Desalination 137 (2001) 167–176

Water desalination by humidification and dehumidification of air: state of the art

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Received 3 November 2000; accepted 17 November 2000

Abstract

The humidification–dehumidification process (HD) is an interesting technique adapted for water desalination when the demand is decentralized. This technique presents several advantages such as flexibility in capacity, moderate installation and operating costs, simplicity, possibility of using low temperature energy (geothermal, solar, recovered energy or cogeneration), etc. Although the common methods of desalination such as distillation and reverse osmosis are the subject of many investigations (archived data and principle of function validated), studies of the HD process are limited at the laboratory step or patents. The aim of this paper is to present the principle of functioning and the characteristics of this technique. The state of the art concerning the HD technique is presented. Several installations functioning worldwide with the HD technique are presented, analyzed and evaluated: solar and geothermal desalination units, a plant functioning by mechanical compression of humid air and an installation functioning by absorbing water from the humid atmosphere. Finally the perspectives of the HD process are evaluated and discussed.

Keywords: Desalination; Humidification; Dehumidification; Air; Vapor; Exchanger; Distilled water; Solar energy; Plant

1. Introduction

The common methods of abstracting fresh water from salt water such as abstracting by distillation, reverse osmosis and electrolysis are intensive-energy techniques. For this reason desalination techniques are competitive only for large-scale production (thousands of m^3/d) Speigler [1]. However, in some circumstances, the desalination needs do not exceed a few m^3/d. This decentralized demand favors local water production by developing other desalination

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Presented at the conference on Desalination Strategies in South Mediterranean Countries, Cooperation between Mediterranean Countries of Europe and the Southern Rim of the Mediterranean, sponsored by the European Desalination Society and Ecole Nationale d'Ingenieurs de Tunis, September 11–13, 2000, Jerba, Tunisia.

processes, especially those using renewable or recovered energy (solar, geothermal, etc.).

The technology of HD satisfies some of these demands, in particular flexibility in capacity with moderate installation and operating costs. The current HD installations are in very compact units containing two exchangers: an evaporator where air is humidified and a condenser where distilled water is recovered. The actual evaporator and condenser are made of resin and polyester (resistant to corrosion) and insulated with sheaths. Heat exchangers made of these materials have the following advantages: they are light weight, inexpensive, technologically suitable, easy to clean, only slightly polluting, corrosion-resistant and resistant to aggressive media.

Compared to other distillation processes, the HD process functions at atmospheric pressure so that the components are not submitted to mechanical solicitations. The only characterestic required is resistance to corrosion.

Though simple in principle, the humidification concept has generally turned out to be economically marginally attractive.

2. Principle of functioning of the HD process

The HD process is based on the fact that air can be mixed with important quantities of vapor. The amount of vapor able to be carried by air increases with the temperature; in fact, 1 kg of dry air can carry 0.5 kg of vapor and about 670 kcal when its temperature increases from 30°C to 80°C [2]. When an airflow is in contact with salt water, air extracts a certain quantity of vapor at the expense of sensitive heat of salt water, provoking cooling. On the other hand, the distilled water is recovered by maintaining humid air at contact with the cooling surface, causing the condensation of a part of vapor mixed with air. Generally the condensation occurs in another exchanger in which salt water is preheated by latent heat recovery. An external heat contribution is thus necessary to compensate for the sensitive heat loss. The exchangers are constructed of tubes placed on perforated plates and supplied by special joints. This makes the eventual dismantling and replacement easier.

Energy consumption is represented by this heat and by the mechanical energy required for the pumps and the blowers. In the HD process, the heat recovery requires an exchange surface more important than distillation for the same production.

The HD process operates, as any distillation process, with only one cross of salt water "once-through" and also with recirculation of the latter. In the first case the evaporation of 1 kg of water causes a decrease of about 60°C in 10 kg of salt water. The amount of distilled water recovered varies from 5% to 20% of the quantity of salt water in circulation: we have a very low concentration of the salt water but a high sensitive heat loss. In the second case a more concentrated solution and lower energy consumption were obtained. The principle of functioning for the HD process is illustrated in Fig. 1.

The basic cycle consists of a heat source, air humidifiers (1) and dehumidifiers (2). The brine is passed through a heater (3) where its temperature rises, then through packed towers where water vapor and heat are given up to the counter-current air stream, reducing the brine temperature. One packed tower, or several in series, may be used as the humidifier depending on results to be achieved and design conditions. Some air must be bled off into the dehumidifier at various points for efficient operation.

The fresh water stream, with its flow rate and temperature increased, leaves the humidifier and passes through a heat exchanger where it gives up its increase in enthalpy to the incoming brine stream. The dehumidifier (2) consists of a series of packed towers, using fresh or salt water as the cooling phase. The air is cooled and dehumidified simultaneously since the humidity

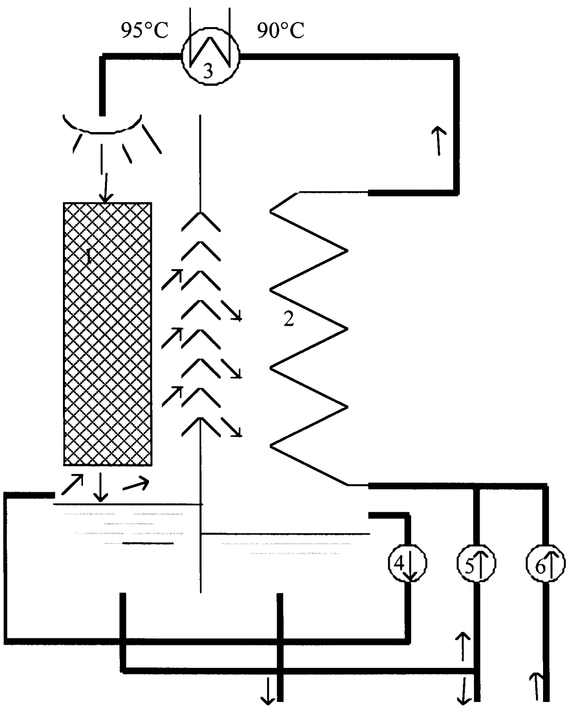

Fig. 1. Principle of the functioning of the HD process.

of saturated air decreases with temperature. The brine enters the heat exchanger where it is preheated by the fresh water stream and is then recycled through the brine water. An amount of water corresponding to the production rate is held from the fresh water stream, and the remainder is recycled to the dehumidifier.

Meanwhile, a portion of the somewhat concentrated brine stream leaving the humidifier is discharged as blowdown to prevent salt build-up, followed by the addition of seawater equal in amount to the discharge plus the fresh water production.

3. General description of process equipment

Specific descriptions of equipment to be used in the HD process vary due to the dependence of size and construction on operating conditions, but the following general guidelines are presented for clarification.

3.1. Packed towers

Packed towers or columns consist of upright shells filled with loose pieces of solid material of uniform size distributed at random. The packing material is of such size and shape to provide a high contact surface and a low pressure drop (Rashig rings, Berl saddles, Pall rings, Lessing rings, and Prym rings). The use of plastic towers packing presents a special interest since these materials are resistant to corrosion. Liquid distribution plates and packing support plates are needed in large packed towers.

3.2. Energy absorber

This item may assume many forms, depending on the energy source (a solar water heater, a steam ejector, geothermal spring, etc.)

3.3. Pumps and blowers

Fresh water pumps may be standard centrifugal; however, brine pumps require special materials to guard against corrosion. Blowers may be standard centrifugal blowers.

3.4. Heat exchangers

The exchangers used can have many configurations. The horizontal tube bundle through which the brine coolant passes in counter-current flow to the fresh water stream surrounding the tube bundle is the most used configuration.

4. Characteristics of the HD process

The HD units are characterized by great functioning simplicity and flexibility, ensured by a low number of apparatus. The principal innovation in the HD process consists of maintaining a continuous humid air flow from the evaporator to the condenser. This allows operation in small desalination plants with heat recovery corresponding to a large number of effects. In the installation described by Nebbia [2], the brine is recycled and the cold brackish water is injected in the evaporator only at quantities corresponding to the evaporated water to avoid any excess in salt water concentration. The brackish water is maintained until its concentration reaches 1.5 to 2 times that of the brine to evaporate. In this manner the sensible heat loss is minimized.

For comparison, we can indicate that energy consumption of about 50,000 kcal/m^3 is only obtained in large multi-flash installations where many effects are juxtaposed. In multi-flash installations mechanical energy consumption is between 2.5 to 5 kWh/m^3.

In HD installations, the two phases — evaporation and condensation — are simultaneous and the two towers are joined by an appropriate pipe to allow humid air circulation between the exchangers. The temperature gap is between 2°C to 5°C for the exchanger elevation. Hence, it is possible to maintain heat consumption at about 5000 kcal/m^3; the mechanical energy consumption for the brackish water needs is maintained between 5–7 kWh/m^3.

At temperature between 70–95°C, heat has to be supplied to the brackish water in circulation by an external energy supply. This allows the use of renewable energies, such as solar and geothermal energy, abundant in many countries (Tunisia, Algeria, Morroco, Egypt, Syria, etc.), and recovery heat (industries using seawater as coolant).

Bourouni et al. [3] analyzed the performances of a HD unit coupled with a geothermal spring in the south of Tunisia. It was shown that this combination allows to make savings of 75% compared to a classical energy source.

Garg et al. [4] investigated the possibility of using HD techniques in the coastal regions of India were many industries using seawater as coolant are implemented. This water, when it is ejected at a temperature of about 55°C, can be used for appreciable recovery of fresh water, doing away with the solar collector unit of the plant which contributes about 28% of the total cost. In some cases the temperature of the brine from such plants is low (40°C); in this case the temperature may be further increased by using the waste heat from the plant such as the heat of exhaust gases.

Concerning the quality of water, we see that in comparison with the other distillation installations functioning with extraction of non-condensable gases, the distilled water produced in the HD installations is saturated with oxygen. In this case it is sufficient to add active carbon and dolmite to improve the taste.

5. HD process: state of the art

Water desalination by humidification and dehumidification has been the subject of many investigations [2–5]. Different experimental data are available for using HD at the pilot or industrial scale. An inspection of these data allows establishing many perspectives for this process.

The principal variant consists in preheating air at the place of preheating salt water. Since the HD process allows low-temperature energy to be used, particular attention was paid to the use of solar energy in this kind of process [4,6]. Efforts have been focused for some time on recovering the latent heat from condensation. Preheating of the feed water by passing it over the glass cover allows only partial utilization of the latent heat, resulting in a limited increase in still production [7,8]. The multiple-effect humidity process allows increasing the efficiency of the system.

The experience acquired in the past by several authors [2,9] shows that a sufficient quantity of heat can be recovered by extracting the mixing air–vapor at different points of the evaporator tower. In the experience of Dini [10], evaporation occurs with a variable flux of air extracted with quantities proportional to the temperature. The described experience concerns extraction with seven different temperatures.

Al-Hallaj et al. [5] investigated a solar desalination unit functioning by humidification and dehumidification (Fig. 2). In their unit the circulated air by natural or forced convection was heated and humidified by the hot water obtained either from a flat-plate solar collector or from an electrical heater. The latent heat of condensation was recovered in the condenser to preheat the saline feed water.

Two units of different sizes were constructed from different materials. The productivity of these units was found to be much higher than those of the single-basin stills. Moreover, these units were able to product a large quantity of saline warm water for domestic uses other than drinking. The authors showed that no significant improvement in the performance of the desalination units was achieved using forced air circulation at high temperatures. While at lower temperatures, a larger effect was noticed. The authors related this behavior to the low mass transfer coefficients at low temperatures and to the non-linear increase in the water vapor pressure with temperature.

The authors highlighted a strong effect of water flow rate on unit production. In fact, the unit production first increases upon increasing the flow rate to an optimum value. Beyond that value the unit production decreases with increasing water flow rate. This is because increased water flow rate increases both heat and mass transfer coefficients as well as the solar collector efficiency. At the same time it lowers the operating water temperature in the unit and hence, lowers the evaporation and condensation efficiency.

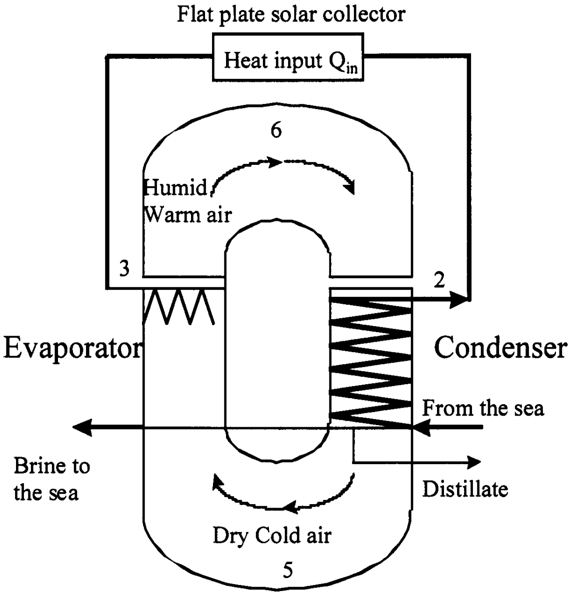

Fig. 2. Schematic diagram of the unit [4].

According to this investigation, it was shown that the mass of the unit is another factor that negatively affects the unit performance. A delay of 3 h was noticed between sunrise and the start of production of fresh water. It was noticed that most of the energy received in these early hours is used as sensible heat to warm up the large mass of the unit, which was about 300 kg. This lag time could be avoided by using a lighter material than galvanized steel for construction.

Water desalination by HD also presents an interesting solution for irrigation purposes. Chaibi et al. [6] investigated three different configurations for water desalination by humidification: a solar desalination plant with a single-effect process using heat pipes collectors, an integrated solar desalination system in a green house and a solar multiple condensation evaporation (SMCE) cycle process. The economy evaluation showed that the integrated solar still

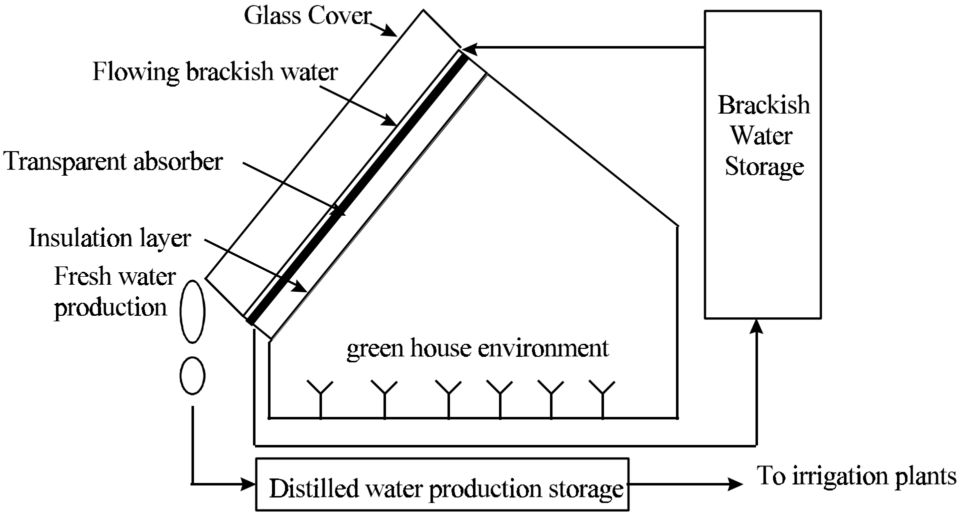

Fig. 3. Integrated solar still as part of a greenhouse with a controlled environment [6].

as a part of a greenhouse with a controlled environment (Fig. 3) is more economical than the assisted solar desalination plants by 35% and 50%, respectively, when compared to the SMCE cycle process and single-effect process using heat pipes.

Metha [3] was the first to introduce an air-recycling system in which air coming from the dehumidifier is recycled in the humidifier. It was shown that the use of air recycling gives a cost reduction of more than 7%. The advantages obtainable by this air-recycling system consist of more than a 20% reduction in the packed height of the humidifier and more stable operation of the plant. He also investigated the economics of combining an HD plant with power plants or with chemical industries using seawater as coolant.

An interesting alternative desalination concept is the collection of potable water by first humidifying an air current by contact with warm seawater and then dehumidifying by cooling. Recent studies of this concept have been conducted by Farid and Alhajaj [11] and Nawayesh [12]. These authors consider the use of solar energy as the heat source and determine the principal operating parameter for the system consisting of a humidifier, a dehumidifier and heating equipment for air and feedwater. Inlet water temperature is singled out as the most significant factor affecting system productivity, and the use of latent heat of condensation to preheat saline feed water is implemented to increase energy efficiency.

A new desalination process based on a combination of the principles of HD and mechanical vapor compression was developed by Vlachogiannis et al. [13]. This process combines the principles of intensive evaporation, vapor compression and heat pump (mechanically intensified evaporation, MIE) [14]. The concept is illustrated in Fig. 4.

Air is injected in the evaporation chamber through a porous bottom wall and is dispersed as small diameter bubbles. The emerging saturated stream is compressed by a blower to a slightly higher pressure ($\Delta p = 0.05$–0.25 bar) and is directed to the adjacent condensation chamber. Because of the increased pressure, water condensation occurs at a slightly higher temperature than evaporation, and the latent heat is transferred

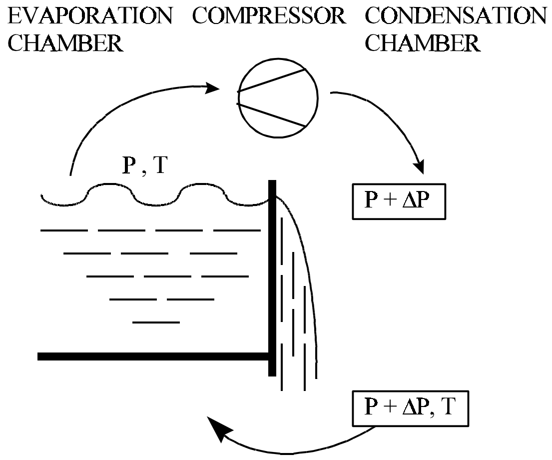

Fig. 4. A combination of principles of HD and mechanical vapor compression [13].

back to the evaporation chamber through the thermally conducting sidewall. The advantages of this process are low-cost construction, simple and flexible operation and suitability for modular design.

To reduce the capital cost of humidification installation, especially the solar collectors, other energy resoures can be used. Bourouni et al. [3] developed a new HD process using geothermal energy. The unit consists of two horizontal-tube, falling-film exchangers (an evaporator and a condenser). Both exchangers are made of horizontal tube bundles made of polypropylene (Fig. 5). In the evaporator the cooled hot water enters at a temperature of about 70°C and moves down in the tubes. The cooling air moves up in the space between the tubes. The salt liquid film is dripped from a distributor in the top of the evaporator and falls from tube to tube. A fraction of water is evaporated and carried by the ascendant air flow, maintained by a blower. At the top of the exchanger the hot humid air is driven to the condenser where distilled water is recovered. Heat recovery in a low-temperature process requires an important exchange surface. For this reason, 2000 m of tubes are used in the evaporator and 3000 m in the condenser.

The difference between this process and the classical HD technique is that the heat required for the evaporation is not provided by air but by hot brackish water (geothermal). For the development of this process two units were tested: the first in a laboratory in France and the second in the south of Tunisia using a geothermal spring.

The results obtained in this investigation showed an important influence of inlet water and air temperatures on the amount of distilled water. Experimental data showed that the evaporated water amount increases linearly with air inlet temperature and decreases with air velocity. The use of the plastic materials in the HD process solves the problems of cooling and corrosion. The use of geothermal energy abundant in the Magrebian countries reduces cost threefold.

Abualhamayel and Gandhidasan [15] developed a new process to obtain fresh water when no salt water is available. This process is based on extracting fresh water from the humid atmosphere (dehumidification). In fact, the ambient atmosphere contains a large quantity of water in varying amounts since water continuously rises into the air in the form of vapor (surfaces of plains, fields, mountains and hills, etc.).

The extraction of water from humid atmospheric air can be accomplished by different methods. Some of the methods are:

- mechanical
- refrigeration (absorption, vapor compression)
- adsorption
- absorption

The authors propose using a suitable liquid desiccant to extract fresh water from the humid atmosphere (Fig. 6).

Night-time moisture absorption and day-time moisture desorption take place in the same unit, which consists of a flat, blackened, tilted surface and is covered with a single glazing. During the night, the strong absorbent flows as a thin film over the glass cover in contact with the humid

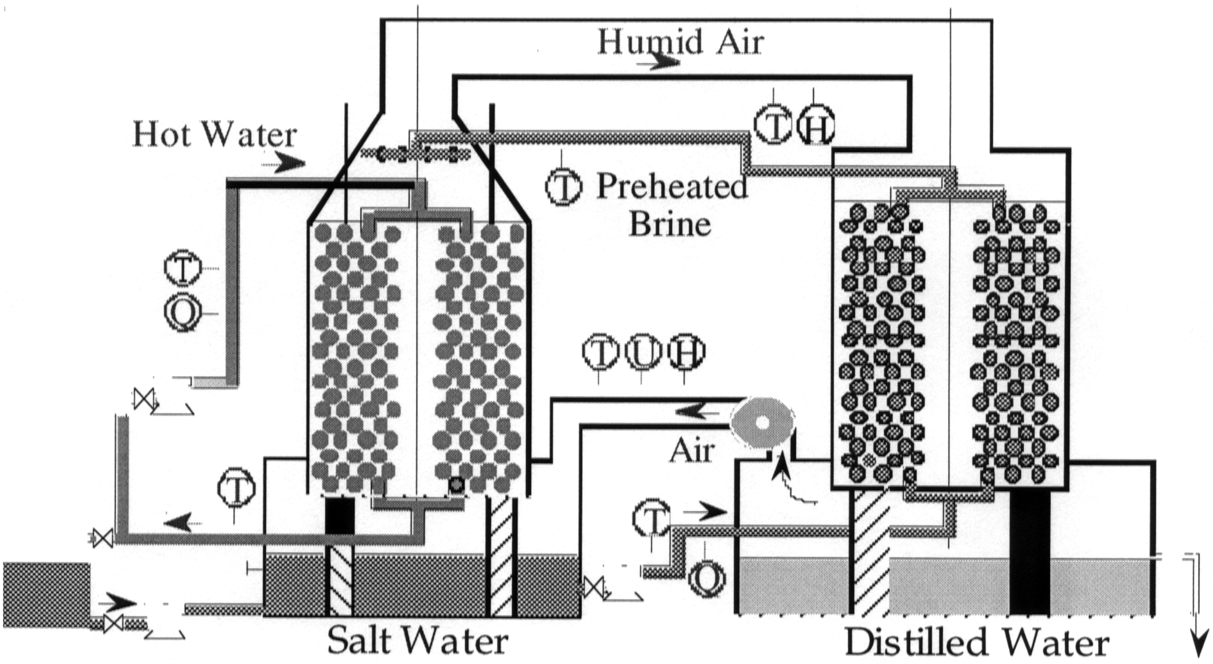

Fig. 5. Aero-evapo-condensation process developed by Bourouni et al. [3].

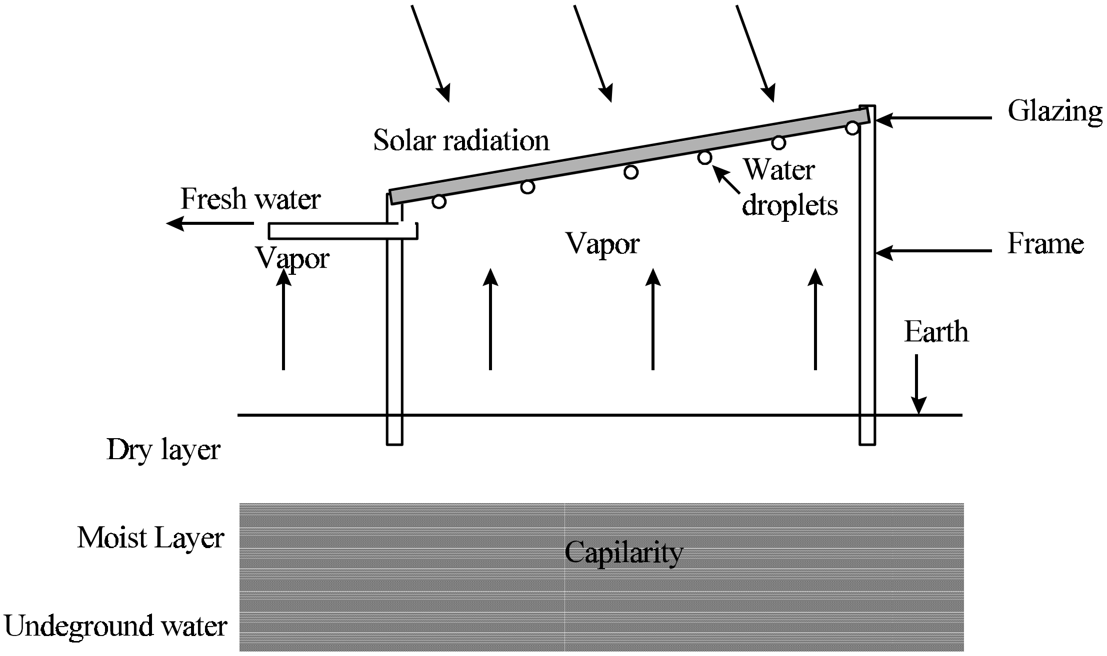

Fig. 6. Principle of earth water collector [15].

ambient air. Due to absorption of moisture from the ambient air at night, the absorbent becomes diluted. In order to recover the fresh water from the weak absorbent, it flows down as a thin film over the absorber during the day and is heated by solar energy. The water that evaporates from the absorbent raises the glass cover by convection where it is condensed on the underside of the glass cover. The absorbent leaving the unit becomes strong and ready for moisture absorption at night. The performance of the unit was computed analytically for typical summer climatic data in Dharan, Saudia Arabia. It was shown that for the given operating conditions it is possible to obtain about 1.92 kg/m^2 of water from the unit.

It was found that the increase in absorbent solution flow rate increases the rate of absorption of water from the atmosphere but decreases the desorption rate of water during day time operation. Experimental studies are in progress, and an economic study is required to determine its feasibility.

6. Conclusions

Desalination is characterized by rapidly evolving technologies. Many new desalination plants are tested and installed each year worldwide. The desalination processes have reached maturity (technical an economic), allowing them to have a more important role in the future in water supply. Such installations can be constructed with different technical techniques and with great flexibility of dimensions and energy consumption (a function of energy resources and the situation). Multistage flash distillation (MSF) is the most commonly used process. About 50% of the installations in the world use this technique. On the other hand, for less production, the efficiency of the classical distillers decreases because it is difficult to realize a certain number of effects in small installations. For these smaller installations (rural regions, for example), classical distillers are not appropriate: the cost of the installation, the energy consumption and hence the water cost are very high.

The HD process presents a very interesting solution for small units (hotels, rural regions, light industry, etc.), especially when new materials are used. The process is very convenient in cases where heat is available at low temperature at an attractive cost (cogeneration, solar energy, geothermal energy, etc.). Bourouni et al. [3] showed that the cost of water can reach \$1.2 in the case of coupling a HD unit with geothermal spring.

HD installations can be used for the low-temperature part of classical distillers to avoid effects in which distillers have to function (vacuum).

Coupling HD units with desalination collectors presents a very interesting solution; however, the water cost is relatively high. One reason for this is that solar heating necessitates significant investment in solar collectors and land. Another is that very large amounts of air need to be recirculated because the quantity of water normally contained in saturated air is minimal. Thus, air pumping alone may represent a prohibitive energy cost [16].

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