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Water Heating and Drying using Solar Energy and Air-Con Waste Heat

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Abstract

In the tropical countries air-conditioning has become a necessity as the ambient temperature is found to be high. In Malaysia most of the apartments are air-conditioned, at least one room. Every KW of electricity which is consumed by the air-conditioner, about 4KW is thrown into the atmosphere. The energy available at the inlet of the condenser is about 80 degree Celsius and can be utilized for useful purposes. The waste heat from the air-conditioner is used for water heating and drying purposes. A water condenser is attached at the exit of the compressor which will absorb most of the superheat and latent heat. A dryer is connected at the exit of the air-condenser so that it can supply clean hot air for drying. Even a recovery of 60% of this waste energy can heat 200 liters of water up to 60 degree Celsius. This system reduces global warming and is quite efficient to be used for domestic and industrial purposes.

Keywords: *Air conditioning, Waste heat recovery, Water heating, Drying, Solar Energy*

1. Introduction

Air conditioning of buildings is essential for countries which are located in the tropical region, particularly those countries which are closer to equator, such as Malaysia and Singapore, where the daily average temperature can be as high as 27.8 degree Celsius [1, 2]. In Malaysia the residential sector is usually made up of 61% linked houses (62% are air-conditioned), 27% apartments (36% are air-conditioned) and 12% detached houses (more than 70% are air-conditioned) [3]. Most of these houses are in need of water heater and cloth dryer. The dissipated heat which is released from the condenser contributes to global warming and also in an effort to reduce the usage of the conventional energy resources, a system was developed to use renewable energy resources (both solar and ambient energy) and air con waste heat for low temperature application. Air-conditioning, water and air heating form an excellent combination, where the air con waste heat will be sufficiently utilized and the solar and the ambient heat can boost it up further depending on the requirements. An evaporator collector, instead of conventional solar liquid or air collector will be used because as it can collect more solar and ambient energy, and with regarding to this even the operating temperature of the evaporator collector will be much lower than the ambient temperature. The collectors will operate at high efficiency, as high as 80 to 85% as the heat losses from the evaporator collector will be very low. The efficiency of the conventional collector is about 60%.

2. The System

The system is the integrated solar assisted heat pump system for water heating and drying. The system’s schematic diagram is illustrated by Figure 1.

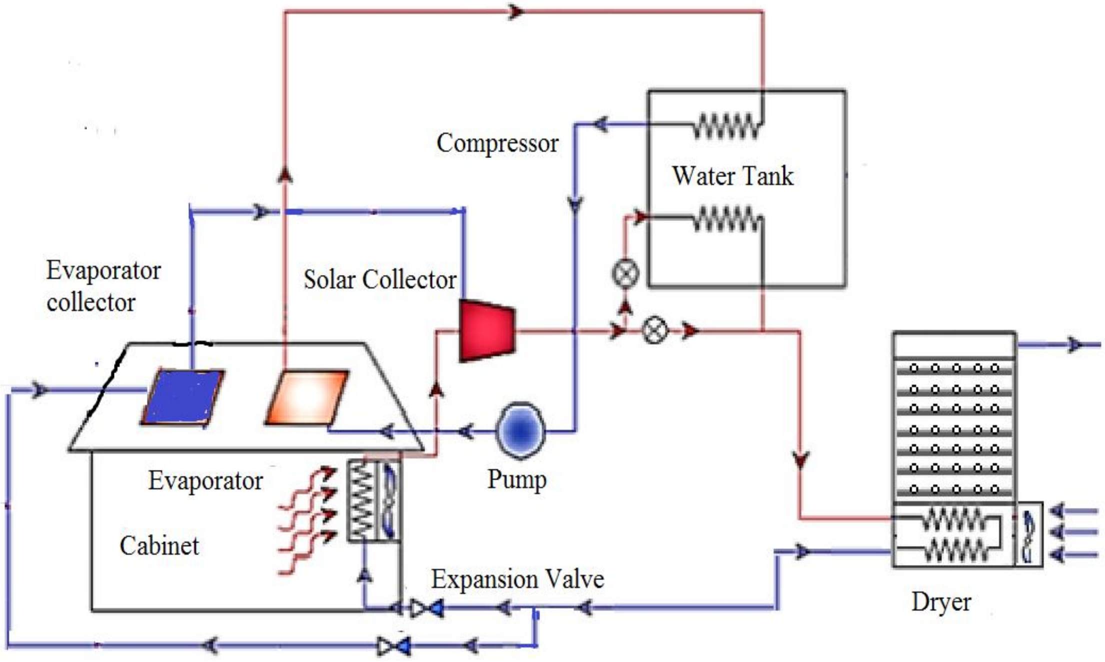

Figure1: Solar assisted heat pump system for water heating and drying

In this system, refrigerant will enter the compressor as saturated or slightly superheated vapor at a lower pressure of the overall cycle. At the compressor, due to energy input, pressure is raised to a higher level and the refrigerant will become superheated. Gradually, the refrigerant will pass through the condenser, where it will reject heat and it will ideally become saturated or slightly sub-cooled liquid. The refrigerant will then be throttled in an expansion valve to an evaporator maintained at a lower pressure of the cycle. The low quality two phase mixtures of the refrigerant in the evaporator will absorb the heat from the surroundings before it will enter the compressor and the cycle will be repeated.

The refrigerant flow path of the system will include the compressor, evaporator, solar evaporator collector, solar water collector, water cooled condenser, air cooled condenser and the expansion valves. The two evaporators will be connected in parallel, whereas the two condensers will be connected in series. After complete condensation, liquid refrigerant will split into two ways. Each of them will expand into a flow regulating device, thermostatic expansion valve, reaching the evaporator in the room and the evaporator collector which is located outside for the collection of the solar and ambient energy.

In the solar evaporator-collector, the two phase refrigerant will flow through the serpentine copper tubeswhich is brazed underneath the absorber plate. It is heated by incident solar radiation and the energy will be absorbed from the ambient air through an absorber plate. The refrigerant super heat level at the evaporator-collector outlet will also be automatically controlled by the thermostatic expansion valve.

Then the refrigerants, which will be arriving from the solar evaporator collector and the room evaporator, will be mixed together and will enter the suction side of the compressor. At this point of the cycle, electrical/mechanical energy will be added to the refrigerant to increase its temperature and the pressure. The high pressure and temperature refrigerant vapor from the compressor outlet will first enter the coil which is immersed in the water of the condenser tank and then passes through the air-cooled condenser. The heat of condensation from the superheated refrigerant vapor is recovered both in air and water-cooled condensers, which otherwise would have been wasted in the normal circumstances. The saturated/sub-cooled liquid refrigerant will split into two paths and will enter the evaporator in the room and the outdoor solar evaporator collector, and the cycle repeats.

3. Analytical Model

The system includes: compressor, Condenser (air condenser and water condenser), expansion valve, solar water collector, evaporator/ room and dryer.

3.1 Air/ Water Condenser

In the air and water cooled condensers the, heat transfer was evaluated by the following equations [5]:

$$Q_r = m_r\,(h_2 - h_1) \tag{1}$$

where,

m_r = mass flow rate of refrigerant, kg/s
h_1 = enthalpy of refrigerant at the inlet to the condenser, kJ/kg
h_2 = enthalpy of refrigerant at the outlet to the condenser, kJ/kg

Effectiveness of the condenser, $\varepsilon_{cond} = 1 - \exp(-NTU)$ (2)

where NTU (number of thermal units) of condenser is given by

$$NTU = (UA)_{cond} / (mc_p)_{min} \tag{3}$$

The temperature variation inside the water storage tank is described by:

$$(Mc_p)\,\frac{dT_s}{dt} = Q_C - Q_L - Q_{loss} \tag{4}$$

where,

M = Mass of water in store
Q_C = heat received by the condenser
Q_L = Energy withdrawal from store to support load
Q_{loss}= Heat losses from the store

3.2 Drying Rate

The variation of moisture content of the drying rate is given by the following equation [6]:

$$\frac{dM}{dt} = -k(M - M_e) \tag{5}$$

where,

M = product moisture content
M_e = equilibrium moisture content
t = time

The drying constant, k , is expressed by the Arrhenius equation [7]

$$k = d\exp(-f/T) \tag{8}$$

3.3 Compressor Work

To drive the reciprocating compressor, the work input required is given by the following equation:

$$W_c = P_1 V_1 m_r \left(\frac{n}{n-1}\right)\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right] \tag{9}$$

where,

P_1 and P_2 are compressor suction and discharge pressure;
V_1 corresponding suction volume and m_r represents refrigerant mass.

3.4 Evaporator Room

The room evaporator usually serves a dual purpose in making the room comfortable for use. Firstly, it brings down the room temperature to a cool and comfortable condition, and secondly, it removes humidity from the room. This means that a combined heat and mass transfer, where both sensible and latent heat transfer, takes place in the direct expansion coil of the room evaporator.

The rate of sensible heat removal from the room is based on the temperature difference as follows:

$$dq_s = h_c A_{evap,r}(T_a - T_{sur}) \tag{10}$$

The rate of latent heat removal from the room is based on the rate of condensation, which is based humidity ratio difference as follows:

$$dq_l = \dot{m}_w h_{fg} \tag{11}$$

Where the rate of condensation is

$$\dot{m}_w = h_D A_{evap,r}(\omega_a - \omega_{sur}) \tag{12}$$

And h_D, which is the mass convection coefficient, is approximated for water vapour as :

$$h_D = \frac{h_c}{C_{p,m}} \tag{13}$$

The total heat gain by the evaporator is the sum of the sensible and latent heat, which is calculated as

$$dq_t = dq_s + dq_l = \frac{h_c A_{evap,r}}{C_{p,m}}(h_a - h_{sur}) \tag{14}$$

The heat gain from the refrigerant is determined from the enthalpy difference of the refrigerant as follows:

$$Q_r = \dot{m}_{r,room}(h_{outlet} - h_{inlet}) \tag{15}$$

Assuming negligible losses, the energy balance for the air condenser is

$$\dot{m}_{r,room}(h_{outlet} - h_{inlet}) = \frac{h_c A_{evap,r}}{C_{p,m}}(h_a - h_{sur}) \tag{16}$$

3.5 Expansion Valve

Both evaporator and evaporator/collector are fitted with individual thermostatic expansion valves. The thermostatic expansion valve is responsible for maintaining constant degree of superheat at the evaporator outlet. For the modelling of the expansion valve isenthalpic expansion process is assumed.

The expansion process is assumed to be isenthalpic, therefore

$$h_{f,i} = h_{f,o} \tag{17}$$

Assuming the capacity of the expansion valve is large enough, the mass flow rate shall be calculated using:

$$M_r = (PD)N\,\eta_v / V_a \tag{18}$$

3.6 Solar water collector

The liquid solar collector used to preheat the feed water has a single glazing, with an aluminium plate as the absorber. The collector is of parallel tube-type, with seven riser tubes positioned in parallel with the collector's length.

The useful energy absorbed by the water, in terms of its inlet and outlet temperature is expressed as:

$$Q_u = \dot{m}_w c_{p,w} (T_{w,out} - T_{w,in}) \tag{19}$$

The useful energy delivered from the collector to the water can be expressed through the Hottel-Willier equation :

$$Q_u = F_R A_C \left[I(\tau\alpha) - U_L (T_{in} - T_a) \right] \tag{20}$$

Overall heat loss coefficient, $U_{L,}$ of the collector is a function of the top, bottom, and edge losses.

$$U_L = U_T + U_B \tag{21}$$

The top loss coefficient, $U_{T,}$ can be expressed as:

$$U_T = \left\{ \frac{N}{\dfrac{C}{T_p}\left[\dfrac{T_p - T_a}{(N+f)}\right]^{e}} + \frac{1}{h_w} \right\}^{-1} + \frac{\sigma(T_p + T_a)(T_p^2 + T_a^2)}{(\varepsilon_p + 0.00591 N h_w)^{-1} + \dfrac{2N + f - 1 + 0.133\varepsilon_p}{\varepsilon_g} - N} \tag{22}$$

Where N is the number of glass covers. Several other correlations were simplified to fit the equation (4.107). These are:

$$f = (1 + 0.089 h_w - 0.1166 h_w \varepsilon_p)(1 + 0.07866 N) \tag{23}$$

$$e = 0.43(1 - 100/T_p) \tag{24}$$

$$C = 520(1 - 0.000051\beta^2) \tag{25}$$

For 0° $<\beta<$ 70°. For 70° $<\beta<$ 90°, use $\beta = 70°$

The bottom loss coefficient, $U_{B,}$ is defined as:

$$U_B = \frac{k}{t} \tag{26}$$

With *k* is the thermal conductivity of the insulation material, and *t* is the insulation's thickness.

The collector heat removal factor, $F_{R,}$ is a quantity that relates actual useful energy gain of a collector to the useful gain if the collector surface is at liquid inlet temperature.

$$F_R = \frac{\dot{m}c_p}{A_c U_L}\left(1-e^{-(A_c U_L F'/\dot{m}c_p)}\right) \tag{27}$$

With F' is the collector efficiency factor:

$$F' = \frac{\dfrac{1}{U_L}}{W\left[\dfrac{1}{U_L\left[D_o+(W-D_o)F\right]}+\dfrac{1}{C_b}+\dfrac{1}{\pi D_i h_{f,i}}\right]} \tag{28}$$

The fluid heat transfer coefficient, for single phase condition, is determined from Dittus-Boelter equation:

$$h_{f,i} = 0.83\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.33}\frac{k_f}{D_i} \tag{29}$$

And C_b is the bond conductivity:

$$C_b = \frac{k_b b}{\gamma} \tag{30}$$

With k_b is the bond thermal conductivity, b is the bond's width, and γ is the bond average thickness.

The function F in the equation 28 is the standard efficiency and it is described as

$$F = \frac{\tanh\left[m(W-D_o)/2\right]}{m(W-D_o)/2} \tag{31}$$

4. Results and Discussion:

a) **Water Heating**

The experiment was conducted to heat the water inside the hot storage tank and seven different cases were conducted to heat the water. The case 1 consists of the air conditioner and water collector, case 2 consists of the water collector only, case 3 consists of the air-conditioner only, case 4 consists of the air-conditioner, water collector and the refrigerant collector, and the case 5 consists of the whole integrated system, case 6 consists of only refrigerant collector and case 7 consists of the water collector and the refrigerant collector. From the figures 2a and 2b we can see that the maximum water temperature achieved was 60.8 degree Celsius for case 5 which was followed by case 2 followed by case 3, case 4, case 6, case 7 and finally case 1. It is seen that temperature of water for case 5 which consists of the whole integrated system is lower than the temperature of water achieved by case 7.

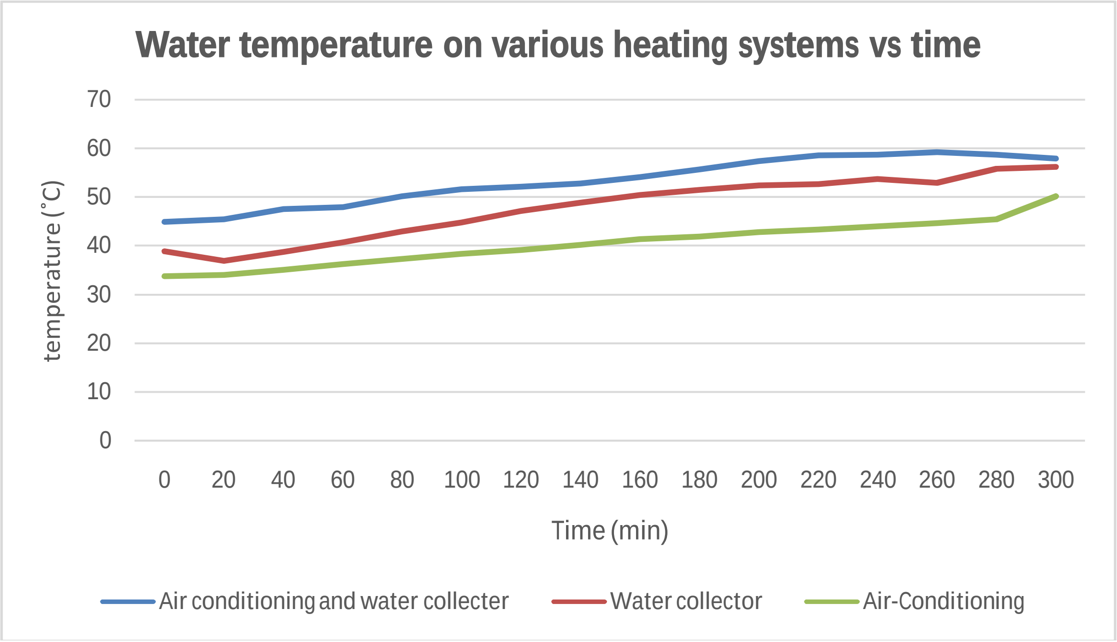

Figure 2a: General findings of water temperature at different experimental setup

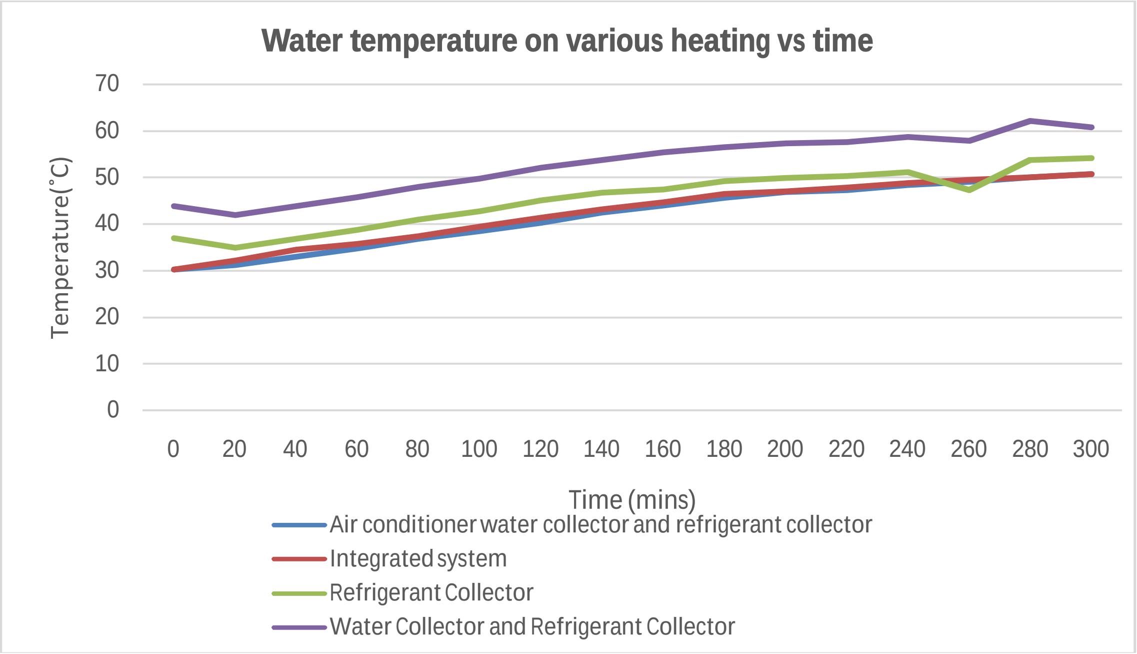

Figure 2b: General findings of water temperature at different experimental setup

b) **Drying**

Different experiments were conducted for drying the cloth to measure the drying time which is required for the cloth to dry. The experiment was conducted for 5 hours. The initial weight of the cloth when dry was 95.5 g while the initial weight of the cloth when wet was found to be 300 g.

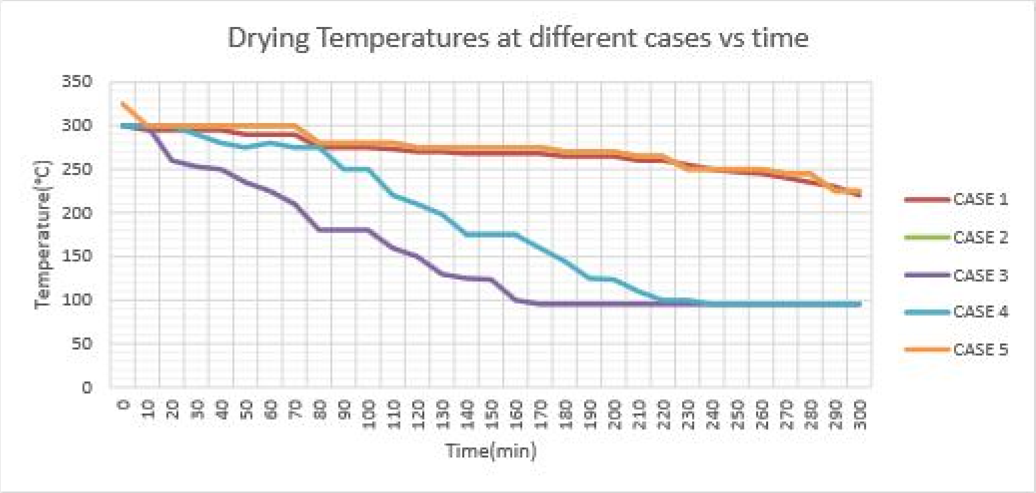

Figure 3: Drying time at different experimental setup

Different cases conducted for the drying of the cloth are as follows: Case 1 consists of the indoor drying, case 2 which consists of outdoor drying, case 3 which consists of air-conditioner with water heating, case 4 consists of air-conditioner with refrigerant panel and finally case 5 which consists of air-conditioner without water heating. Case 1 was done by placing the drying chamber inside the room without blowing the air towards the cloth and for case 2, the drying chamber was placed under the sun radiation for 5 hours. For case 3, case 4 and case 5, hot air is blowed from the condenser fan into an air vent connected to the drying chamber. From Figure 3, we see that drying time for case 4 should have been lesser when compared to case 3, but the result was inversed. This was because the humidity of the ambient was little higher during the experiment for case 3 when compared to the humidity during the case 4. As the ambient becomes more humid the ambient temperature will be colder so the evaporating molecules in the wet cloth will be smaller. On contrary, the climate during the experiment for case 4 was cloudy and little rainy where the rain droplets fall on the cloth for every ten minute interval of time.

5. Conclusion:

This research has been developed to utilize the waste heat from the air-conditioner which can save the energy wasted from being thrown away to the environment. Air-conditioner rejects 4KW heat to the surroundings which is more than enough to provide thermal applications. Several experiments were done in different cases to observe the outcome of the system. The objective was claimed and this system is marketable especially in countries which are near the equator.

6. References:

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