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REVIEW ARTICLE

Review on Solar Humidification- Dehumidification Process for Pure Water Production

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Abstract

Humidification dehumidification desalination (HDH) is a promising technology for small-scale water production applications. There are several embodiments of this technology which have been investigated by researchers around the world. Major desalination processes consume a large amount of energy derived from oil and natural gas as heat and electricity. Solar desalination, although researched for over two decades, has only recently emerged as a promising renewable energy-powered technology for producing fresh water. The system which, can be used in an open or closed cycle for air, is a modular one. It has the following independent components: two solar collectors, an evaporator and a condenser. Solar desalination based on the humidification-dehumidification cycle presents the best method of solar desalination due to overall high-energy efficiency. In this paper, we analyse the thermodynamic performance of various HDH cycles by way of a theoretical cycle analysis. This paper presents the characteristics of a solar desalination system based on the humidification-dehumidification principle

Introduction

Water and energy are two of the most important topics on the international environment and development agenda. The social and economic health of the modern world depends on sustainable supply of both energy and water. Many areas worldwide that suffer from fresh water shortage are increasingly dependent on desalination as a highly reliable and nonconventional source of fresh water. So, desalination market has greatly expanded in recent decades and expected to continue in the coming years. In the developing world, water scarcity led to the pressing need to develop inexpensive, decentralized small-scale desalination technologies that use renewable resources of energy. This study reviews one of the most promising of these technologies, humidification–dehumidification (HDH) desalination powered by solar energy. The different types of HDH cycle design and its constituents (humidifier, solar heaters, and dehumidifiers) have been investigated. The review also includes water sources, demand, availability of potable water and purification methods. It is concluded that HDH technology is a promise process for decentralized small-scale water production applications, but it needs additional research and development to enhance the system efficiency and economy.

Principle of HDH Process:

The most promising recent development in solar desalination is the use of the humidification- dehumidification (HD) process. The HD process is based on the fact that air can be mixed with large quantities of water vapour. The vapour carrying capability of air increases with temperature: 1 kg of dry air can carry 0.5 kg of vapour and about 670 kcal when its temperature increases from 30°C to 80°C.

When flowing air is in contact with salt water, a certain quantity of vapour is extracted by air, which provokes cooling. Distilled water, on the other hand, may be recovered by bringing the humid air in contact with a cooled surface, which causes the condensation of part of the vapour in the air. The condensation occurs in another exchanger in which salt water is preheated by the latent heat of condensation. An external heat contribution is therefore necessary to compensate for the sensitive heat loss.[1]

The HD technique is especially suited for seawater desalination when the demand for water is decentralized. Several advantages of this technique can be presented which include flexibility in capacity, moderate installation and operating costs, simplicity, and possibility of using low-grade thermal energy (solar, geothermal, recovered energy or cogeneration). In this process, air is heated and humidified by the hot water received from a solar collector. It is then dehumidified in a large surface condenser using relatively cold saline feed. Most of the latent heat of condensation is used for preheating the feed.

Performance and operating parameters

As a first step for understanding the HDH cycles the following performance parameters are defined.[2]

1. **Gained-Output-Ratio (GOR):**
   GOR is the ratio of the latent heat of
   evaporation of the water produced to the heat input to the cycle. This parameter is, essentially, the effectiveness of water production and an index of the amount of the heat recovery effected in the system. Latent heat is calculated

   with the operating pressure assumed as saturation pressure.

2. **Top temperature:**
   In HDH systems, either water or air is heated (for example, in a solar collector). The top temperature of the cycle is the temperature of the fluid being heated at the exit of the heater.
3. **Bottom temperature:**
   The feed water to the dehumidifier enters the cycle at the bottom temperature of the cycle.
4. **Terminal temperature difference (TTD):**
   TTD is the stream to stream temperature difference at either end of the heat exchanger (humidifier /dehumidifier)
5. **Pinch point temperature difference (P):**
   Pinch point temperature difference is the minimum local stream-to-stream temperature difference at any point within the heat exchanger and is lower than both the terminal temperature differences. In some cases, however, the pinch can be equal to one of the terminal temperature differences.
6. **Modified heat capacity ratio (HCR):**
   For heat and mass exchange devices like the
   humidifier and the dehumidifier, we had previously defined a parameter called the modified heat capacity ratio. The modified heat capacity ratio is the ratio of maximum possible enthalpy change of the cold stream to the maximum possible enthalpy change of the hot stream.

Based on the source of energy used: Renewable
Non-Renewable

Based on the cycle configuration: Closed Water/Open Air (CWOA) Closed Air/Open Water (CAOW)

Based on heating substance: Air heated
Water heated

Closed Water/Open Air (CWOA):

In a CWOA cycle the closed-water circulation is in contact with a continuous flow of cold outside air in the evaporation chamber.

The air is heated and loaded with moisture as it passes upwards through the falling hot water in the vaporation chamber. After passing through a ondenser cooled with cold seawater, the partially ehumidified air leaves the unit, while the ondensate (distillate) is collected. The water is cycled or recirculated. Incoming cold air provides cooling source for the circulating water before it

-enters the condenser. The productivity of units orking on this principle is high, but the power quired for the circulation is also very high. One isadvantage of CWOA cycle is that when the umidification process does not cool the water ufficiently, the water temperature to the inlet of e condenser is higher, resulting in lower air ehumidification and lower water production. owever, in the case where efficient humidifiers are used, cooling the water as low as possible up to the limit of the ambient wet-bulb temperature, the closed water system yields more water than the open water system.[4]

Closed Air/Open Water (CAOW):

In a CAOW cycle the humidifier is irrigated with hot water and the air stream is heated and humidified using the energy from the hot water stream. The humidified air is cooled in a heat exchanger using seawater as a coolant. The seawater gets preheated in the process and is further heated by a heat source before it returns to the humidifier. The dehumidified air stream from the condenser is then circulated back to the humidifier. For the closed air, water heated cycle natural circulation of air yields better efficiency then forced circulation of air.

The performance of system heavily depends on whether the air or water is heated. There is extensive knowledge of solar water heating device but relatively little work has been done on air heating solar collectors.

Typically, air-heated systems have higher energy consumption than water heated systems because in the air-heated cycle the air heats up the water in the humidifier and this energy is not subsequently recovered from the water.

On the other hand, in the water-heated cycle, the water stream is cooled in the humidifier and the energy is transferred or recovered in the air stream. Enhanced latent heat recovery is needed to minimize the energy consumption and the resulting cost of these cycles.[5]

Effect of relative humidity of the air entering and exiting the humidifier:

The temporal variations of relative humidity and temperature at inlet and outlet of the humidifier are shown in figure The relative humidity of inlet air of humidifier (RH_{in}) was about 1% because of a relatively high outlet temperature of the solar air field as shown in figure The temperature difference between inlet and outlet of the humidifier (T_{inh} and T_{outh}) widened as the air inlet temperature increased (T_{inh}), which should be caused by lower density and specific heat capacity of the air flow.

The air temperature at the outlet of the humidifier was between 40 and 55 °C, and the relative humidity was between 80% and 90%. Here higher outlet air temperature and relative humidity increased the absolute moisture content of the air flow, which improved fresh water production of the unit under the same cooling condition. Also, figure shows that the relative humidity of outlet air flow decreased with the inlet and outlet air temperatures

increasing, for inadequate heat and mass transfer between air flow and sprayed seawater flow, which means that, the seawater flow rate should be increased along with increasing air temperature.[6]

Effect of component effectiveness (ε_h, ε_d).

Figure illustrates the variation of performance of the cycle at various values of component effectiveness. In Fig. 4(a), the top temperature is fixed at 80°C, the bottom temperature is fixed at
30°C and the dehumidifier effectiveness is fixed at
80%. The mass flow rate ratio was varied from 1 to
6.

It is important to observe that there exists an optimal value of mass flow rate ratio at which the GOR peaks. It can also be observed that the increase in performance is fairly linear with increasing humidifier effectiveness, ε_h. In Figure, the top temperature is fixed at 80°C, bottom temperature is fixed at 30°C, and humidifier effectiveness is fixed at 80%.[2]

The cycle performance changes more dramatically for higher values of dehumidifier effectiveness. These trends are consistent for various values of top and bottom temperatures. Hence, higher dehumidifier effectiveness is more valuable than higher humidifier effectiveness for the performance (GOR) of the cycle. In the previous discussion, we have observed that the dehumidifier exit air relative humidity is more important than the humidifier exit air relative humidity. Hence, based on these results, we can say that for a water-heated cycle the performance of the dehumidifier is more important than the performance of the humidifier.

Effect of top temperature ($T_{w,2}$).

Figure illustrates the effect of top temperature on the cycle performance (GOR). In this particular case, the bottom temperature ($T_{w,0}$) was fixed at 35°C and humidifier and dehumidifier effectiveness were fixed at 92%. Top temperature ($T_{w,2}$) was varied from 60°C to 90°C. The optimal value of mass flow rate ratio increases with an increase in top temperature. Depending on the humidifier and dehumidifier effectiveness this trend changes. At lower component effectiveness, the top temperature has little or no effect on the cycle performance. This result is counter-intuitive.

However, it can be explained using a new parameter called the modified heat capacity ratio. We define modified heat capacity ratio (HCR) as the ratio of maximum possible enthalpy change in the cold stream to the maximum possible enthalpy change in the hot stream. We also described how the entropy generation in a heat and mass exchange device is minimized for a given effectiveness when HCR = 1 („balanced" condition). We are going to use this understanding here to explain the trends obtained at various top temperatures. Figures show the variation of GOR with the heat capacity ratio of humidifier (HCR_h) and the dehumidifier (HCR_d) respectively. At the given inlet conditions the humidifier and dehumidifier are not balanced at the same point (same mass flow rate ratio). Hence the optimum GOR is not at HCR = 1 for both components. Rather, it can be seen that GOR maximizes at $HCR_h > 1$ and $HCR_d = 1$. The maximum occurs at a balanced condition for the dehumidifier which, as we have shown in the preceding paragraphs is the more important component.[2]

Further, it can be noticed that the degree of balancing of the humidifier at the optimum GOR condition reduces (HCR_h moves farther away from 1) as the top temperature increases. Hence, the irreversibility of the humidifier (and the total irreversibility of the system) increases with increase in top temperature. A system with higher total irreversibility has a lower GOR. This explains the decrease in GOR with top temperature. Also, as the top temperature increases the dehumidifier is balanced at higher mass flow ratio and hence the optimum value of GOR occurs at higher mass flow ratios.

Effect of bottom temperature ($T_{w,0}$).

The bottom temperature of the cycle ($T_{w,0}$) is fixed by seawater temperature at the location where the water is drawn. Figure illustrates a case with top temperature of 80°C and component effectiveness"s of 92%. A higher bottom temperature of the cycle results in a higher value of GOR as illustrated in the figure.

This result can again be understood by plotting HCR of humidifier and dehumidifier versus the GOR of the system. The degree of balancing of the humidifier at the optimum condition for GOR decreases with decrease in bottom temperature. Hence, the irreversibility in the humidifier (and the total irreversibility of the system) increases with decreasing bottom temperature and GOR declines.[2]

Psychrometry associated with HDH process:

Figure shows the different states in the psychrometric chart that moist air experiences respectively for the cases of closed system and open one. These results are obtained for the values of 0.05, 0.05, 8 and 24 respectively for the non- dimensional parameters N2, N3, N4 and N5. The mass flow rate ratio, N1 takes the values of 0.8, 1.6, 2.4 and ∞. The flesh water production is obtained by means of the state variation of air in the evaporator and in the condenser. One can observe that for a case of a closed system, the air is loaded with an important amount of vapour at the outlet of the humidifier. These figures show that the closed system is more efficient than the open system.

It is also of interest to note the strong effect of the normalized liquid flow rate on the performance of the system. For the limiting case, corresponding to a very large liquid mass flow rate, the water temperature in nearly constant in the circuit and the potential of evaporation and condensation is nearly zero.

Also, a very low mass flow rate of the feed water is not beneficial to increase the productivity of the system. Figure indicates the variation of the quantity (3º- 4º) with the change of the normalized mass flow rate of the seawater. It shows that there exists an optimum mass flow rate ratio corresponding to a maximum flesh water production.[7]

Comparison of cycles

The various HDH cycles analyzed in this paper are compared in Table 1. The comparison is based on the gained-output-ratio. The bottom temperature for all the cycles is maintained at 35°C. The top temperature for all the cycles is maintained at 90°C. These cycles are designed for humidifier TTD_{min} of > 2.8°C and dehumidifier TTD_{min} of > 4°C. Using a simple thermodynamic analysis of a reversible system the maximum possible GOR was calculated as 122 (see appendix). The commonly used air-heated cycles are much less efficient than the water-heated cycles (GOR is roughly 2.5 times larger for the water-heated case). Multi-staging for air-heated cycles does not improve the performance greatly. However, the proposed modification to the air-heated cycle can make it better than the water heated cycle (GOR is 25% larger than the water- heated cycle and >300% better than the common air-heated cycles).[2]

A high value of GOR (3 to 4.5) for a system which has balanced stream-to-stream temperature difference in the components. We also observed similar values of GOR using the concept of balancing. Balancing the components in a cycle for heat capacity ratio close to one improves the performance greatly. For a multi-extraction air heated cycle, the GOR can reach a value of 4.5. Vacuum operation improves the performance of the air-heated cycle further, but at the expense of larger heat and mass transfer area. An air-heated HDH cycle which is balanced and is operating under sub- atmospheric conditions is a very efficient thermally-driven HDH system. Varied pressure HDH if driven by thermo-compression can be more efficient (GOR >5) than the air-heated system. Performance will depend on our ability to design an efficient ejector and also on the availability of steam.[2]

A comprehensive study to understand and optimize the performance of HDH cycles has been carried out. The following significant conclusions are arrived at from this study:

1. The performance of a basic water-heated cycle depends on: (a) the modified heat capacity ratio in the humidifier and the dehumidifier; (b) the humidifier and dehumidifier effectiveness; (c) top and bottom temperatures and (d) relative humidity of air at the exit of the humidifier and the dehumidifier.

2. The air-heated cycles previously reported in the literature are inefficient. A novel air-heated cycle has been proposed in this paper. This new cycle is more efficient than even the water-heated cycle.

3. Closed air and closed water cycles have similar thermodynamic characteristics and hence similar performance.

4. The dehumidifier is more vital than the humidifier to the performance of a conventional water heated cycle. However, for the novel air- heated cycle proposed in this paper both the humidifier and dehumidifier effectiveness have similar impact on the cycle performance.

5. Balancing the humidifier and the dehumidifier to attain HCR close to 1 will improve performance greatly. In all of the studied cycles, balancing the dehumidifier was found to yield a higher performance than balancing the humidifier.

6. The novel concept of operating HDH under vacuum is proposed in this paper. Vacuum operation increases performance but at the expense of heat exchanger size.

7. Varied pressure systems which have better performance than single pressure systems have also been proposed in this paper. These systems can be mechanically or thermally driven. They have high performance compared to all conventional HDH systems.

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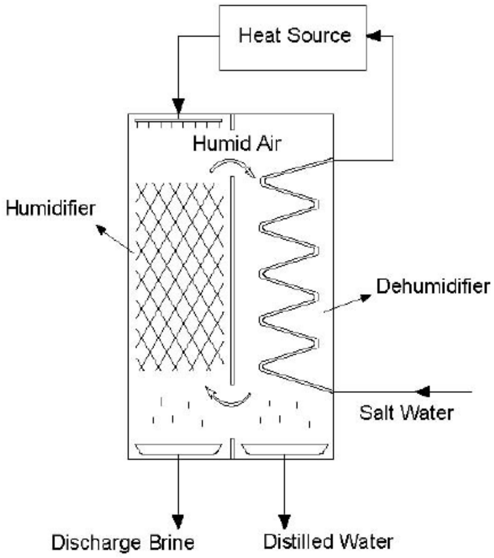


Figure 1 Principle of HD process[1]

Types of HDH process:

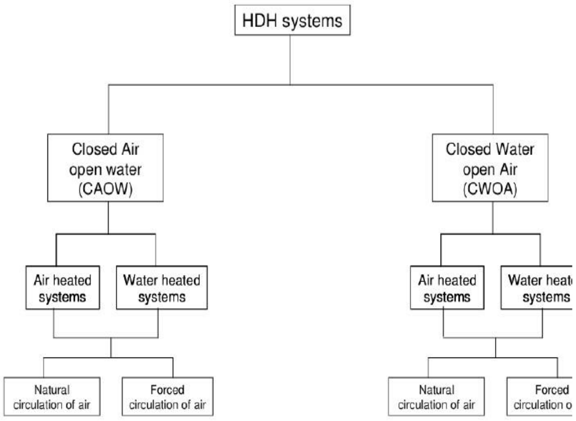


Figure 2 Types of HDH Cycles[3]

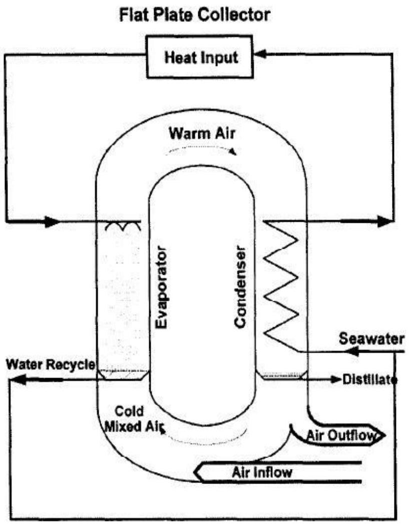


Figure 3 Closed Water-Open Air Cycle[4]

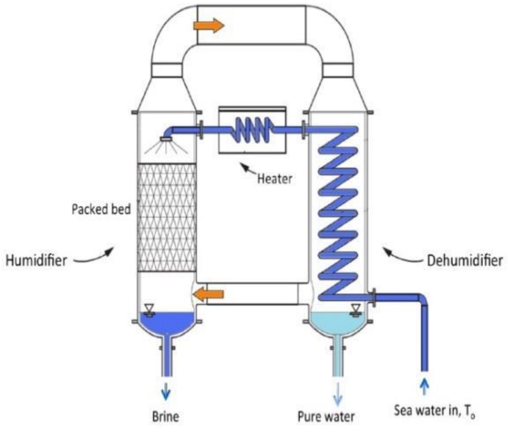


Figure 4 Closed Air-Open Water Cycle

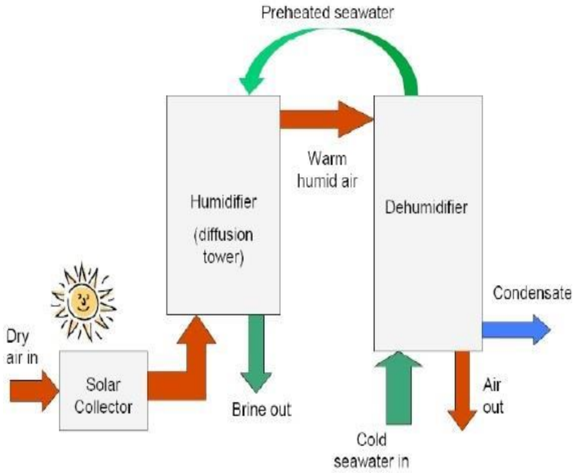


Figure 5 Air-heated Cycle

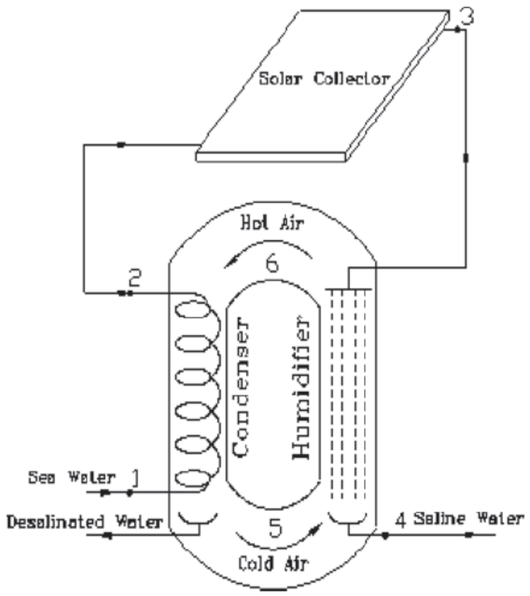


Figure 6 Natural Draft Air Circulation[5]

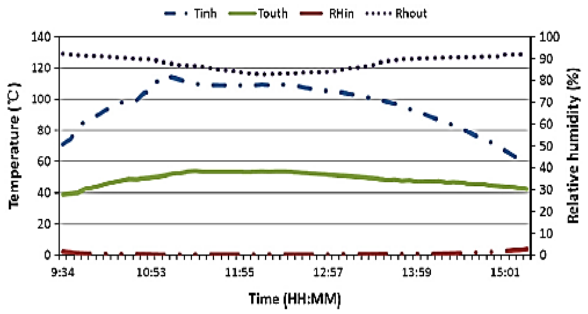


Figure 7 Effect of relative humidity of the air entering and exiting the humidifier[6]

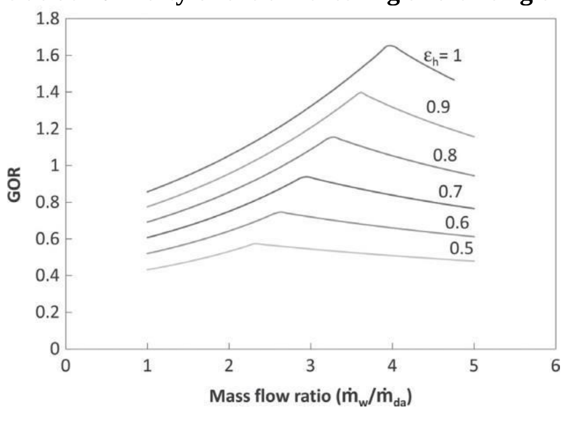


Figure 8 Effect of Humidifier Effectiveness[2]

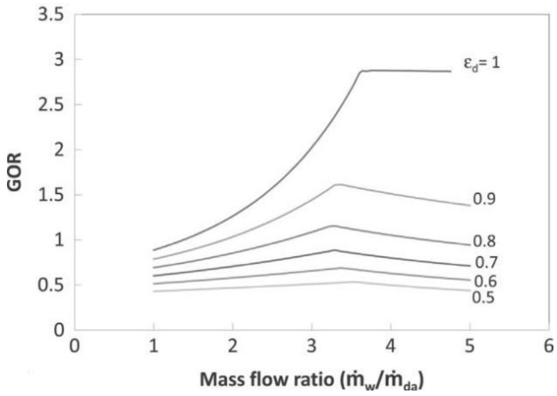


Figure 9 Effect of Dehumidifier Effectiveness[2]

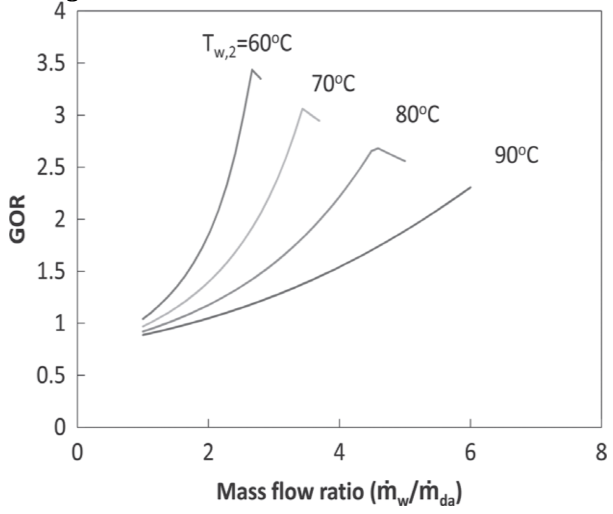
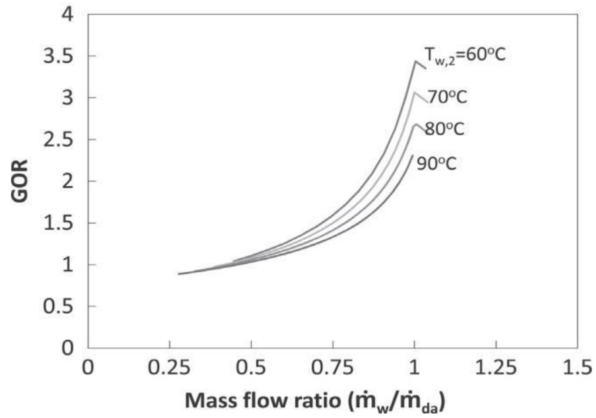


Figure 10 Effect of top temperature[2]



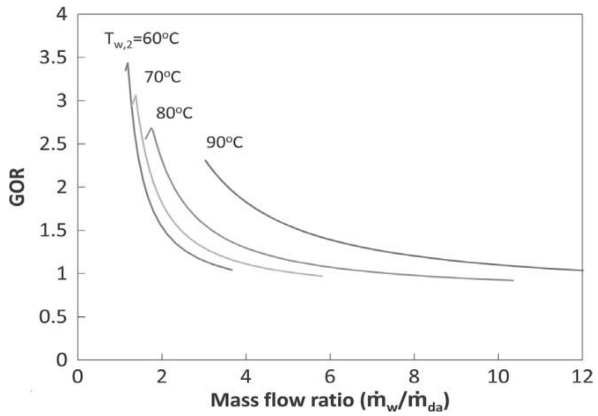


Figure 11 Effect of top temperature

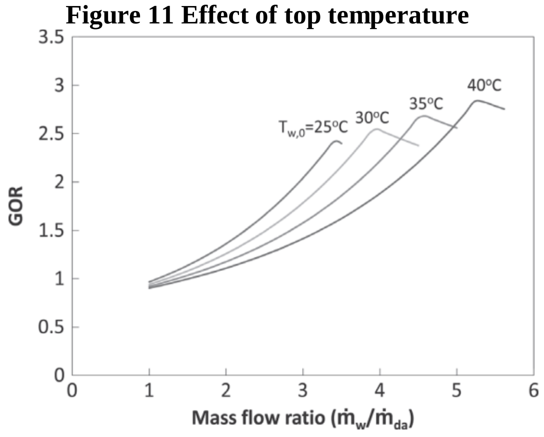


Figure 12 Effect of bottom temperature

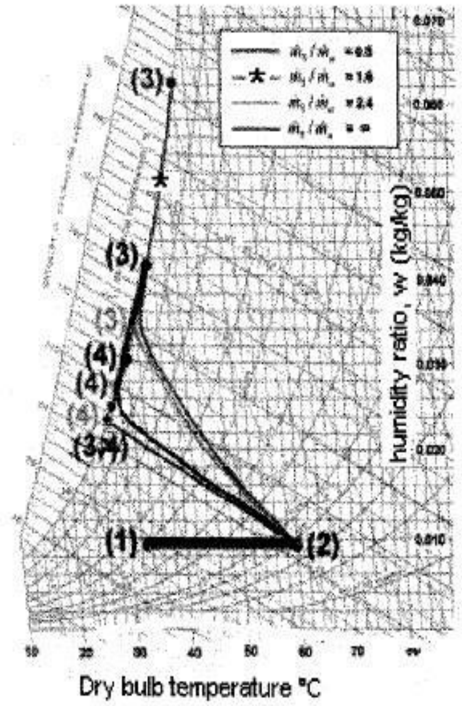


Figure 13 Open Cycle

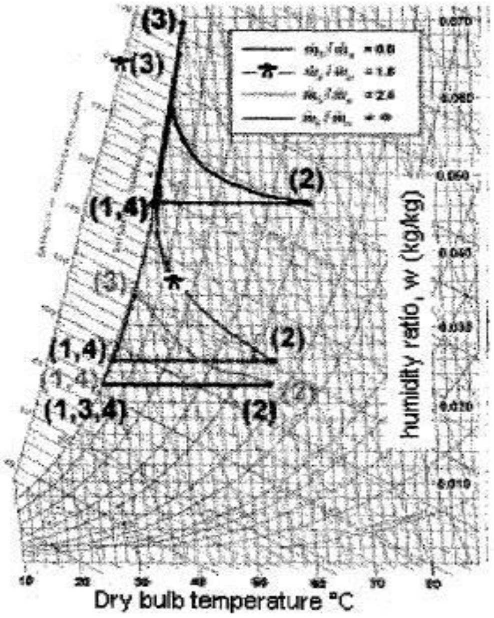


Figure 14 Closed Cycle