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Design and Fabrication of a Humidification-Dehumidification Desalination Plant

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Abstract: The global need for freshwater sources for the world's growing human population has been on a steady increase. This has led to the need for technological advances in the process of desalination for obtaining freshwater from saline water. A major challenge in many salination processes that already exist, is the high energy consumption involved in their operations. This paper proposes a desalination process that uses the technique of humidification and dehumidification to accomplish the necessary desalination. The paper presents also the technical processes of design and fabrication of a plant to achieve this purpose. The major advantage of this plant design is its lower energy cost and the ease of fabrication and installation.
Keywords: Desalination, humidification, heat exchanger, material balance, energy balance.

I. INTRODUCTION

Water is the most abundant resource, covering three-fourth of the planet's surface. However, about 97% of the earth's water is salt water in oceans and a tiny 3% is fresh water. This small percentage of the earth's water which supplies most of human and animal needs exists underground, in lakes and rivers [1]. Water is a fundamental necessity for human life because all daily human activities are in one or more ways dependent on its availability. Water is a basic human requirement for domestic, industrial and agricultural purposes. The continuous rise in the world's population and the expansion of industrial facilities around the globe have resulted in growing demand for fresh water supply from natural resources (rivers, fresh water lakes, and brackish wells). These resources have been steadily declining in quality due to industrial, agricultural and domestic wastes. Basic chemistry reveals that pure water necessary for life should be colourless, odourless and tasteless and should not contain dissolved substances which cause a deviation from these ideals. Therefore the need for new fresh water resources to balance the growing consumption rate has been a serious concern facing governments and world organizations for the past 50 years. The fact that 96% of the earth's surface is covered with saline water has been a substantial catalyst for developing water desalination technologies [2].

Desalination is the process of removing salt and dissolved minerals from water to provide essential water for drinking, irrigation and industry. The basic techniques that can be used to remove salt and other dissolved solids from water include: Distillation, Reverse Osmosis (RO), Electrodialysis (ED), Ion Exchange (IX) and Freeze Desalination. Distillation and freezing involve removing pure water, in the form of water vapour or ice from salty brine. RO and ED use membranes to separate dissolved salts and minerals from water. In addition is the most recent method of desalination; humidification-dehumidification desalination process. Today, there are more than 7500 desalination plants in operation worldwide. Humidification-dehumidification desalination is a salt water desalination process involving the principle of heat and mass transfer as well as liquid-vapour phase change. The main objective of this work is the design and fabrication of a humidification-dehumidification desalination process plant with less energy requirement, moderate installation and operating costs, simplicity of units to meet the teeming need for fresh water for domestic, industrial and agricultural use, especially in areas where fresh water is not readily available.

II. HUMIDIFICATION AND THE HUMIDIFYING EQUIPMENT

A. Humidification

Humidification simply involves a systematic process of increasing the amount of water vapour carried by a given mass of air. This is usually achieved by bringing air and water into intimate contact until a desired humidity is reached while manipulating the physical conditions in order to achieve this. This is largely achieved by varying the temperature of the air since, to a large extent, the humidity of air depends on its temperature. For example, assuming air at ambient conditions is at 25^{o}C, its volumetric humidity is 22g/m^3 at saturation point. If the temperature of the air is increased to 50^{o}C, the relative humidity of the system reduces to about 23% and it would require 50g of water to saturate 1m^3 of air. Thus, in order to increase the amount of water in the air sample, the temperature of the air is increased.

B. The Humidifying Equipment

From the concept of humidification discussed above, it follows that the equipment for achieving humidification must comprise most especially of a medium of bringing into contact the air and the water and also a medium for increasing the temperature of the air stream. The most common contacting medium for the air stream and the water is usually by means of a systematically packed column where enough interface for contact is achieved. It is also natural that the water is introduced at the top of the tower since it falls freely under gravity while the air is introduced from beneath the tower since it is gaseous in nature and is less dense than water.

C. Dehumidification

Dehumidification is the reverse of humidification and it is the process of extracting water from an air stream. This is actually achieved by cooling the air stream to a temperature below its dew point such that the air stream loses water corresponding to the new temperature to which it is cooled.

Assuming a saturated air stream is at 50^{o}C, its volumetric humidity is about 83 g/m^3 at atmospheric pressure from a standard chart. If this air is cooled to room temperature (25^{o}C), since saturated air at this temperature is at a volumetric humidity of 23g/m^3, this means that cooling 1m^3 of saturated air at 50^{o}C to room temperature, it loses 50g of water.

This is usually achieved by passing a cold fluid through the inside of formed tubes arranged in banks through which air is blown. The outside surface of the metal tubes must be below the dew point of the air so that water will condense out of the air and the new temperature of the air becomes the dew point of that particular air stream.

D. Desalination by Humidification-Dehumidification

The principle of humidification and dehumidification explained above can be applied in the desalination of saline or brackish water. It is a salt water desalination process involving the principle of heat and mass transfer as well as liquid-vapour phase change. In this process, water vapour first diffuses from saline water in dry air through evaporation in a diffusion tower, thus humidifying the air (humidification). The water vapour is then carried away by the air to a condenser where the water vapour is condensed out from the humidified air through condensation to produce fresh water (dehumidification).

1) *Process Summary:* The entire desalination process consists of three main flow circulation sub systems. In the saline water sub system, saline water is circulated by a pump and sprayed into the top of a diffusion tower usually a packed column, in this tower, it is in direct contact with the dry air and a portion of the saline water evaporates and humidifies the air. In order to improve the fresh water productivity, the saline water is heated using the most economic method possible since both the rate of water evaporation and the humidity ratio of the existing air increase with temperature. The concentrated salt solution is collected at the bottom of the diffusion tower. In the air/vapour subsystem, dry air is pumped into the bottom of the diffusion tower and as the upward flow proceeds, the air is humidified by the saline water through an evaporation process. The warm and humid air leaving the diffusion subsystem is drawn into a condenser and by a process of heat transfer, the warm and humid air temperature is reduced beyond the dew point of the humid air, thus, part of its water content is removed. The dehumidified air is then released or resent into the diffusion tower depending on the design of the system. The system can be designed in different ways in order to improve the system's energy efficiency as well as the fresh water productivity of the system.

E. Advantages of Humidification-Dehumidification Desalination over other Desalination Processes

Humidification-dehumidification desalination process is a distinct method of water desalination compared to the conventional methods of desalination such as Multi-Stage Effect Distillation (MED), Multi-Stage Flash Distillation (MSF) and Reverse Osmosis (RO) desalination that are technologically mature and are widely used. Certain advantages of this process make it a better replacement or compliment for these other desalination technologies.

1) *Reduced Energy Requirements:* The other methods of desalination are much more energy intensive desalination unlike humidification-dehumidification desalination which can be run from feed streams near ambient conditions and also with waste energy from other industrial processes. Distillation, for example, requires that the saline water be heated to its boiling point and then re-condensed to produce fresh water either at atmospheric pressure and high heat requirement or at very low pressures and lower heat requirements. Reverse osmosis on the other hand requires that the saline water be passed through a permeable membrane and this is achieved at extreme pressures. This is the advantage that humidification-dehumidification has over the other methods which therefore makes it a better desalination method.
2) *Simpler Equipment Requirements:* Humidification-dehumidification desalination operates on simpler equipment (compact units) which are very easily assessable at cheaper prices compared to the other desalination processes. Thus home desalination units can also be produced at cheaper prices using this process of desalination.

3) *Operation near Ambient Conditions*: Humidification-dehumidification desalination, unlike other methods of desalination, operates very close to ambient conditions thus making the operation easier to handle and also much more economical to operate when compared to the other methods of salt water desalination. This also reduces the rate of corrosion of its equipment as well as the capital cost of the system.
4) *Moderate Installation and Operating Costs:* Based on its simplicity, easy access to the equipment is made possible and at cheaper prices. In addition, the cost of operating the plant as well as maintenance is also moderate compared to other desalination techniques.
5) *Flexibility in Capacity:* It is flexible in capacity and therefore easy to dismantle due to the simplicity of the units as well. Thus, it unlike the other methods of desalination that are not economical except on large scale can be used either as a decentralized system or as a large scale method of fresh water production.

F. Material Selection

Corrosive environment and plant operating conditions are the two important considerations in the selection of materials. Plain Carbon Steels, Copper-base alloys, Stainless steels, Cast irons and Titanium are the main metallic materials used in the construction of desalination plants [3].

III. TECHNICAL DESIGN SPECIFICATIONS

This section describes the technical considerations that were made in the design of the different parts of the plant.

A. Humidification Column

The humidification column is the part of the system where vaporization of a part of the sea water feed takes place in an air medium. This unit is basically an air-water contacting column packed adequately with materials of good surface area, where heat and mass transfer operations takes place simultaneously. Thus, the design of this unit is done to obtain a very good contact time as well as a large interphasial surface area for mass transfer. Basically, design parameters that are obtained from this analysis are: Height of packing required, kind and size of packing, Diameter of column, exit temperatures of air and water.

1) *Material Balance*: A material balance is carried out to obtain the air input flow rate and exit flow rate as well as the saline water exit flow rate assuming saline water feed through-put of 20kg on a basis of 1 minute and that 7.9% of the saline water is vaporised into the air stream. Fig 1 shows a schematic of the humidification column.

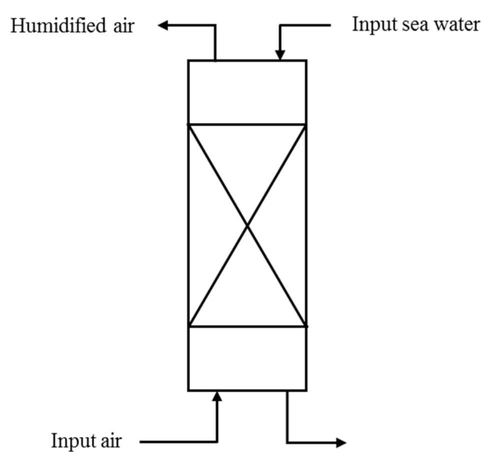

Fig. 1 Schematic diagram of the humidification column

2) *Determination of Column Diameter:* The column diameter of the humidifying column is fixed such that the flow of liquid and gas does not result to flooding in the humidifier. The type and size of packing to be used is 50mm Plastic Raschig rings with a column voidage of 78%. The packing factor for the packing arrangement, $f = 120m^2/m^3$.
3) *Determination of Column Height*: The height of the column and the final temperatures of the air and water stream are obtained from energy balance and mass transfer calculations on the column. The energy balance is described here. As the air rises from the base of the column, its enthalpy increases as well as its temperature. The reverse occurs for the saline water from the top of the column to the bottom. An energy balance about the humidification column produces an operating line for the humidification column, shown in Equation (1).

$$G'\left(H_{G_2} - H_{G_1}\right) = L'C_L(\theta_{L_2} - \theta_{L_1}) \quad (1)$$

where $\frac{L'C_L}{G'} = 1.27$ is the slope of the operating line, C_L is the heat capacity of the liquid stream, θ_{L_1} is the inlet temperature of the liquid, θ_{L_2} is the exit temperature of water, H_{G_2} is the exit enthalpy of the leaving air from the humidifier. The enthalpy of the entering gas stream is given by Equation (2).

$$H_{G_1} = \left(1.005 + 1.900H_{G_1}\right)\left(\theta_{G_1} - 0\right) + \lambda_{G_1}H_{G_1} \quad (2)$$

where λ_{G_1} is the latent heat of vaporization at the air temperature. The absolute humidity of the exit air stream is fixed, thus a trial and error algorithm is used to obtain H_{G_2} by using trial values of θ_{L_2} to obtain a temperature that will produce an exit air stream of the given air humidity. Fig. 2 shows the Algorithm for obtaining the Exit temperatures for water and air.

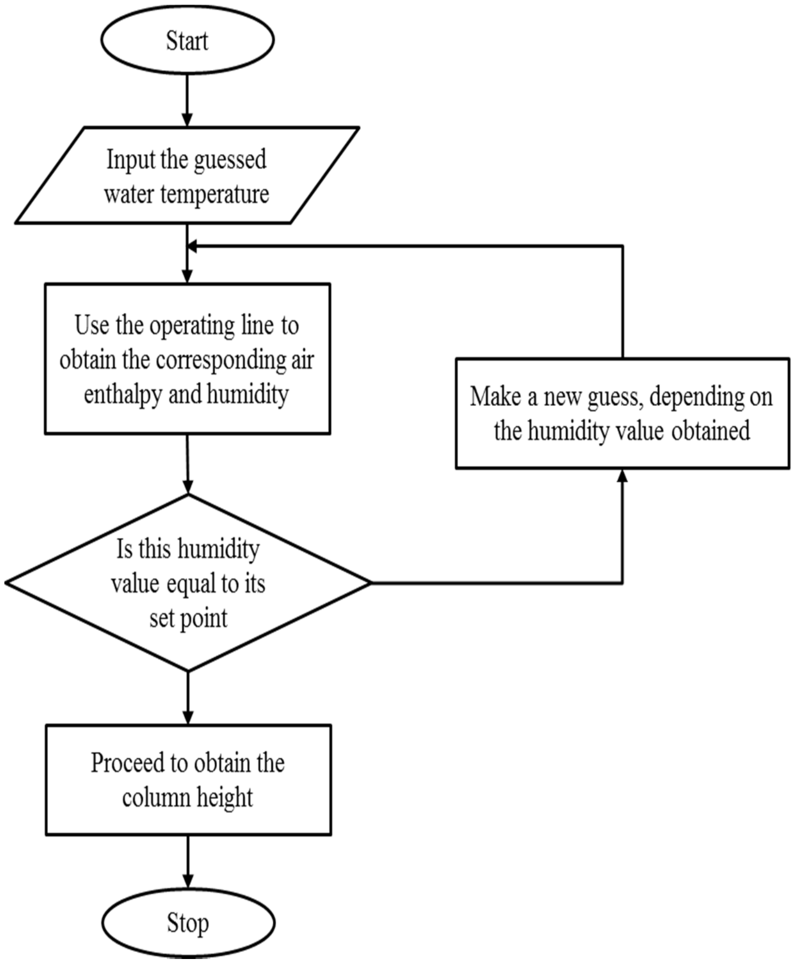

Fig. 2 Algorithm for obtaining the Exit temperatures for water and air

An exit water temperature of 25°C is used to obtain the required air exit humidity. From the operating equation, the temperature of the air is also obtained as 40°C from standard humidity charts ($\theta_{L_2} = 40^oC$). From mass transfer correlations [4], Equation (3) is obtained.

$$\frac{dH_G}{H_f - H_G} = \frac{h_D\alpha\rho}{G'}dz \quad (3)$$

where z is height of column, H_f is enthalpy of air at the interphase, $h_D\alpha$ is interphasial mass transfer coefficient, ρ is air density. An assumption that the air at the air-water interphase is saturated is made [4], thus, the enthalpy of the air at the interphase is the enthalpy of saturated air at that temperature. The integral is obtained numerically such that the humidifying column is taken to have a uniform temperature profile from the base of the column at θ_{L_1} to the top of the column at θ_{L_2}. The area under the curve of $1/H_f - H_G$ against H_G is given as the integral $\int_{H_{G_2}}^{H_{G_1}} \frac{dH_G}{H_f - H_G}$ and is shown in Fig. 3.

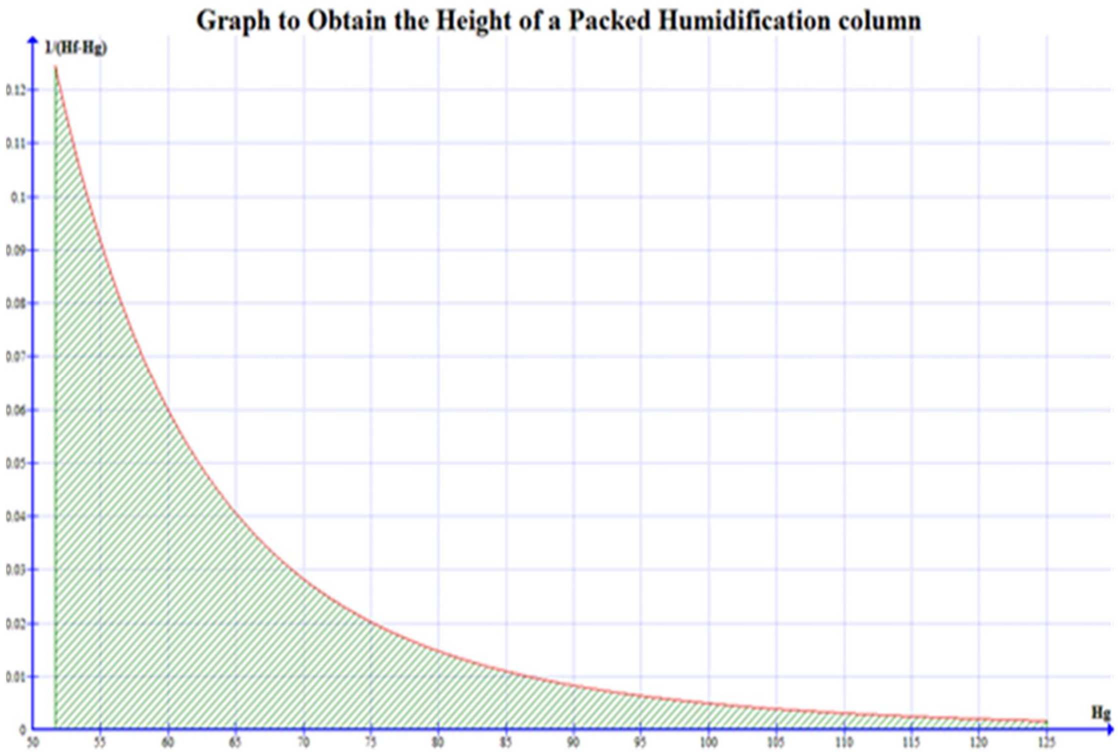

Fig. 3 Graph of $1/H_f - H_G$ against H_G for obtaining the height of packing required

The values to be plotted are obtained by drawing the operating line for the column and an enthalpy-temperature graph for saturated air from which the values of H_f and H_G can be calculated at different temperatures. The values obtained are shown in Fig. 4.

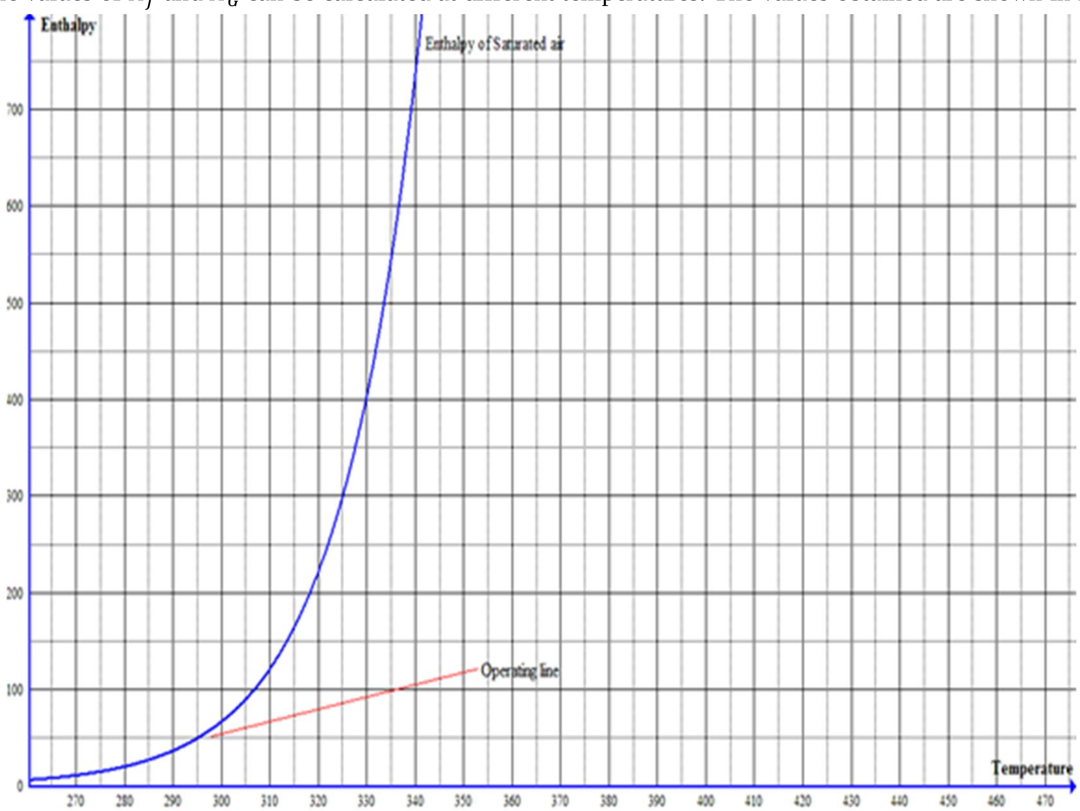

Fig. 4 Operating line for Humidification column

The values for obtaining the required column height are shown in Table I.

TABLE I TABLE OF VALUES FOR OBTAINING THE COLUMN HEIGHT REQUIRED

H_G	$\theta_f(K)$	H_f	$H_f - H_G$	$1/H_f - H_G$
51.64	298	59.15	7.51	0.1332
54.36	300	66.84	12.48	0.0801
66.97	310	121.08	54.11	0.0185
79.59	320	220.04	140.45	0.0071
86.62	325	297.88	310.81	0.0047
92.45	330	403.26	310.81	0.0032
105.24	340	735.73	630.66	0.0016
126.00	353	1612.00	1486	0.0006

The area under the curve is obtained as 1.0949, that is, $\int_{H_{G_2}}^{H_{G_1}} \frac{dH_G}{H_f - H_G} = 1.0949$.

B. Materials Handling Equipment Design

Basically, the materials used in the desalination system are air which is pushed through the plant by an air blower and saline water which is supplied by a centrifugal water pump. The basic design parameters for these equipment are their power ratings which are obtained thus:

1) *Blower:* The blower supplies are through the desalination system at a given flow rate and at a pressure which is enough to withstand the pressure drops resulting from the equipment design. As earlier stated, the basic design parameter required for this equipment is its power rating which obtained using Equation (4) [5].

$$Power = 2.78 \times 10^{-4} m_v P1 \ln\frac{P_2}{P_1} \quad (4)$$

where m_v is volumetric flow rate (m^3/hr), P_1 is inlet pressure and P_2 is exit pressure.

2) *Pump:* For this process, the pump is employed basically for lifting the saline water up the humidification column. The power rating of the pump required for the given process is given in [6] by Equation (5).

$$Power = \frac{\Delta P Q_p}{\eta_p} \times 100 \quad (5)$$

where ΔP is the pressure increase required (kPa), $Q_p$is the mass flow rate of water required (m^3/s), η_p is pump efficiency. The pressure required is dependent basically on the elevation at which the water is required.

IV. PROCESS FLOW

Saline water is supplied from an overhead reservoir tank and passes through the dehumidifier where it serves as the cooling medium for heat exchange with the humid air. This process preheats the water before it is sent into the heater where it is heated to 80^{o}C which is the temperature required in the humidification column. The resulting hot saline water is then sent up the humidification column by means of a centrifugal pump. On the other hand, air is supplied by means of an air blower to the bottom of the humidification column where it is contacted with the falling water and by means of heat and mass transfer. Part of the water from the hot saline water vaporises into the air stream thus making it humidified. The resulting humidified air, which is at a higher temperature, is then sent to the dehumidifier where it transfers heat and reduces in temperature. This reduction in temperature results in condensation since the air is cooled beyond its dew point. The resulting fresh water is then collected from the dehumidifier while the air is allowed to escape from the system. A more concentrated saline water solution flows down the humidification column and it is collected beneath the column. This process continues till the water in the reservoir tank is exhausted.

V. EXPERIMENTAL RESULTS AND DISCUSSIONS

On completion of the desalination plant, tests were carried out to ascertain the flow rate of water that will give the highest yield of fresh water while keeping the air flow rate constant. The reservoir tank was filled with 3.5% sea water and its supply valve is opened gradually to supply water into the water heater through the dehumidifier. After enough water has been received in the heater, the water supply valve is closed and the heater is allowed to heat to the required temperature (80^{o}C). The air blower is started and the humidification column water supply valve is turned open. The volume of fresh water received after 1minute for different flow rates of water is measured and recorded in Table II.

TABLE II
TABLE OF EXPERIMENTAL RESULTS

Flow Rate (kg/s)	Volume (ml)
0.05	120
0.10	300
0.15	432
0.20	480
0.25	496

The given experimental data above shows that the amount of fresh water produced increases gradually although non-linearly as the flow rate of the hot saline water is gradually increased. Although at a certain point, a marginal value is reached such that further increase in the flow rate of saline water results in a reduction in the fresh water feed produced.

This is because, since the flow rate of air is kept constant, a certain point is reached where the air can no longer accept more water and thus, the amount of water produced would not increase. Also, as the flow rate of the water is increased gradually, the amount of interphasial contact between water and air reduces since the contact time is reduced as a result of increased flow rate, thus the fresh water product obtained is reduced. In addition, as the amount of water in air is increased, the exit temperature of air also reduces since the latent heat of vaporisation has to be supplied by the sensible heat of the hot saline water, thus, the heat transfer obtained in the humidifier would be reduced. If more amount of humid air enters the humidifier, the heat transfer required would be much more since the latent heat of vaporisation must be lost from the humid air for condensation to occur, else the air leaves the dehumidifier humid without much condensation.

From these and many other considerations, it can be observed that the experimental result obtained agrees sufficiently with the information gathered from literature. Therefore, in operating a humidification-dehumidification desalination process plant it should be noted that the flow rates of the process streams affects the quantity of the product obtained.

VI. CONCLUSIONS

From positive results obtained, it can be seen that humidification-dehumidification desalination is a promising method of solving the problems of fresh water scarcity in coastal areas and is also practical for small scale decentralised water desalination systems. From the careful study of this process, it can be observed that the process depends very much on the temperature of the feed streams (air and water) as well as on their flow rates. Thus, in operating this desalination system, much emphasis is to be laid in obtaining the optimal process variables required for each process stream such that much more product would be produced at the least energy utilization. Typically, for the humidification-dehumidification desalination system, using air flow rates of $14m^3$/min and a hot water temperature of 80^oC, water flow rates of about 0.10-0.15kg/s would result in optimal production of fresh water. If the temperature of the water is further increased, this variable would also change.

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