 2001). This paper didn't take the water consumption into consideration.

Direct and indirect evaporative cooling techniques are described, analyzed and the outside

conditions of temperature and humidity are identified when they can be profitable as a function of inside set conditions and load distribution between sensible and latent by Lazzarin (2007). The Mollier Psychometric diagram has been divided into seven zones as a function of external air conditions. Also, the climate limits to direct and indirect operation are set on the Mollier psychometric diagram in different zones where the use of free cooling techniques is advisable or not (Lazzarin, 2007).

All the energetic advantages had been evaluated by an economic point of view, in terms of net present worth and discounted payback period of the investment by Lazzarin and Noro (2009). They concluded that evaporative cooling techniques are energy saving for a wide range of climates, typically in buildings where internal heat gain is high enough to need cooling also when the outside air temperature is lower than the desired inside air temperature. Moreover, they showed very interesting energy savings in different European climates during summer period, an important increase of the savings with indirect evaporative cooling with respect to direct evaporative cooling. Such a benefit is obtained by means of greater water consumption (Lazzarin and Noro, 2009).

Khmmas (2010) suggested using the indirect evaporative cooling system (forced or natural) instead of the direct system. The air-cooler is modified to operate as a cooling tower to produce cooling water by evaporation process; this represents the outdoor unit. The cooled water is pumped to the indoor unit which consists of a fan coil unit. The results showed that the Evaporation Cooling Effectiveness, (ECE) was reduced by 15% for forced evaporation case, and by 22% for the natural case, as compared with the direct case (Khmmas, 2010).

In this work thermal, energetic, and economic comparison of employing two possibility of indirect evaporative air-conditioning in typical Jordanian residential building will be investigated

theoretically. This will be as a guideline for all Mediterranean countries in feasibility of using indirect evaporative cooling. Two scenarios for indirect evaporative air-conditioning will be studied; the first is where the primary and secondary streams are supplied from the outside and return air from the building, respectively. The second scenario will be changed the streams to be return air from the building as a primary stream and fresh air from outside as a secondary stream.

II. MODEL

TRNSYS Simulation software is an acronym for a TRAnsientSYstem Simulation program. TRNSYS is a complete and extensible simulation environment for the transient simulation of systems, including multi-zone buildings. It is to validate new energy concepts, from simple domestic hot water systems to the design and simulation of buildings and their equipment, including control strategies, occupant behavior, alternative energy systems such as wind, solar, photovoltaic and hydrogen systems (TRNSYS, 2006). The calculations are influenced by climatic factors such as outdoor temperature, solar radiation and the relative humidity. Properties for the indoor climate of the building can be calculated based on these simulated results.

Type 56 in TRNSYS was chosen to simulate the annual cooling load. This model is a non-geometrical balance model with one air node per zone, representing the thermal capacity of the zone air volume and capacities which are closely connected with the air node. Thus the node capacity is a separate input in addition to the zone volume. The cooling load mathematical model is described as the following;

$$\dot{Q}_{Total\ Cooling\ Load} = \dot{Q}_I + \dot{Q}_E \quad (2)$$

where;

\dot{Q}_I : internal annual cooling load, kWh

\dot{Q}_E : external annual cooling load, kWh

The external cooling load covers energy which enters from outside via the building enclosure surfaces, where this must be removed from the room air. This is divided, as a basic principle, into heat flow paths through external walls, roof and floor, $\dot{Q}_{e,wall}$ and windows \dot{Q}_w .

The effect of an air change due to joint ventilation and infiltration in the building is taken into account using the $\dot{Q}_{vent.}$, and $\dot{Q}_{inf.}$ components, respectively. Hence the following applies:

$$\dot{Q}_E = \dot{Q}_{e,wall} + \dot{Q}_w + \dot{Q}_{vent.} + \dot{Q}_{inf.} \quad (3)$$

The internal annual cooling load is a summation of heat emissions from person \dot{Q}_p , heat emission from equipment \dot{Q}_E , heat emission from lighting \dot{Q}_L , and heat from adjacent rooms via the internal surface $\dot{Q}_{i,wall}$:

$$\dot{Q}_I = \dot{Q}_p + \dot{Q}_E + \dot{Q}_L + \dot{Q}_{i,wall} \quad (4)$$

INSEL is an acronym for INtegrated Simulation Environment Language. It provides an integrated environment and a graphical programming language for the creation of simulation applications (INSEL, 2009). A full set of models for the simulation of evaporative cooling system is implemented in the inselST toolbox.

In this work two models of indirect evaporative air-conditioning will be simulated by INSEL and TRNSYS software's in order to investigate the performance of indirect evaporative air-conditioning. INSEL software produces the useful temperature (supply air temperature) due to introducing indirect evaporative air-conditioning. Then, this temperature is used as input to TRNSYS software to calculate hourly cooling load required for indoor comfort.

The schematic of first model is shown in Figure (1). The supply air entering the primary stream comes from the room while the supply air entering the secondary stream comes from outside at ambient temperature. The cooling due to ventilation (hot air entering the building) is calculated in TRNSYS software separately.

Figure (1): First Model

The second model considers the outside and room air as supply air entering the primary and secondary stream, respectively. The cooling due to ventilation is set to be zero in TRNSYS software because it is already included in INSEL software. The schematic of this model is shown in Figure (2).

Figure (2): Second Model

The typical Jordanian residential building located in Amman is selected in this study, as shown in Figure (3).

Figure (3): Typical Jordanian Residential Building Plan

This residential building is under construction now and it can be described as follows:

1. The floor area is about 154 m², perimeter is 43.4 m and ceiling height is 3 m. It consists of three bedrooms, living room, guest room, Kitchen and three bathrooms, as shown in Figure (3).

2. The building is a rectangular shape located in Amman region, well insulated according to Thermal Insulation Code (Thermal Insulation Code, 2009) and ventilated according to ASHRAE Standard 62.2 (ASHRAE, 2004). With proper thermal insulation added to walls and ceiling a good reduction of the cooling demand has been achieved.
3. The overall heat transfer coefficient (U) is $0.398 \text{ W/m}^2\cdot\text{K}$ and $0.469 \text{ W/m}^2\cdot\text{K}$ for wall and ceiling, respectively.
4. The climatic data (solar radiation, ambient temperature, relative humidity...) is hourly data obtained from INSEL library (INSEL, 2009).
5. Number of occupants is 6 persons.
6. Cooling thermostat setting (indoor set point temperature) is adjusted at 24°C for cooling in summer and the relative humidity is set 50% (ASHRAE, 2008).
7. All windows are aluminum-framed ($U=2.27 \text{ W/m}^2\cdot\text{K}$), sliding with tight double glazing ($U=2.83 \text{ W/m}^2\cdot\text{K}$ and $g=0.775$).

III. RESULTS

The hourly cooling load is calculated by TRNSYS software. The total cooling load is 8,773 kWh/a. The maximum cooling load is 6.11 kW. The peak load is occurred during the period July – August. Also, a small cooling load is occurred in March, April and November.

The thermal performance of indirect evaporative air-conditioning with flat plate heat exchanger (cross flow) will be investigated for the two scenarios as follows:

First Scenario:

The first model –entering air is the return air from building in primary stream – is simulated by INSEL at three air flow rate 100 l s^{-1} , 500 l s^{-1} and 1100 l s^{-1} .

The results show that the max load that covered by indirect evaporative air conditioning at

flow rate of 100 l s^{-1} was 1.14 kW whereas at 500 l s^{-1} was 3.29 kW. Moreover, this model can cover around 29.3%, and about 78.0% from the total cooling load at flow rate 100 l s^{-1} and 500 l s^{-1} respectively. These results are illustrated in Figure (4).

Figure (4): Cooling Load PartlyCovered in First Scenario

The cooling load is covered by 95% by using indirect air-conditioning system with flow rate of 1100 l s^{-1} , as shown in Figure (5).

Figure (5): Cooling Load PartlyCovered in First Scenario at flow rate 1100 l s^{-1}

Second Scenario:

The second model –introducing air from outside at ambient temperature in primary stream– is simulated by INSEL at three air flow rate 100 l s^{-1} , 500 l s^{-1} and 1100 l s^{-1} .

The thermal performance of the above scenario is illustrated in Figure (6). This Figure shows that the max load that covered by indirect evaporative air conditioning at flow rate of 100 l s^{-1} was 1.03 kW whereas at 500 l s^{-1} was 3.01 kW. Moreover, around 24.89% at air flow rate 100 l s^{-1} and 68% at flow rate 500 l s^{-1} from the total cooling load can be covered.

Figure (6): Cooling Load PartlyCovered in Second Scenario

About 86% of the annual cooling load can be covered at flow rate of 1100 l s^{-1} , as shown in Figure (7). Furthermore, the maximum load is 3.97 kW.

Figure (7): Cooling Load PartlyCovered in Second Scenario at flow rate 1100 l s^{-1}

The results show that the first scenario is technically better than the second one. Figures (8) –

(10) show the deviation between first and second scenarios.

Figure (8) shows that the first scenario at 100 l s^{-1} can cover around 15.05% of the annual cooling load more than the second scenario at the same flow rate.

Figure (8): First and Second Scenario at flow rate 100 l s^{-1}

Figure (9) shows that the first scenario at 500 l s^{-1} can cover around 13.15% of the annual cooling load more than the second scenario at the same flow rate.

Figure (9): First and Second Scenario at flow rate 500 l s^{-1}

Figure (10) shows that indirect evaporative air-conditioning system with 1100 l s^{-1} can fulfill most of the load requirement in first scenario, around 95% of the total cooling load. In second scenario the same flow rate is capable only to cover about 86% from the total cooling load. Moreover, Figure (10) shows that first scenario can cover around 9.88% of the annual cooling load more than the second scenario at the same flow rate. Thus, the first scenario is technically better than second scenario.

Figure (10): First and Second Scenario at flow rate 1100 l s^{-1}

Figure (11) shows the psychrometric process for both models at Ambient Temperature 35 C and 22 C.

Figure (11): Psychrometric chart for First and Second Model
at Ambient Temperature 35 C and 22 C

IV. FEASIBILITY STUDY

The feasibility of using indirect evaporative air-conditioning (first scenario), to cover 95% of total cooling load of the selected residential building at flow rate of 1100 l s^{-1} , will be calculated using the simple Payback Period method. This method is the time required for the indirect evaporative air-conditioning system to recover its initial cost from the savings in electricity resulting from using this system. Therefore, the Payback Period can be written as;

$$\text{Payback Period} = \frac{\text{System Cost}}{\text{Energy Saving Cost} - \text{Running Cost}} \quad (5)$$

In order to estimate the feasibility study of using indirect evaporative air-conditioning and compare it with traditional air-conditioning which operates with electricity, the following assumptions are set:

1. The traditional air-conditioning has Coefficient of Performance (COP) of 2.5.

The water cost is considered as current tariff in Jordan (<http://www.miyahuna.com.jo>)

Electricity cost is considered as current tariff in Jordan (<http://www.nepco.com.jo>)

2. The indirect evaporative air-conditioning system initial cost is $0.4 \text{ JD}^* \text{ s. l}^{-1}$.

The running cost of indirect evaporative air-conditioning is the summation of the water cost, supply and exhaust fans electricity cost in addition to water pump electricity cost.

The fan power P_s required by the supply air (Bomet *al.*, 1999) is estimated from

$$P_s = Q_s \Delta p_s / \eta_f \quad (6)$$

The fan power P_e required by the exhaust air is estimated from

$$P_e = Q_e \Delta p_e / \eta_f \quad (7)$$

* JD (Jordanian Dinar) = 1 Euro

where

P_s : fan power for supply air, W

Q_s : volume flow rate of supply air, m^3s^{-1}

Q_e : volume flow rate of exhaust air, m^3s^{-1}

P_e : fan power for exhaust air, W

Δp_s : pressure drop of supply air caused by fluid friction, pa

Δp_e : pressure drop of exhaust air caused by fluid friction, pa

η_f : overall efficiency of fan and motor or product of fan and motor efficiencies.

The pressure drop of supply air caused by fluid friction, pressure drop of exhaust air caused by fluid friction and overall efficiency of fan and motor are equal to 150 pa, 125 pa and 35%, respectively. Thus, the annual electricity consumption (primary and secondary fans) is 1340 kWh/a. That's equal to running costs of 113.96 JD/a.

Since Jordan is one of the ten most water-deprived countries in the world; the water consumption of indirect evaporative air-conditioning should be calculated. The calculation yields that the annual water consumption is about 27.05 m^3 .

The traditional air-conditionings are becoming very popular in Jordan these days. In order to cover the current annual cooling load, traditional air-conditionings with running cost of about 3509 kWh/a which equal to running costs around 397 JD/a will be used. That's mean energy saving of 2169 kWh/a will be achieved once traditional air-conditionings is replaced by indirect evaporative air-conditioning.

The payback period of indirect evaporative air-conditioning from energy saving occurred due to replacing electricity-driven air-conditioning is less than two years.

Also, with rapid population growth and increase in various economic activities, more energy is

consumed; to really identify the impacts of the amount of saving, the macro economic analysis should be considered. Once only 500,000 residential buildings in Jordan use indirect-evaporative air-conditioning instead of traditional air-conditioning system (first scenario), around 92.18 million JD/a will be saved annually. Moreover, about 637,873 Tons of CO₂ emissions will be reduced annually (On average, electricity source emits 588.3 g CO₂ per kWh (<http://www.eia.doe.gov>)).

V. DISCUSSION

Indirect evaporative air-conditioning can provide superior cooling and ventilation while consuming less energy, reduced global warming and heal the environment than traditional air-conditioning. In this paper guideline in feasibility of using indirect evaporative cooling was set. On the other hand, this work hasn't discussed before especially for Mediterranean region.

The results show that first scenario of indirect evaporative air-conditioning behaves technically better than the second scenario. It can be concluded from this research that first scenario is able to cover the whole load at $T \leq 27.14$ C while at temperature between 27.14 C - 34 C first scenario is sufficient to cover the cooling load partially. There is only 1.7% from total cooling hours where first scenario can cover less than 60% of the cooling demand. These hours are from 14:00 – 18:00 in July, August and September. Moreover, at Temperature above 35 C, there is no cooling load from evaporative cooling system can be utilized

In contrast, Legionnaires' disease is not a problem with evaporative cooling system. Legionella growth is relative to the temperature of water. The optimum growth is occurring at about (37–41)C [Puckorius, 1995]. In this research indirect evaporative cooling system operate with water temperatures less than 24 C where the legionella bacteria are not active. Moreover, heat

exchanger in indirect evaporative cooling system is designed with two discreet air passages. Water and air are circulated over the secondary air passage of the heat exchanger, while hot air passed through the primary air passage. The net effect is air that was cooled without contacting water or increasing in moisture content. Regularly maintaining, draining, cleaning and drying out of the indirect evaporative cooling system coupled with water treatment should be sufficient to reduce the possibility of Legionella originating.

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- In typical residential building in Mediterranean region, indirect evaporative air-conditioning can be covered most of the total annual load at 1100 l s⁻¹
- Once indirect evaporative air-conditioning is used instead of traditional one in Mediterranean region, the annual estimated energy saving can be about 1,084 GWh/a and the annual total avoided CO₂ emission can be 637,873 Ton.
- The payback period of indirect evaporative air-conditioning from the saving that occurred is less than two years.

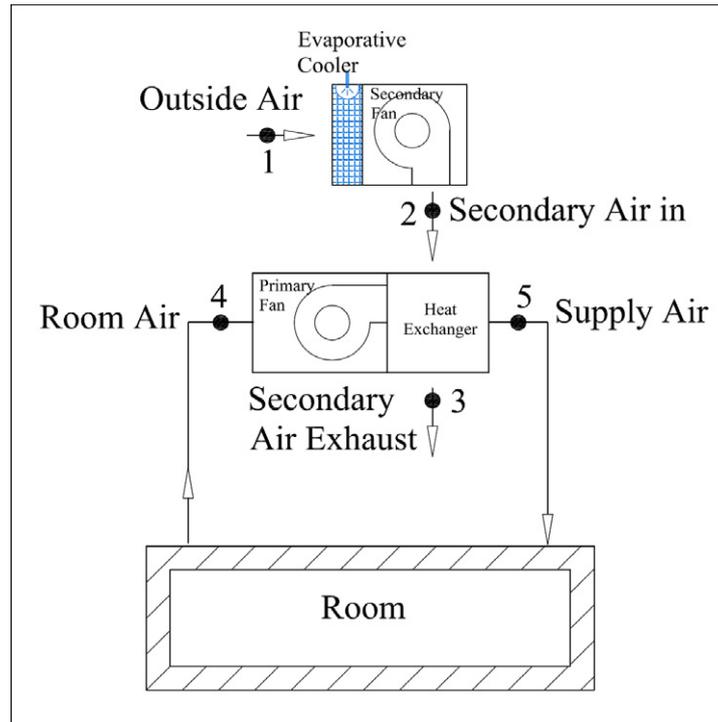


Figure (1): First Model

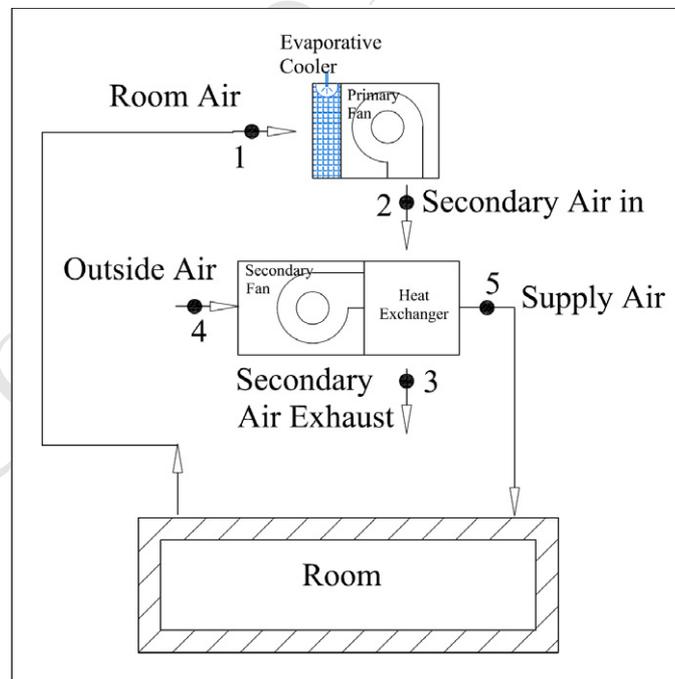


Figure (2): Second Model

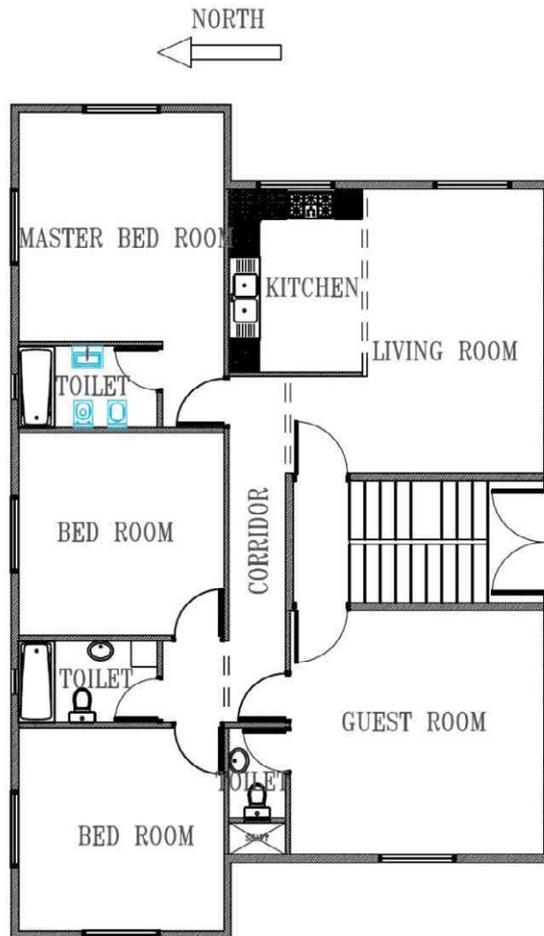


Figure (3): Typical Jordanian House Plan

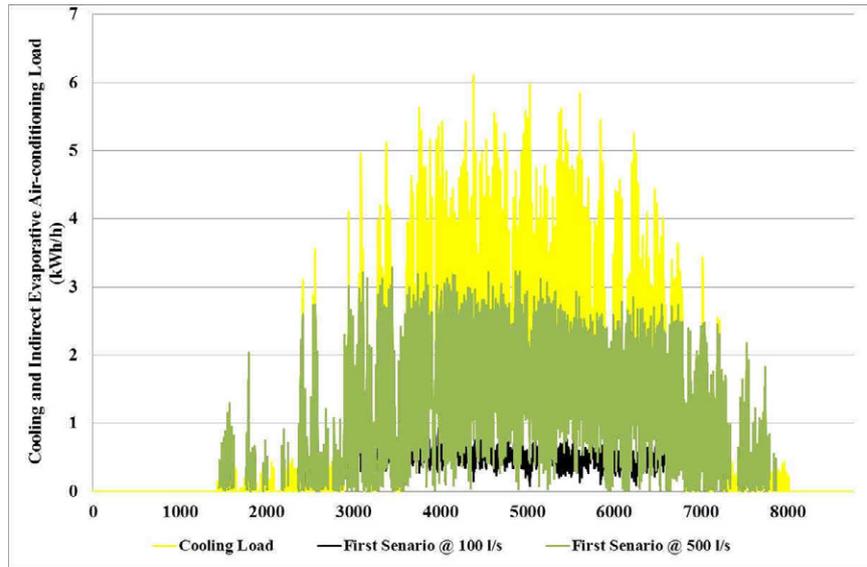


Figure (4): Cooling Load Partly Covered in First Scenario

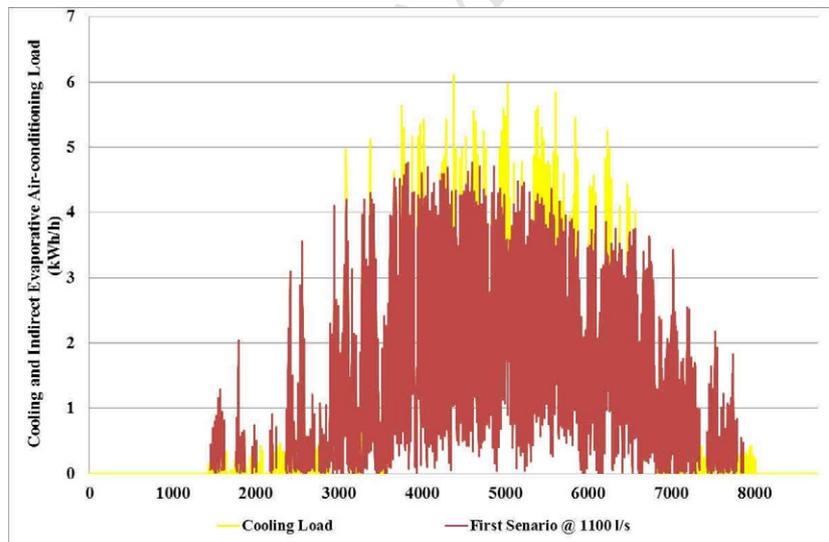


Figure (5): Cooling Load Partly Covered in First Scenario at flow rate 1100 l s^{-1}

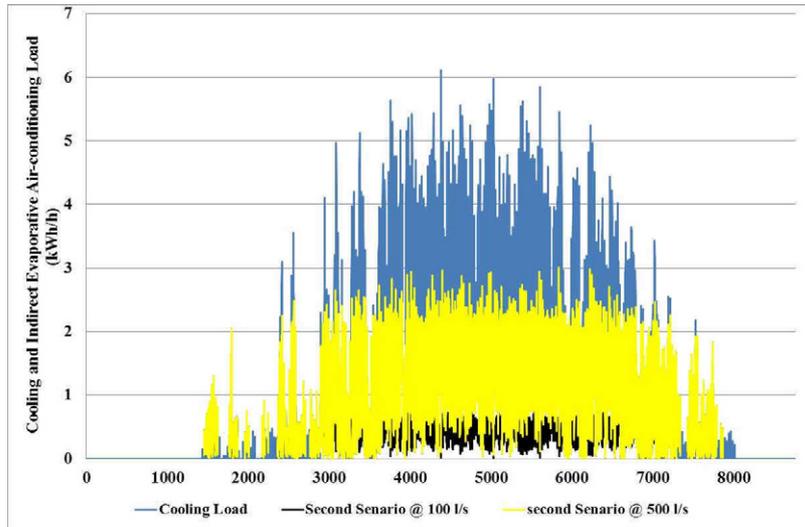


Figure (6): Cooling Load Partly Covered in Second Scenario

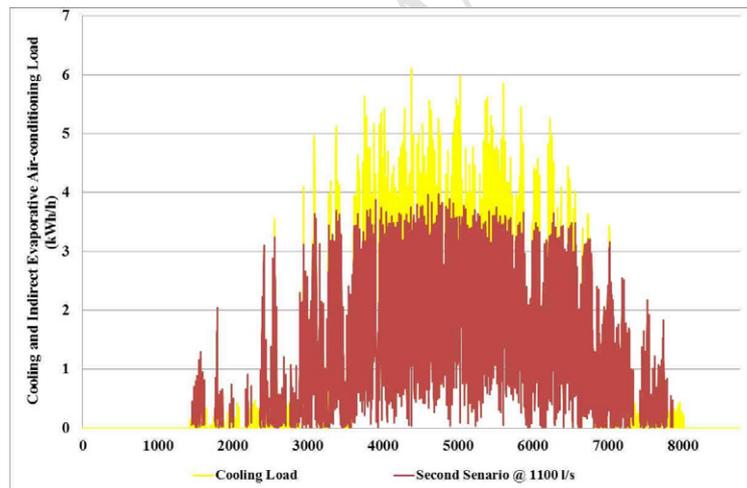


Figure (7): Cooling Load Partly Covered in Second Scenario at flow rate 1100 l s^{-1}

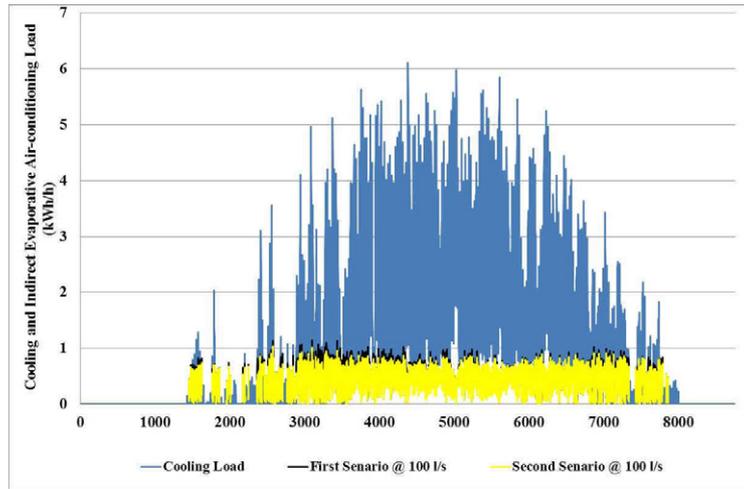


Figure (8): First and Second Scenario at flow rate 100 l s^{-1}

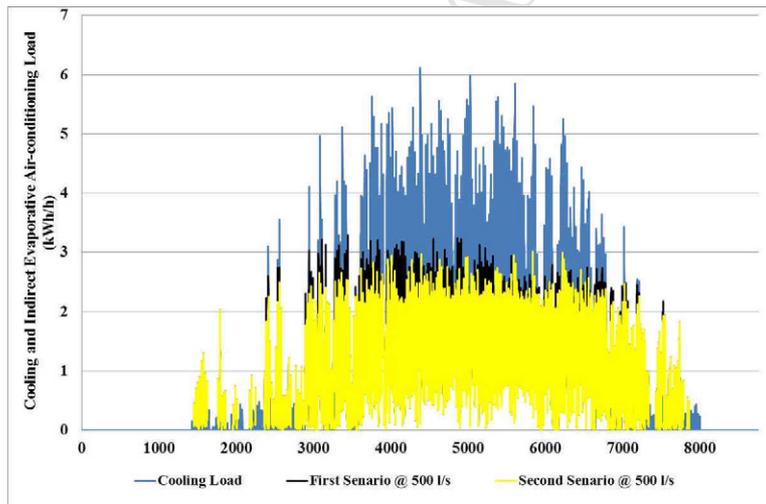


Figure (9): First and Second Scenario at flow rate 500 l s^{-1}

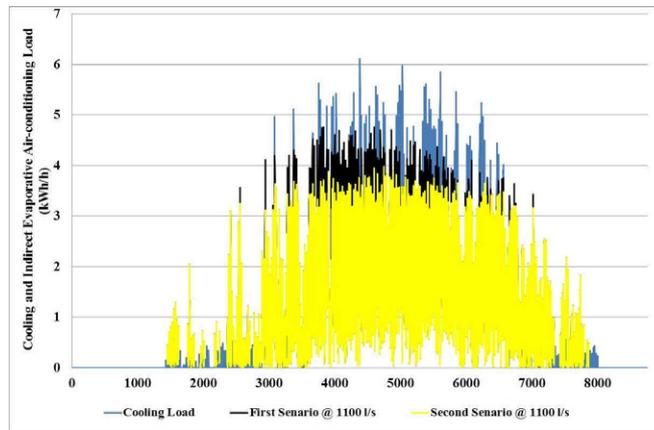


Figure (10): First and Second Scenario at flow rate 1100 l s^{-1}

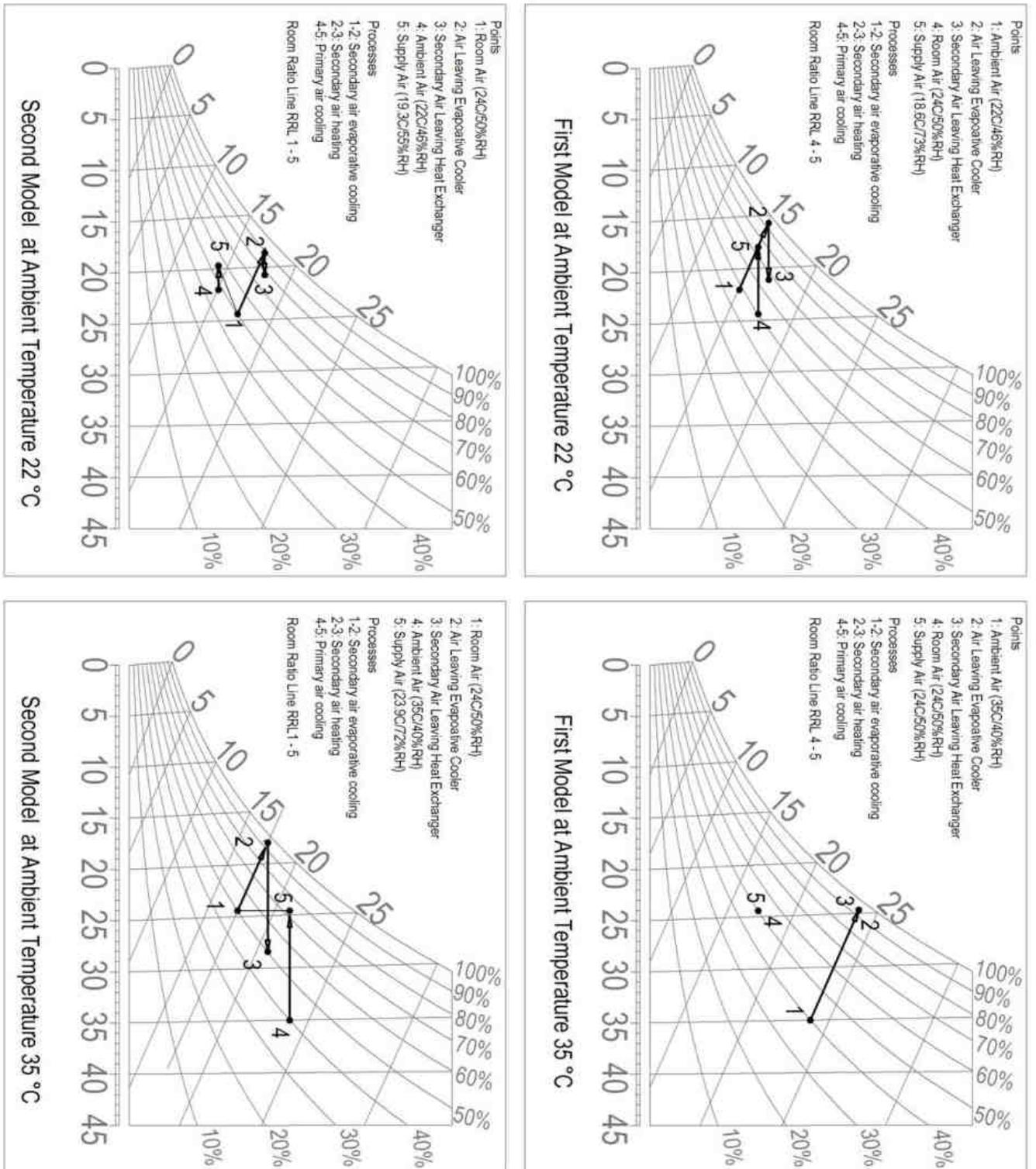


Figure (11): Psychrometric chart for First and Second Model at Ambient Temperature 35 C and 22 C