Simple Domestic Air Conditioning by using the Ice Thermal Storage Capacity

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ABSTRACT:
In this paper, a special design of an experimental rig was used to study and evaluate the performance of using the ice thermal storage capacity for cooling purpose. Nowadays ice thermal storage system is mostly used because it is practical due to the large heat of fusion of ice to change into water. Thermal storage techniques have provided opportunities to store cooling energy in ice when the power price is relatively low.

The experimental rig that was built is a simple domestic air conditioning prototype that can be used to cool small spaces with ice bank which are prepared for this purpose.

Encouraging results were obtained in this paper where two different air flowrate was used to compare between them; it was found that the performance of using the ice storage capacity is effective in which the coefficient of performance (COP) is relatively high compared to a conventional air conditioning. The results showed that the COP for higher air flowrate is lower than the COP for lower air flowrate due to lower power consumed by the system. And the outlet temperature for the higher air flowrate is higher than the outlet temperature for the lower air flowrate due to the more time of contact between the air and the ice banks.

As a conclusion we found that the ice storage capacity process is an effective process of using a chiller or refrigeration plant to build ice during off-peak hours to serve part or the entire on-peak cooling requirement.

I. INTRODUCTION:

Refrigeration:

Refrigeration can be defined as the process of removing heat from any substance which may be a solid, a liquid, or a gas; it maintains the temperature of the substance below that of its surroundings. Refrigeration is therefore the science of moving heat from low temperature to high temperature [ref. 1].

There are two common methods of refrigeration; these methods are natural and mechanical. In the mechanical refrigeration a refrigerant which is a substance capable of transferring heat that it absorbs at low temperatures and pressures to a condensing medium. By means of expansion, compression, and a cooling medium, such as air or water, the refrigerant removes heat from a substance and transfers it to the cooling medium.

In the natural refrigeration, ice has been used in refrigeration since ancient times and it is still widely used. In this natural technique, the forced circulation of air or water passes around blocks of ice [ref. 2]. Some of the heat of the circulating air is transferred to the ice, thus cooling the air, particularly for air conditioning applications.

Refrigeration by Natural Ice:

Historically, an inscription from 1700 BC in northwest Iran records the construction of an icehouse, "which never before had any king built." In China, archaeologists have found remains of ice pits from the seventh century BC, and references suggest they were in use before 1100 BC. Alexander the Great around 300 BC stored snow in pits dug for that purpose. In Rome in the third century AD, snow was imported from the mountains, stored in straw-covered pits, and sold from snow shops [ref. 3].

Before the 19th century, there was no mechanical refrigeration, and all the artificial cooling of air has used ice, snow, cold water or evaporative cooling. In the 1800s natural refrigeration was a vibrant part of the economy. Natural ice harvested from the pristine rivers and lakes of the northern US was in demand [ref. 4].

Ice harvesting is still a good way to beat the cost of refrigeration. In China, "Citizens collect ice blocks cut from the ice on the Songhua River in Mudanjiang, northeast China's and store ice cubes at their cellars in winter for summer use. They buried it in sawdust, ice can last all summer at zero cost and energy consumed [ref. 5].

In natural ice refrigeration, cooling is accomplished by melting ice. Owing to its melting point of (0 °C), Ice is used as an effective cooling agent because to melt it, ice must absorb 333.55 kJ/kg (about 144 Btu/lb) of heat.
This method is used for small-scale refrigeration such as in laboratories and workshops, or in portable cooler, and foodstuff maintained near this temperature have an increased storage life.

Sustainable cooling with thermal energy storage:

Thermal energy storage (TES) is sometimes defined as a way of producing an energy sink or source, and provides methods and systems that allow storage of either cooling or heating produced at one period in time for later use at another period in time. TES results in two significant environmental benefits: (i) the conservation of fossil fuels through efficiency increases and/or fuel substitution, and (ii) reductions in emissions of such pollutants as CO_2, SO_2, NOx and CFCs [ref. 6].

Thermal storage can either take the form of sensible heat storage (SHS) or latent heat storage (LHS). Latent heat storage is accomplished by changing a material's physical state whereas SHS is accomplished by increasing a material's temperature [ref. 7].

Ice as (LHS) is one of the more common thermal storage materials used today. Ice provides one of the highest theoretical thermal storage densities (and, therefore, the lowest storage volumes). Ice systems have been shown to be excellent for smaller and even for some larger packaged installations [ref. 8].

The annual electricity consumption for air conditioning systems can account for over than 30%. Thus, stored energy for ice (focus on phase change) can be used instead of electricity when the demand for energy is high to reduce energy consumption in hot climates.

II. THE RESEARCH GOAL:

The goal of this research is to carry out a study of cooling system performance through a simple domestic air conditioning prototype by using the ice thermal storage capacity as an alternative method in air conditioning system for the following reasons:

1. To reduce the pollution and global warming by reducing the usage of oil fossil for producing electricity. With global warming, extremely hot weather may become more common, so, the ice thermal storage can provide potential solution for hot weather cooling issue [ref. 9], and avoid forced shutdown during hot weather.
2. To benefit from the lower electricity charge during night time, the ice thermal storage technology is an essential solution, where part of the electricity consumption during peak hours at mid-day could be shifted to off-peak hours at night [ref. 10]].
3. It can be used to cool building spaces when the main electrical power is blackout.

III. EXPERIMENTAL RIG DESIGN:

An experimental rig was designed and fabricated for this research as shown in the schematic drawing and the experimental construction [figure 1] to represent a small prototype of a simple domestic air conditioning system using ice thermal storage to cool the air for small conditioned space with overall dimension of (3m X 2m X 2.8m height).

The unit has two parts, the first part is the cooling unit and the second is the power supply unit which includes a charger and battery.

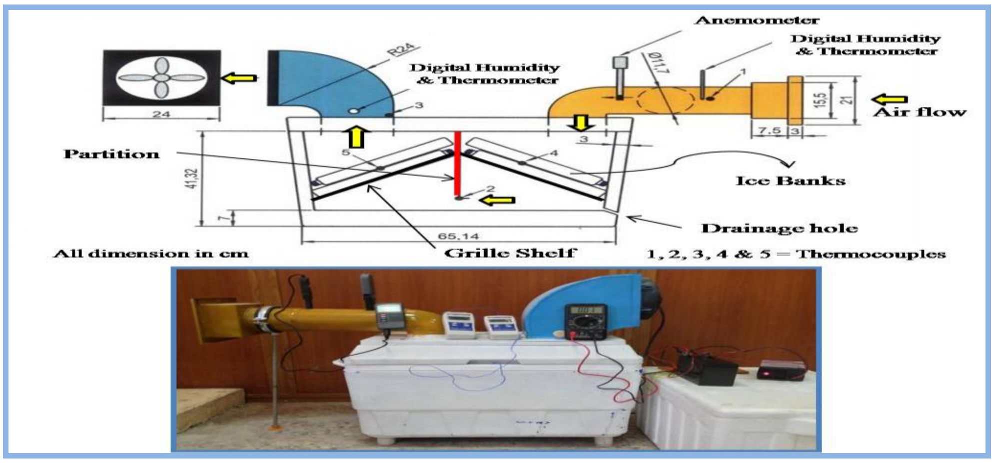

Figure (1): Schematic drawing & the Experimental rig of a simple domestic air conditioning.

The cooling unit:

1. ***The cooling box (container):***

A plastic cold box of (60 X 40 X 50 cm) was designed and fabricated for the experimental study of this research as shown in the schematic drawing [Figure 1]. The box was partially divided into two chambers by using metallic plate (partition) without upper space in order to ensure that the cover is tightly closed to direct the air flow through a longitudinal lower space (passage) of about (50 mm) where the air flows through from the first to the second chamber.

Two grille shelves were placed in oblique position on both sides of the metallic central plate (partition), on each of them a bank of (11) ice contained in a thin sheet plastic bottles of (0.5 liter volume) to avoid direct contact of air with ice were placed and to be modeled as a component of a heat exchanger, these bottles are used to cool the air and reduce its humidity.

An opening draining hole of (12.5 mm) was made in one corner of the box to drain water that accumulates due to vapor condensation.

The box was lifted from ground by four legs, one of these legs is an adjustable leg to ensure that the condensate vapor to be accumulated at the draining hole to complete its draining out of the cooling box.

The box cover was fabricated with two opening on both sides to introduce two ducts, the first duct was made of galvanized plate with one end of rectangular cross section, its opening is square shaped of (240 x 240 mm), in which a fan is placed and fixed by screws at its end [figure 2].

The used fan is a DC motor has a maximum power of (80 Watt) and the working voltage is (12 Volt).

Figure (2): The air outlet duct and the used fan, the air inlet duct.

The second duct was made of plastic pipe (PVC) of (100 mm in diameter) and (600 mm length) ended by another diverging square shaped duct with grill made of galvanized sheet to produce uniform air flow [figure 2].

2. ***Power supply unit:***

This unit consists of two parts:

a) The charger, which converts the electric voltage received from main circuit from (220V AC) to (14V DC) to charge the battery.
b) The battery, it supplies electric power to the fan; the maximum obtained voltage is (14 Volt).

3. ***The measuring instruments:***

The measuring instruments used in this experiment are:

1- Two digital thermometers each of two thermocouple sockets in order to measure temperature in four positions [referring to figure 1]:
- First thermocouple was connected to the first bank of ice bottles (4) which is insulated from the airflow.
- The second thermocouple is connected to the second bank of bottles (5) which is insulated from the airflow.
- The third thermocouple is connected to the central plate (2) to measure the temperature between the two ice banks.
- The fourth thermocouple is connected to the duct at the cold air outlet (3).

2- Humidity meter: is placed in two positions, the first one inside the pipe to measure the RH, temperature (1) and dew point temperature of air entering the unit, the second one inside the duct fan to measure RH and the dew point temperature of the air leaving out the unit.
3- Air flow meter; to measure velocity of the air, it is placed inside the pipe at the air flow entrance.
4- Ammeter and voltmeter to measure the fan power consumed at different air flow passing through the experimental rig.

IV. THEORETICAL ANALYSIS:

To study the thermal energy system, it will consider in this paragraph the performance analysis of conventional domestic air conditioning using the ice thermal storage capacity.

To write down the energy balance for this system, the temperatures and the relative humidity and the dew point temperature of the contained vapor in the air flow were measured at different positions in the system, these positions are:

a) The temperature and the relative humidity at inlet & outlet of air flow into the c box.
b) The air mass flow rate ($\dot{m}$) entering the system.
c) The temperature of air flow between the two Ice banks.
d) The consumed power of the fan by the ammeter and voltmeter.

The calculation can be done to find the required parameters and studying the performance of this system, by using the following formulas relating [ref. 11].

1) The Humidity Ratio:

To measure the humidity ratio of moist air (**ω**) which is the ratio of the mass of water vapor (m_w) to the mass of dry air (m_a).

$$\omega = \frac{m_w}{m_a} = \frac{R_a}{R_w} . \frac{p_w}{p_{at} - p_w}$$

R_a = the gas constant for dry = (0.2871) (J/kg.K)

R_w = the gas constant for water vapor = (0.461) (J/kg.K)

$$\omega = 0.62198 \frac{p_w}{p_{at} - p_w}$$

2) The Air pressure:

To measure the air pressure, the following equation is used:

$$p_a = p_{at} - p_w \qquad \ldots\ldots \; Pa \left(\frac{N}{m^2}\right)$$

$\boldsymbol{p_w}$ = vapor pressure at the dew point temp.

3) The air mass flow rate:

The mass flow rate of the air passing through the system can be calculated by measuring the air volume of the air, which is equal to:

$$\dot{V} = A * v_{air}$$

Where: A = the cross-sectional area of the entrance pipe (m^2)

$$A = \frac{\pi}{4} * D^2{}_{pipe}$$

D_{pipe} = the diameter of entrance pipe (m)

v_{air} = the air velocity inside the entrance pipe (m/s).

The air mass ($\dot{m}$) flow rate then can be calculated by using the following formula:

$$\dot{m} = \rho_m * \dot{V}$$

Where: ρ_m = the air density (mixture of dry air and vapor) …. (kg/m^3)

$$\rho_m = \rho_a + \rho_w$$

$$\rho_a = \frac{P_a}{R_a * T}, \quad \rho_w = \frac{P_w}{R_w * T}$$

ρ_a = the dry air density …. (kg/m^3)

ρ_w = the vapor density …. (kg/m^3)

T = temperature of dry air (^oC)

4) The Enthalpy of Moist air:

The moist air is a mixture of dry air and water vapor, so, the enthalpy of the moist air can be evaluated as:

$$h = h_a + \omega . h_w$$

where: h_a = the enthalpy of dry air (kJ/kg)

h_w = the specific enthalpy of water vapor (kJ/kg)

$$h = h_a + \omega * h_w$$

$$h_a = C_{pa} * T$$

$$h_w = h_{go} + C_{ps} * T$$

Where: h_{go} = specific enthalpy of saturated water vapor at (0 ^oC), its value can be taken as (2500 kJ/kg).

In temperature range of (0 to 60 ^oC), the mean value of the specific heat of dry air (C_{pa}) can be taken as (1.005 kJ/kg.K), and the specific heat of water vapor (C_{ps}) can be taken as (1.88 kJ/kg.K), then the specific enthalpy of moist air (h) is given by:

$$h = 1.005 * T + \omega * (2500 + 1.88 * T) \quad (kJ/kg)$$

5) The Heat Loss by the air:

When a moist air passing through a cooling or heating medium, it will loss or gain heat (Q). That means there is a change in its state of temperature and content of water vapor (a change in the humidity ratio). It can be calculated as:

$$Q = \dot{m} * (h_2 - h_1)$$

Where: h_1 = the enthalpy of inlet moist air (kJ / kg)

h_2 = the enthalpy of outlet moist air (kJ / kg)

Thus, the heat loss of air flow rate passing through a cooling system can be evaluated as:

$$Q = \dot{m}\{1.005 * (T_2 - T_1) + 2500 * (\omega_2 - \omega_1) + 1.88 * (\omega_2 * T_2 - \omega_1 * T_1)\}$$

And to calculate the average of heat removed (Q_{av}) during any time of the cooling cycle, the trapezoidal rule can be used which states below:

$$Q_{av} = \frac{\Delta t}{t_c} \cdot \left(\frac{Q_1 + Q_n}{2} + Q_2 + Q_3 + \dots\dots + Q_{n-1} \right)$$

Where: Δt = the time interval (min)

t_c = the period time of cooling (min)

6) The System Performance:

The system performance of a cooling system is expressed by the ratio of a useful heat gain to work done by the system, it is called as the coefficient of performance (COP), and it can be evaluated as follows:

$$COP = \frac{Q}{W}$$

Where:

COP = coefficient of performance (dimensionless)

W = the work done by the system (kW)

The work done by the domestic air conditioning system in this project is equal to the power consumed by the working fan, and this power is equal to:

$$W = V.I$$

Where:

V = the measured voltage of the power supply (Volt)

I = the measured amperage to working fan (Ampere)

V. RESULTS & DISCUSSION:

The experiment's procedure was carried out to study the performance of the simple domestic air conditioning. The measuring values for the air flow velocity, temperatures, relative humidity, Dew point temperature and the power consumed by the working fan were measured by using ice packed in the bottles with a deep freeze temperature of (- 6 ^oC) for two different air flowrate to make a comparison to study the effect on performance when the flowrate is altered.

Figure (3) shows the temperature variation through the cooling system for two different air flowrate [0.0321 and 0.0229 kg/s] with time for the air inlet temperature (T_1), the air outlet temperature from the first ice bank (T_2) and the air outlet temperature from the second ice bank to the outlet of the system (T_3).

It was noticed from figure (3) that the temperature difference between inlet and outlet temperature is higher for low air flowrate (0.0229 kg/s) than for higher flowrate (0.0321 kg/s) due to more time of contact for the air with the ice blocks and this leads to better heat exchange between the air and ice block.

The figure shows too that the temperature leaving the first ice bank is highly decreased compared to the air temperature leaving the second ice bank. The difference is attributed to the fact that as the temperature difference decreases between the two heat mediums, this caused the transferred heat to be lowered as it is observed that for lower air flowrate ($T_3 – T_2$) is lower than ($T_3 – T_2$) for higher flowrate.

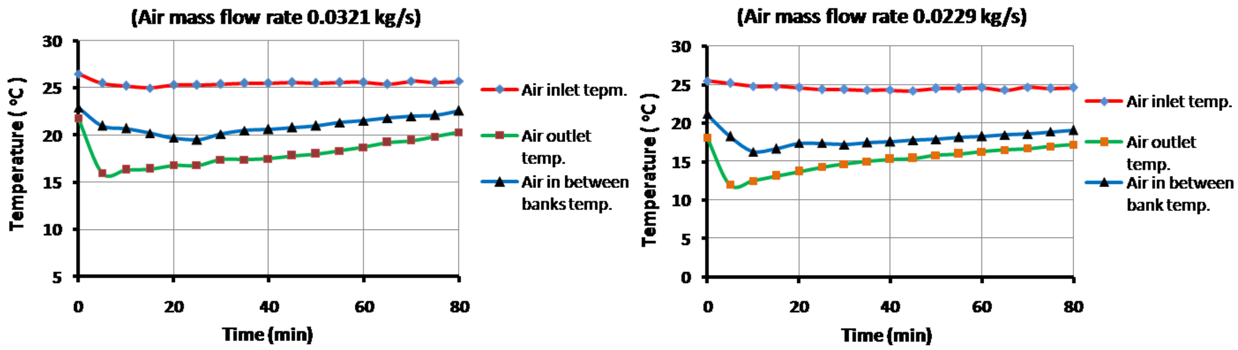

Figure (3): The graph showing the air temperature variation across the cooling system.

Figure (4) shows the vapor content variation of air at inlet and outlet for the cooling system for two different air flowrate, it shows the drop in vapor content with time at outlet as the air passes across the system.
It is observed that more condensation occurs for the lower air flowrate (0.0229 kg/s) than for the higher air flowrate (0.0321 kg/s) due to more time of contact and better heat exchange between the air and ice block. As well, when a lower flowrate is used the heat loss of air is less and ice block will last and need more time to melt.

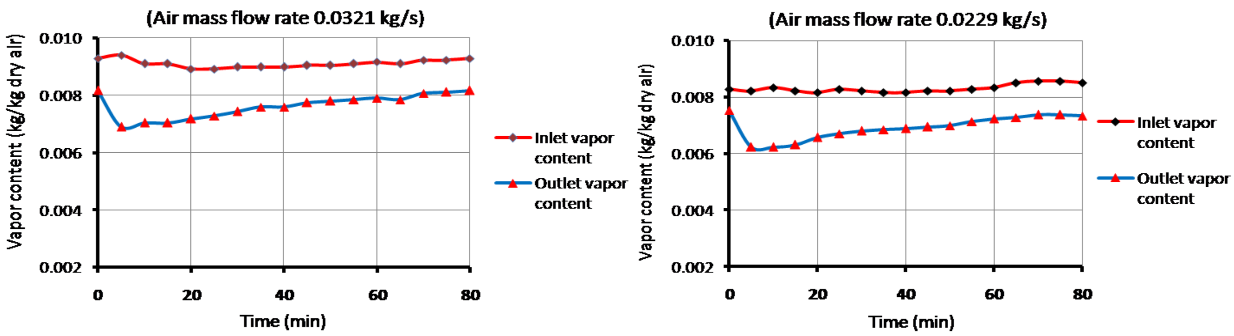

Figure (4): The graph showing the variation of air vapor content across the cooling system.

Figure (5) shows the heat loss of the air flowrate that is passing through the cooling system for the two different air flowrate with time, this heat represents the difference between the heat content of the entering air flow enthalpy (h_1), and the leaving air flow enthalpy (h_2**)** from the outlet of the cooling system.
It is observed from figure (5) that the lost or removed heat from the air moving across the cooling system is decreased with lower air flowrate (0.0229 kg/s) than with higher air flowrate (0.0321 kg/s) because the air flowrate quantity plays as an active factor to dominate the increasing in heat exchange than increasing in temperature difference.

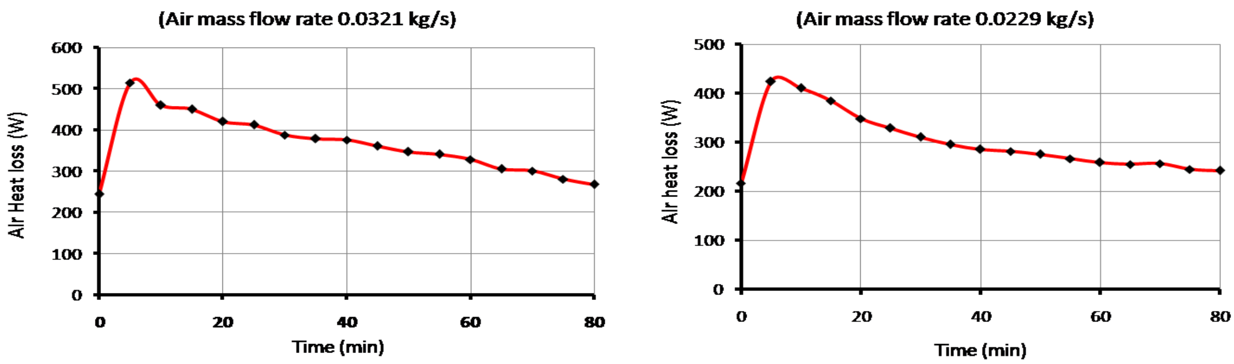

Figure (5): The graph showing the variation of the removed heat from the air with different flowrate.

Figure (5) shows too that the curve for the higher air flowrate (0.0321 kg/s) is steeper than the lower air flowrate which explains that with higher air flowrate the removed heat is faster than lower air flowrate (0.0229 kg/s), on contrary the curve for the lower air flowrate becomes flatter with time which means the heat is gradually removed from the ice pack of both banks.

Figure (6) shows the coefficient of performance (COP) for this cooling system. It is observed from this figure that the COP increases as the air flowrate is decreased; this is because as the air flowrate is decreased the fan consumes less power according to the fan third law.

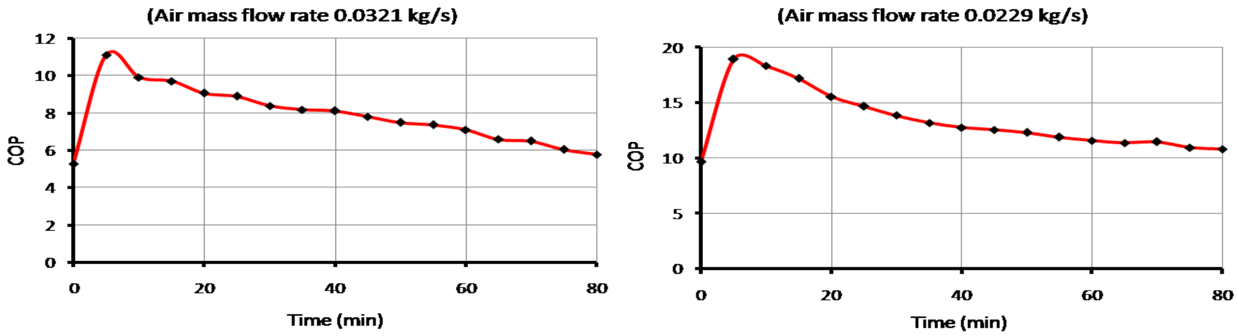

Figure (6): The graph showing the variation of COP of the cooling system with different air flowrate.

Figure (6) shows too that for higher air flowrate (0.0321 kg/s) the obtained COP has a maximum value of about (10) and it goes down with time, but for lower air flowrate (0.0229 kg/s) the obtained COP has a maximum value of about (19) and it goes down with time.

Figure (7) shows the average heat removed from the air with time for two different air flowrate. It is noticed from the figure that the average heat removed from the air is higher with higher air flowrate (0.0321 kg/s) which is approximately around (400 W) at the end of the test compared with lower air flowrate (0.0229 kg/s) which is approximately about (300 W) at the end of the test.

That means with lower air flowrate the ice pack will last and stand for more time to melt, whereas with high air flowrate the ice pack will melt faster but gives better heat removing to meet the heat demand for cooling.

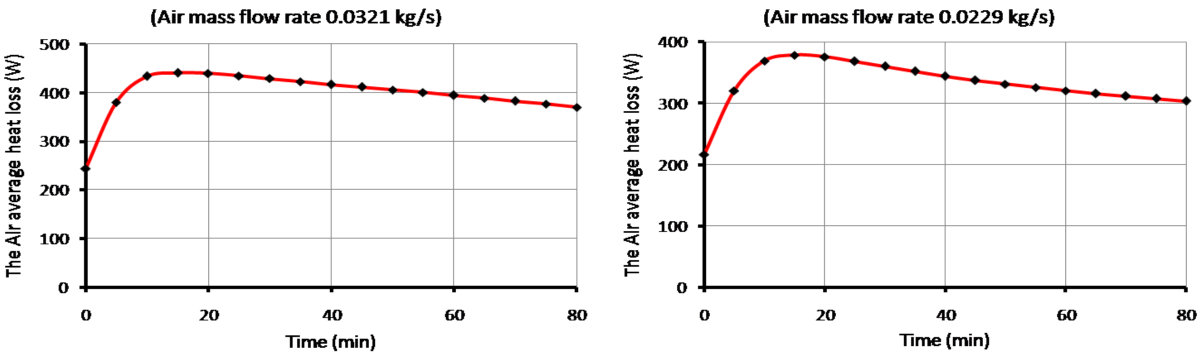

Figure (13): The graph showing the variation of average heat removed from the air with different air flowrate.

VI. THE CONCLUSIONS:

As a conclusion, the results shows that the test carried out on this simple domestic air conditioning is a small prototype to simulate a bigger cooling system shows that using ice thermal storage capacity to decrease the cooling load on the cooling system at the on-peak time and in turn it will decrease the capacity of a cooling system for hot climate which means decreasing the system volume and for cooling a small spaces.

Beside what mentioned above, it will the pollution and global warming by reducing the usage of oil fossil for producing electricity, and to take the benefit of lower charge of electricity at the off-peak time.

It can be used too in developing countries where the electrical power is blackout at programmed time for shutting due to lake in electrical power supplying or at countryside and far away areas.

The COP of such systems will increase when the air flowrate decreases, but the removed heat (Q) will be less and with a lower air outlet temperature, in this case it needs more time to remove or absorb the same heat quantity from the cooling space, this point is open for discussion to balance between getting better COP or to meet the cooling load as fast as possible when using a cooling system using the ice thermal storage capacity.

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