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Experimental & Investigation of Atmospheric Water Generation by using Vapour Compression system with Subcooling

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Abstract

Water is one of the basic necessities in life and its preservation is essential. People in countries like India face the problem of drinking water shortage particularly in summer usually or in the areas where rainfall is very less. Hence to get fresh water many sources are available one of which the moisture in the air. Air as a source of water is renewable and clean and amount of water in atmospheric air is evaluated as 14000 cubic Kilometer, and the amount of fresh water in the earth is only about 1200 cubic kilometer. The extraction of water from atmospheric air can be done by different methods the most easy method is cooling moist air to a temperature lower than air dew point temperature. The cooling systems used commonly are Vapor compression System or Vapor Absorption System of refrigeration, as vapor compression system is more effective and reliable to cool air. Part of cooled air from evaporator can be used to sub-cool the refrigerant in condenser which can increase COP of the system. Remaining air from the evaporator can be used to condition the space. Increased COP will reduce the efforts of the compressor so that running cost of system will be low.

Keywords:*EWG, VCC, Sub-cooling, Dehumidification, Water cooled condenser, R134a.*

1. Introduction

Because of pure water scarcity in many regions worldwide, finding alternative methods for pure water generation becomes beneficial enough to motivate many researchers to work on related topics. Evaporative cooling generation is one of the promising methods for getting pure water. The concept of extracting water vapour from the surrounding air has been applied in Evaporative cooling water generators (EWGs). There are two popular types of AWGs: Cooling condensation type and Wet desiccation type. A cooling condensation type EWG applies the vapour compression refrigeration cycle and a fan which moves the filtered air over the evaporator coil. The temperature of air is lowered below its dew point and the water vapour in the air condenses. This type of EWGs produce drinking quality water and they require moist air and electricity. A wet desiccation type EWG uses a concentrated brine solution to absorb the water vapour in the air. The absorbed water is extracted from the solution and purified. Hence tis paper focuses on the following **objectives,1. To achieve Atmospheric Water Generation by using Vapor Compression System this is more efficient refrigeration system. 2. Increase the performance of system by sub-cooling of refrigerant in condenser. 3. Use of the air from the evaporator for cooling or conditioning.**This paper focuses on a cooling condensation type EWG which uses electricity to drive the compressor.

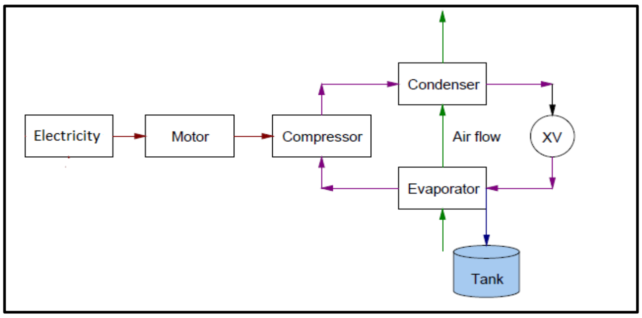

Fig.1 Schematic Diagram of EWG Using Electricity

In this we have done the literature survey and the survey is written as follow, Abdulghani A. Al-Farayedhi and all, (2014) worked on “Condensate as a water source from vapor compression systems in hot and humid regions” in this paper, analytical and experimental investigations in determining the condensate from a vapor compression air conditioning system as an additional water source are presented.The condensate is dominantly affected by the air humidity and temperature. The analytical model predictions of the condensate correlate well with the experimental data with a correlation factor of more than 90% [1].Magrini A. and all, (2015), worked on “Integrated systems for air conditioning and production of drinking water – Preliminary considerations” in this paper preliminary investigation on a design of an integrated HVAC system for the air conditioning of a hotel combined with water production is presented. The calculations are referred to the climatic conditions of the Arab Emirates coast. The preliminary calculations show that the produced water could be efficiently used for various destinations and, in some cases, its treatment could be finalized to produce drinking water [2].Ahmed M. Hamed and all, (2010), worked on “A technical review on the extraction of water from atmospheric air in arid zones” the technology of water extraction from atmospheric air is still at an early stage compared with other systems such as water distillation. However, if the experience of the studies carried out in desiccant cooling is applied in this area, improved and more efficient units could be designed. Also, rapid development of appropriate and reliable systems for water recovery from atmospheric air could be facilitated by adapting financial investment and using friendly energy sources. Collecting dew is still a viable option to get water from air, however, the application of dew collection is restricted by the availability of dew [3]. S.A. Nada and all, (2015), worked on "Performance analysis of proposed hybrid air conditioning and humidification–dehumidification systems for energy saving and water production in hot and dry climatic regions", the proposed systems aim to energy saving and systems utilization in fresh water production. The results show that (i) the fresh water production rates of the proposed systems increase with increasing fresh air ratio, supply air temperature and outdoor wet bulb temperature, (ii) powers saving of the proposed systems increase with increasing fresh air ratio and supply air temperature and decreasing of the outdoor air wet bulb temperature, (iii) locating the evaporative cooling after the fresh air mixing remarkably increases water production rate, and (vi) incorporating heat recovery in the air conditioning systems with evaporative cooling may adversely affect both of the water production rate and the total cost saving of the system [4]. Gustavo Pottker and PegaHrnjak, (2014), worked on " Effect of the condenser subcooling on the performance of vapor compression systems", this paper presents a theoretical study about the effect of condenser subcooling on the performance of vapor-compression systems. It is shown that, as condenser subcooling increases, the COP reaches a maximum as a result of a trade-off between increasing refrigerating effect and specific compression work [5]. Xiaohui She and all, (2014), worked on "A proposed subcooling method for vapor compression refrigeration cycle based on expansion power recovery", this study proposes a new subcooling method for vapor compression refrigeration cycle based on expansion power recovery. In a main refrigeration cycle, expander output power is employed to drive a compressor of the auxiliary subcooling cycle, and refrigerant at theoutlet of condenser is subcooled by the evaporative cooler, which makes the hybrid system get much higher COP [6]. Justin P. Koeln, (2014), worked on "Optimal subcooling in vapor compression systems via extremum seeking control: Theory and experiments". In this paper, an alternative system architecture, which utilizes a receiver and an additional electronic expansion valve, is used to provide independent control of condenser subcooling. Simulation and experimental results show there exists an optimal subcooling which maximizes system efficiency; however, this optimal subcooling changes with operating conditions. Therefore, extremum seeking control is implemented to find the optimal subcooling in an adaptive, model-free manner. Experimental results demonstrate a 9% increase in efficiency using the alternative architecture and extremum seeking control [7].

2. Design of system.

Design and Selection of Components: At DBT=260 C& RH= 46% [9]. We get dew point temperature =13.49^{0}C. Specific humidity = 0.012 kg of water/kg of dry air.

Table 1 Calculation for amount of dry air.

$$\textbf{Specific humidity} = \frac{\textbf{Amount of water present in air}}{\textbf{1 kg of dry air}}$$

By taking references from Research papers,[9]

Water present in air	Water extracted	Dry air
0.0012 kg	0.0048 kg	1 kg
5 kg	2 kg	518.13 kg

Extraction efficiency = 40%

Water to be extracted = 2 liter.

For 2 liters of water extraction we require 5 kg of water to be present in air.

For this 518.13 kg of air is required

Q_{air}= 518.13/1.77 = 440.21/(24 x 60 x60) = 5.09 x 10^{-3} m^3/sec.

2.1 Evaporator design

Q_{air}= Face area x Velocity of air

5.09 x 10^{-3} = Face area x 0.1

Average velocity of air measured inside room using Anemometer = 0.1 m/sec, Face area = 0.0509 m^2. Evaporator of such area available in market is [23 x 23] cm^2 fin and tubetype evaporator. Thus face area of evaporator = 0.0529 m^2.

2.2Compressor selection

Refrigeration effect/ cooling capacity

= $m_a C_p dT + m_w . L$ (1)

$$= \frac{518.13 \times 1.005 \times (26-17)}{24 \times 60 \times 60} + \frac{2 \times 2260}{24 \times 60 \times 60}$$

= 106.49 W

From LG compressor catalogue it is seen that for Coolingcapacity of 106.5 W Compressor with cooling capacity of 107W is available [10].Model of compressors having above specified coolingcapacity are :-MA42LFJM, MA42LJJG, MA42LMJG MA42LHJM. Out of above any compressor can be selected. We select MA42LPJG which is easily available and has identical specification as of above.

2.3 Condenser design

Here we have selected water sub cooled condenser for minimizing size and to increase the performance.

h_0 = convective heat transfer coefficient outside tube

hi = convective heat transfer coefficient inside tube

U = Overall heat transfer coefficient of condenser
Nusselt number [8]

$$Nu = \frac{h_0 Lc}{K} \qquad (2)$$

Lc = Characteristic length = Mean hydraulic diameter = D = 6.35 mm
K = Thermal conductivity of water

$$\overline{\mathrm{Nu}}_L = 0.68 + \frac{0.67\,\mathrm{Ra}_L^{1/4}}{\left[1+(0.492/\mathrm{Pr})^{9/16}\right]^{4/9}} \qquad (3)$$

Ra = Gr x P

$$Gr = \frac{D^3 x \varrho^2 x g x \Delta T \; x \; \beta}{\mu^2} \qquad (4)$$

It is assumed that water enters at 28^0C and is heated up to 58^0C.
ΔT = To – Ti
To = outlet temperature of water = 58^0 C
Ti = inlet temperature of water = 28^0 C
ΔT = 58 – 28 = 30^0 C
β = 1/Tavg (5)
Tavg= (58+28)/2 = 43^0 C (6)
Tavg = 43 + 273 = 316 K
$\beta = 1/316 = 3.164 \times 10^{-3}\ K^{-1}$
From property table,

Table 2 Variation of Dynamic Viscosity against Temperature

Temperature	(μ) Dynamic viscosity
28^0 C	0.8324×10^{-3}
58^0 C	0.466×10^{-3}

$\mu avg = 0.6492 \times 10^{-3}$
Substituting above values in equation (4),

$$Gr = \frac{D^3 \; x \; \varrho^2 \; x \; g \; x \; \Delta T \; x \; \beta}{\mu^2}$$

$$= \frac{(6.35 \; x \; 10^{-3})^3 \; x \; (1000)^2 \; x \; 9.81 \; x \; 30 \; x \; 3.164 \; x \; 10^{-3}}{(0.6492 \; x \; 10\text{-}3)^2}$$

= 565,706.13
From property table,

Table 3 Prandtl Number

Temperature	Prandtl number
28^0 C	2.9175
58^0 C	5.3605

Pravg = 4.139
Ra = Gr x Pr (7)
= 565,706.13 x 4.139
= 2.3414 x 106
Substituting above values in equation (3)

$$\overline{\mathrm{Nu}}_L = 0.68 + \frac{0.67\,\mathrm{Ra}_L^{1/4}}{\left[1+(0.492/\mathrm{Pr})^{9/16}\right]^{4/9}}$$

Nu = 22.122
We have equation (2),

$$Nu = \frac{h_0 Lc}{K}$$

From property table,

Table 4 Thermal Conductivity [11]

Temperature	Thermal conductivity of water
28^0 C	0.6166
58^0 C	0.65215

K_{avg}= 0.6343 W/m.K
Substituting in equation (2),

$$Nu = \frac{h_0 L_c}{K}$$

We get, h_0= 2210 W/m^2.K

From specification table
Temp of condenser = 45^0C
Outlet to compressor = 70^0C
Inlet to compressor = 12^0C
Suction pressure = 0.5 bar
Discharge pressure = 13 bar

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- From P-h chart,

h1 = 610 kJ/kg, h4 = 475 kJ/kg

Cooling capacity =$m_r(h_1\text{-}h_4)$ 107 x 10^{-3} (8)
0.1457 = m_r(610-475) 107 x 10^{-3}
(from LG electronics)

m_r= 7.9 x 10^{-4} kg/sec

$$Q = m_r/\varrho = \frac{7.925 \; x \; 10^{-4}}{1169.5} = 6.77 \; x \; 10^{-9} \qquad (9)$$

From property table of R134a at 45 ^{0} C
ϱ = Density of refrigerant in liquid state = 1169.5 kg/m^3
μ= Dynamic Viscosity = 175.55 x 10 $^{-6}$Pa.s
ὐ = 0.15 x 10^{-6} m^2/sec
C_p = 0.7255
K = 78.995 x 10^{-3} W/m.K
Q = A x V (10)

$$6.77 \; x \; 10^{-9} = \frac{\pi \; (5 \; x \; 10^{-3})^2}{4} \; x \; Velocity$$

Velocity = 3.447 x 10^{-4} m/sec. We have,

$$\text{Reynolds number (Re)} = \frac{\varrho \; V \; D}{\mu}$$

$$= \frac{1169.5 \; x \; 3.447 \; x \; 10^{-4} \; x \; 5 \; x \; 10^{-3}}{175.55 \; x \; 10^{-6}}$$

= 11.49 < 2000 Therefore flow is laminar ,
For laminar flow,
Pr = 3.1, Nu = 4.363

$$Nu = \frac{h_i L_c}{K}$$

$$4.364 = \frac{h_i \; x \; 5 \; x \; 10^{-3}}{78.995 \; x \; 10^{-3}}$$

$(h_i)_{liquid =}$ 68.9 W/m^2 K
m_r= 7.9 x 10^{-4} kg/sec

$Q = m_r/\varrho = \frac{7.925 \times 10^{-4}}{5.28} = 1.5 \times 10^{-4}$

From property table of R134a at 45 ^{0}C

ϱ = Density of refrigerant in vapour state = 5.28 kg/m^3

μ= Dynamic Viscosity = 12.6 x 10 $^{-6}$Pa.s

C_p = 886 J/Kg K

K = 0.015 W/m.K

Q = A x V

$6.77 \times 10^{-9} = \frac{\pi (5 \times 10^{-3})^2}{4} \times$ Velocity

Velocity = 7.6m/sec.

We have,

$$\text{Reynolds number (Re)} = \frac{\varrho V D}{\mu} \quad (11)$$

$$= \frac{5.28 \times 7.6 \times 5 \times 10^{-3}}{12.6 \times 10^{-6}} = 15923.8 > 2000$$

Therefore flow is turbulent,

For turbulent flow,

Pr = 0.744

$$Nu = 0.023\ Re^{4/5}\ Pr^{0.3} \quad (12)$$

$= 0.023\ (15923.8)^{4/5}\ (0.744)^{0.3} = 48.39$

Also equation (2),

$$Nu = \frac{h_i L_c}{K}$$

$$48.39 = \frac{h_i \times 5 \times 10^{-3}}{0.015}$$

$(h_i)_{gas}$ =145.19 W/m^2 K

$(h_i)_{average}$ = (68.9 + 145.19)/2

= 107.045 W/m^2 K

We have,

$$1/U = 1/h_i + 1/h_0, \quad (13)$$

U = 102.099 W/m^2 K

Tank/shell dimensions is taken as 25.5 x 25.5 x 30 (L x B x H in cm); Consider water is filled up to 22 cm height, thus mass of water,

$$Mw = \varrho \times \text{Volume} \quad (14)$$

$= 1000 \times (25.5 \times 25.5 \times 22) \times (10^{-2})^3$

= 14.3055 kg

This 14.3055 kg of water is heated for one hour for temperature rise of 28 to 58^{0}C

We know that

Heat absorbed by water = Heat rejected by refrigerant

$$M_w \times C_{pw} \times (T_2\text{-}T_1) = U\ A\ \Delta T \quad (15)$$

$$\frac{14.3055 \times 4.18 \times 10^3 \times (58\text{-}35)}{3600} = 102.099 \times A \times (70\text{-}45)$$

A = 0.14 m^2

Hence a condenser coil of about 0.14 m^2 is manufactured

d = 6.35 x 10^{-3} m

Deciding the length and turns of coil

A= 0.14 m^2

0.14 = π d L

Therefore L = 7.0 mConsider coil diameter D = 22cm

π D x N = L

N = 10 , For condenser,

O.D of tube (d_0) = 6.35 x 10^{-3} m

I.D of tube (d_i) = 3.64 x 10^{-3} m

Coil diameter D = 22 cm

N = Number of turns = 10, Length of coil = 7.0 m.

3. Results of Design of System

From the above design calculations we have selected the standard components as a result of Vapor Compression system available easily in market whose specifications nearly approaches the calculated values in section 2 for the ease of experimentation.The following components of the Vapor Compression system as a result which are tabulated below,

3.1Compressor

Table 5- Selection on the base of designofCompressor

Product	Compressor
Model	MA42LPJG- Hermatically sealed.
Net weight	8.1 kg
Input wattage	96W
Voltage/Frequency	220V/50HZ,1PH
Manufactured By	LG Electronics India Pvt. Ltd.
Cooling Capacity(HP)	1/7
EER(Btu/W.h)	3.8
Suction pressure	0.5bar
Discharge pressure	12-14bar

3.2 Evaporator

Table 6- Selection on the base of design of Evaporator

	Evaporator
Type	Fin and tube type
Tube material	Copper
Tube diameter (OD)	3/8”
Overall dimensions in cm(Lx H x D)	23 x 24 x 9.5
Tube arrangement	Non-staggered
Type of fin	Plate type
Fin material	Aluminum
Number of fins/inch	9
Face area (L x H) sq.cm	23 x 24
Number of rows	2
Number of tubes	9

3.3 Expansion Valve

Table 7 Selection on the base of design of Expansion Valve [9]

Product	Expansion device
Type of Expansion device	Constant restriction type- Capillary tube
Capillary length	1.59m
Capillary diameter(ID)	0.80mm
Capillarymateria	Copper

3.4 Condenser

Table 8 Selection on the base of design of Condenser (Water Cooled Condenser)

Product	**Condenser**
Type	Shell and coil
Shell material	Stainless steel
Shell Dimensions (L x B x H) in cm	25.5 x 25.5 x 30
Coolant in shell	Water
Tube material	Copper
Tube diameter (OD)	1/4”
Coil diameter	22cm
Number of turns of coil	9

4. Results of experimentation

Experiment was conducted for the entire month of January 2017. Reading of the water collected for every hour from 7:00 hour to 21:00 hour was noted. The volume collected of water from air by system is tabulated in Table no. 9 as shown below.The experimental and analytical hourly rates of condensate extraction for typical dry days of January summarized in Table 9. It is observed that the condensate yield is more during the morning, then falls down in afternoon and again increases in evening. It is also observed that the maximum hourly condensate yield occurs during 7.00 AM with a value of 241.25 ml during the morning (7:00–8:00 AM). On the other hand, the minimum hourly condensate yield occurs during the day time with a value of 59.6 ml.

5. Experimental Set up

Fig 2 Experimental Set up of Evaporative Water Generation

Experimental set up consisting of 1. Compressor
2. Water cool condenser for sub cooling 3. Evaporator
4.Expansion valve

Fig 3 Experimental set up test rig.

Table 9 Hourly condensate extraction of January 2017

	Time	7am -8am	8am -9am	9am -10am	10am -11am	11am -12am	12am -13am	13am -14am	14am -15am	15am -16am	16am -17am	17am -18am	18am -19am	19am -20am	20am -21am
Date	Water volume collected in mililitre														
01/01/2017		220	192	186	145	100	65	52	59	54	48	52	71	88	105
02/01/2017		221.2	186	187.2	146.2	101.2	66.2	53.2	60.2	55.2	49.2	53.2	72.2	89.2	106.2
03/01/2017		255	187.2	188.4	147.4	102.4	67.4	54.4	61.4	56.4	50.4	54.4	73.4	90.4	107.4
04/01/2017		256.2	188.4	189.6	148.6	103.6	68.6	55.6	62.6	57.6	51.6	55.6	74.6	91.6	108.6
05/01/2017		257.4	189.6	190.8	149.8	104.8	69.8	56.8	63.8	58.8	52.8	56.8	75.8	92.8	109.8
06/01/2017		258.6	190.8	192	151	106	71	58	65	60	54	58	77	94	111
07/01/2017		259.8	192	196	152.2	107.2	72.2	59.2	66.2	61.2	55.2	59.2	78.2	95.2	112.2
08/01/2017		261	193.2	197.2	153.4	108.4	62.5	60.4	67.4	62.4	56.4	60.4	79.4	96.4	113.4
09/01/2017		262.2	194.4	190.4	154.6	109.6	63.7	61.6	60.6	63.6	57.6	61.6	00.6	97.6	114.6
10/01/2017		263.4	195.6	199.6	155.8	110.8	64.9	62.8	69.8	64.8	58.8	62.8	81.8	98.8	115.8
11/01/2017		264.6	201	200.0	157	112	66.1	64	71	66	60	64	03	100	117
12/01/2017		265.8	202.2	202	158.2	113.2	67.3	65.2	72.2	67.2	61.2	65.2	84.2	101.2	118.2
13/01/2017		267	203.4	203.2	159.4	114.4	68.5	66.4	73.4	68.4	62.4	66.4	85.4	102.4	119.4
14/01/2017		222	204.6	204.4	160.6	115.6	69.7	67.6	74.6	69.6	63.6	67.6	86.6	103.6	120.6
15/01/2017		223.2	205.8	205.6	161.8	116.8	70.9	68.8	75.8	70.8	64.8	68.8	87.8	104.8	121.8
16/01/2017		224.4	207	189	163	124.9	72.1	55.26	49.56	62.55	54.36	74.36	89	106	123
17/01/2017		225.6	208.2	190.2	164.2	126.1	73.3	56.46	50.76	63.75	55.56	75.56	90.2	107.2	124.2
18/01/2017		226.8	105	191.4	165.4	127.3	74.5	57.66	51.96	64.95	56.76	76.76	91.4	108.4	125.4
19/01/2017		228	106.2	192.6	166.6	128.5	75.7	58.86	53.16	66.15	57.96	77.96	92.6	109.6	126.6
20/01/2017		229.2	107.4	193.8	167.8	129.7	76.9	60.06	62.3	67.35	59.16	79.16	93.8	110.8	127.8
21/01/2017		230.4	108.6	156.8	188	130.9	78.1	61.26	63.5	68.55	60.36	80.36	95	112	129
22/01/2017		231.6	109.8	158	189.2	132.1	79.3	62.46	64.7	69.75	61.56	81.56	96.2	113.2	130.2
23/01/2017		232.8	111	159.2	190.4	133.3	80.5	63.66	65.9	70.95	62.76	82.76	97.4	114.4	131.4
24/01/2017		234	112.2	160.4	191.6	134.5	81.7	64.86	67.1	72.15	63.96	83.96	98.6	115.6	132.6
25/01/2017		235.2	113.4	161.6	192.8	135.7	82.9	66.06	68.3	73.35	65.16	85.16	99.8	116.8	133.8
26/01/2017		236.4	114.6	162.8	194	136.9	84.1	67.26	69.5	74.55	66.36	86.36	101	118	135
27/01/2017		237.6	115.8	164	195.2	138.1	85.3	68.46	70.7	75.75	67.56	87.56	102.2	119.2	136.2
28/01/2017		238.8	117	165.2	196.4	139.3	86.5	69.66	71.9	76.95	68.76	88.76	103.4	120.4	137.4
29/01/2017		234	118.2	166.4	197.6	140.5	87.7	70.86	73.1	78.15	69.96	89.96	104.6	121.6	138.6
30/01/2017		235.2	119.4	167.6	198.8	141.7	88.9	72.06	74.3	79.35	71.16	91.16	105.8	122.8	139.8

6. Result and Discussion

Results of two random days of experiment are plotted in graph in figure 4.

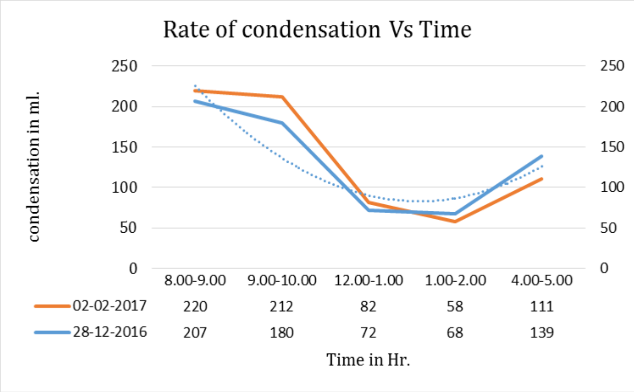

Fig 4 Graph of the relationship between time and condensation rate

Above graph shows the relationship between time and condensation rate, definitely this depend on the percentage humidity also.

1. The dotted line shows the ideal behaviour of the condensate generation to make potable water generation.
2. The first line in blue colour shows the reading taken in December and during winter season rate of condensation at morning is noted 207 ml per hour.
3. The rate of condensation is more at morning and it decreases at afternoon and again shows the rise during evening (since the condensate is dominantly affected by the relative humidity).
4. Experiment conducted in Februry 2017 and results were plotted in graph the behaviour of the curve is same except the volume of condensate which is different from that of December (since the rate of condensate is also the function of inlet air temperature).

7. Conclusion

From results and discussions it seen that,

1) Water generation by this system is not constant for whole day because as per results this system gives more water generation at low temperature i.e. more at night time a compare to day time or more during morning as compare to afternoon when temperature is high.

2) The rate of condensate extraction from the system is mainly a function of the air inlet and outlet humidity ratios and temperatures. However, the effect of the humidity ratio is more significant. The trend of the condensate extraction variation generally follows the relative humidity variation. The rate of condensate is largely depend on the temperature and the relative humidity of inlet air, condensate rate will be high at high relative humidity and temperature of inlet air.

3) It may give cooled air which is dry for space cooling too as a byproduct of water generation from atmospheric air after extracting moisture or water from it.

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