# Exergy analysis of dehumidifier in a combined two stage desalination and cooling plant

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**ABSTRACT**

In this study, the performance of dehumidifiers is evaluated with different cooling media in a two stage solar humidification-dehumidification (HDH) desalination plant. The first stage dehumidifier is circulated with normal cooling water for dehumidification whereas chilled water is used in second stage dehumidifier. Dehumidifier is an essential component in desalination plant, which will influence fresh water output, so a detailed exergy analysis of the dehumidifier is carried out. Irreversibility loss, second law efficiency variations are studied against the cooling water inlet temperature of the humidifier. A minimum irreversibility loss of 0.066 kW and 0.13 kW are observed at first and second dehumidifiers respectively at 27 ˚C inlet temperature and 225 LPH volume flow of cooling water. The second law efficiency is increased with increasing in flow rate but there is no significant impact above 250 LPH for first dehumidifier and 150 LPH for second dehumidifier. The optimum operating inlet water temperature and air cooling is obtained between 25˚C – 32˚C and 13˚C - 25˚C respectively for normal water and chilled. An increase of 0.6 LPH of fresh water is observed with the chilled water cooling, compared to normal water cooling.

**KEY WORDS:** air, dehumidification, desalination, exergy, irreversibility.

## 1. INTRODUCTION

In past recent years energy conservation is major research point. A lot of research has been done on using renewable energy sources as energy source. Solar energy is major renewable energy source which falls on earth and return back unused. Solar energy is one of largest source of energy freely available. The proposed system uses solar energy to desalinize water and air conditioning. This makes the plant less dependent on electricity, which is ideal for hot places where sun radiation is high and having water scarcity.

Nawayseh (1997), showed solar desalination with humidification and dehumidification (HDH) process to be efficient method for solar energy utilization. Yamli (2008), did experiment on HDH process and concluded that with increase in mass flow rate of the air fresh water productivity remains same. Orfi (2007), did theoretical study on solar desalination system using HDH technique and showed an optimum water to air mass ratio ranges from 1.6 to 2.2 for a maximum yield of 0.05 grams of fresh water per unit kg of dry air. Lai (2010), introduced a hybrid system which produces thermal energy via both electricity and town gas from and showed large amount of electricity consumed in air conditioning of a commercial building. A lot of work has been done in area of integration of energy systems. Tamm (2003), had used cooling system in their combined thermal power and cooling cycle. Srinivas (2014), invented a new cooling cogeneration cycle by coupling vapor power cycle and vapor absorption refrigeration cycle. Chiranjeevi (2014; 2015), developed a model for parametric study of a combined two stage HDH desalination plant integrated with cooling system. They also carried out experiments on pilot plant and compared the experimental results with simulated results.

The exergy analysis concept is considered as a potential tool to for analysis and performance evaluation of a given system. Muthusamy (2015), has done energy and exergy analysis for a modified HDH desalination plant and showed the enhanced system produced 45% increase of productivity when compared to conventional system. Also, the modified system enhanced the heat output and productivity equivalent to a power saving of 40% and 13% respectively for same input power. Mohammed A Elhaj (2013), developed a model to determine the component exergy destruction and exergetic efficiencies of desalination system and concluded that the exergy efficiency of the humidifier increases by increasing the mass ratio and decreasing the outlet air temperature. Shaobo Hou (2007), conducted an exergy analysis on the components of a multi effect HDH desalination system and identified the solar collectors have lowest exergetic efficiency. Ashrafizadeh (2012), developed exergy losses relations for closed air open water-water heating and closed air open water-air heating desalination systems based on individually irreversibility factors. The results showed that the mass transfer phenomenon does not have any effect on the total exergy losses of the HDH system. Fahad Al-Sulaiman (2013), carried exergy analysis of a water desalination system using combined humidification-dehumidification and reverse osmosis technology and identified the 50 % of the total exergy destruction occurs in the thermal vapour compressor, dehumidifier also affects the performance of the system. Martin Salazar-Pereyra (2011), studied energy and exergy analysis for moist air and generated psychrometric charts to analyse the air thermodynamic behaviour for different environmental variations. Karan H Mistry (2010), studied irreversibility analysis on humidification-dehumidification desalination cycles to minimise the specific entropy generation. It is also observed that each cycle have one limiting component that cannot be substantially improved. Fawzi Banat (2008), calculated the thermodynamic losses in a solar-powered membrane distillation unit using the exergy concept and found that highest exergy destruction occurs in the membrane distillation module.

## 2. METHODOLOGY

Humidification is the process of addition of vapor to the dry air, which can be achieved by spraying hot water into the stream of dry air or passing hot dry air in a water container. The vapor carrying capability of air increases with increase in air temperature, this process takes place in humidifier. For efficient humidification packing material is kept in the humidifier to provide more surface area for water. Dehumidification is the process of extracting/condensing excess vapor from the humid air by passing it over a cold steam of air or water leads to the production of fresh water, which takes place in dehumidifier. A humidifier can be a surface condenser with chiller water or air will flow through tubes and humid air flow over the tubes. SHDD system can be operated with closed air open water (CAOW) arrangement or open air closed water (OACW) arrangement.

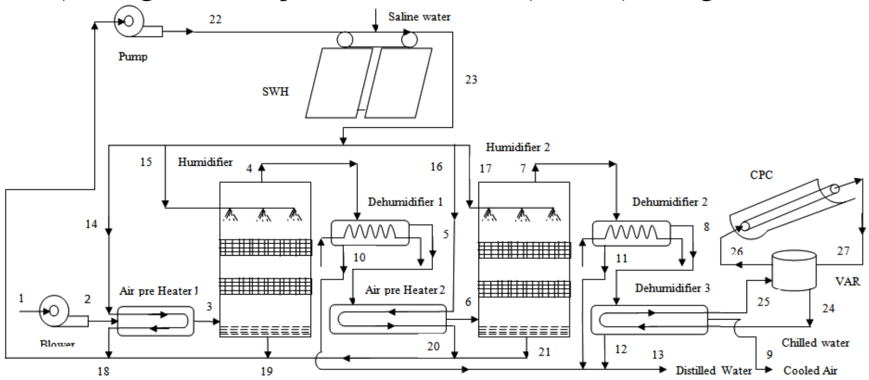


**Fig.1. Schematic diagram of two stage desalination plant**

A schematic diagram of the proposed two stage OACW system is shown in Fig.1. The state properties are tabulated in Table 1 for the flow diagram shown in Fig. 1. A blower is located at the inlet of desalination plant, forces the atmospheric air into the first air preheater. The temperature of the air is increased by using hot water supplied from solar water heater (SWH). The hot air then enters the first humidifier will pass through the wetted packing. As the temperature of hot water is more than the inlet air from the first air preheater, heating and humidification results in humidifier. The water temperature at the exit of first humidifier will decrease by latent loss to air. Depending on the heat and mass transfer conditions air at the exit of first humidifier picks the moisture from hot water. After heating and humidification the humid air enters into an air cooled dehumidifier for the first stage desalination. The cooling and dehumidification results in condensed distilled water at state 10 collected at point 13. The processes in the first stage are repeated in the second stage desalination. To achieve more yield in desalination the air coming from second dehumidifier is further cooled by chilled water. The chilled water is generated in vapor absorption refrigeration (VAR) system using solar energy.

Solar flat plate collectors are used to generate the hot water and stored in a daily storage tank which can be used for air preheating and humidification of air. The outlet conditions of the air at state 4 depend on the hot water temperature, spray characteristics and the inlet conditions of air at state 3. The VAR plant considered can be a single effect system having ammonia-water mixture as a working fluid. The heat required to generate ammonia vapor is given by a thermic fluid circulated through a solar concentrated parabolic collector and a generator. The total energy supplied to the HDH plant is the sum of heat supply in SWH, heat taken away by chilled water and parasitic power to operate blower, pump and fans. Fig.2 represents the experimental setup fabricated with instrumentation per the schematic show in Fig.1.


**Fig.2. Experimental setup with instrumentation**

Exergy is known as the available useful work and second law efficiency is the measure of effective utilization of energy in the process. The effective utilization depends on both system and surrounding. The results from exergetic analysis can be used in further improvement of the plant components. Following are the formulae used for exergy analysis of dehumidifier.

Entropy of air:

$$S_a = C_{pa} ln\frac{T}{T_0} - R\, ln\frac{P}{P_0} + w\, S_g \qquad (1)$$

Entropy of water:

$$S_w = C_{pw} ln\frac{T}{T_0} \qquad (2)$$

Exergy of particular stage:

$$e = h - T_o\, S \qquad (3)$$

Exergy loss by dehumidifier:

$$E_{loss} = m_{ai}e_{ai} + m_{wi}e_{wi} - m_{ao}e_{ao} - m_{wo}e_{wo} - m_{fw}e_{fw} \qquad (4)$$

Exergy efficiency of dehumidifier:

$$\eta_2 = 1 - \frac{E_{loss}}{E_{in}} = 1 - \frac{E_{loss}}{m_{ain}e_{ain} + m_{win}e_{win}} \qquad (5)$$

Effectiveness of dehumidifier:

$$\varepsilon = \frac{(T_{cwo} - T_{cwi})}{(T_{ai} - T_{cwi})} \qquad (6)$$

## 3. RESULTS AND DISCUSSION

The second law analysis is carried out for optimization of the dehumidifier design. The varying parameters considered are cooling water inlet temperature and cooling water mass flow rate. Irreversibility loss and exergy efficiency has been plotted against the varying parameter to conclude which is most efficient operating condition for the dehumidifier. Experimentation on the dehumidifier has done for both cases with normal cooling water and with chilled cooling water.

MATLAB code has been developed for the optimization of dehumidifiers design. Fig.3 shows the variation of irreversibility loss with change in temperature of cooling water, for different cooling water mass flow rate. First irreversibility starts decreasing with increase in temperature up to a certain temperature after that it starts increasing. The optimum temperature for each mass flow rate is between 25˚C - 32˚C. For higher mass flow optimum temperature is nearer to 25˚C and for lower mass flow rates it's nearer to 32˚C. For 100 LPH it can be observed that the optimum temperature is seems to be fall after 45˚C. But there is no need for analyzing after 45˚C because the inlet temperature of humidified air is 50˚C. It can be observed that irreversibility loss is minimum around 27˚C. Also for a fixed temperature irreversibility loss decreases with increase in mass flow rate of inlet water. The loss is higher at lower temperatures with increase in temperature it decreases till 25˚C then starts increasing.

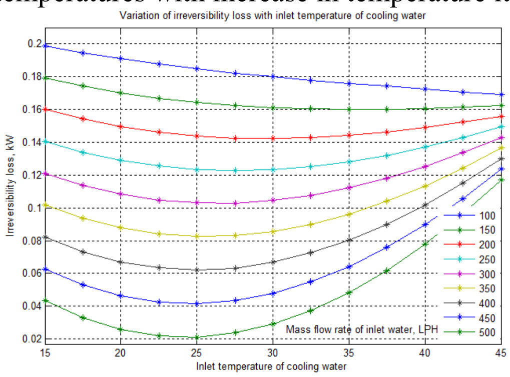


**Fig.3. Variation of Irreversibility loss with change in temperature of cooling water**

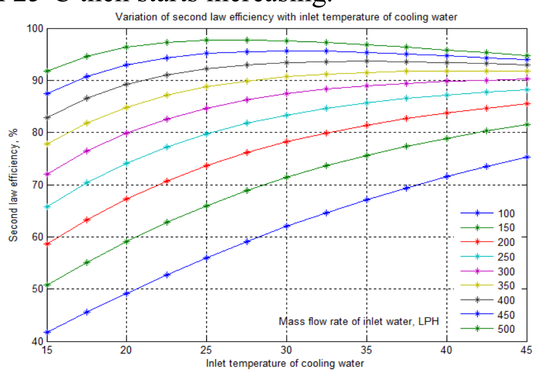


**Fig. 4. Variation of exergy efficiency with variation in temperature of cooling water**

Fig.4 shows the variation of exergy efficiency with variation in inlet cooling water temperature for different mass flow rate of inlet cooling water. For a particular temperature, second law efficiency increases with increase in mass flow rate as irreversibility has observed decreasing. It can be observed that for every temperature there is a maximum limit of mass flow rate. After which exergy efficiency will go more than 100% which is not possible. Also for high mass flow rate, with increase in temperature second law efficiency increases up to certain point after that it starts decreasing but for low mass flow rate values it keeps increasing. It can observe that the range maximum exergy efficiency for high inlet water mass flow rate lies between 25˚C and 32.5˚C.

From the graph it can be observed that the optimum mass flow rate can be achieved is 500 LPH at 25˚C. Also for any temperature 500 LPH mass flow rate gives maximum exergy efficiency, but power of pump required for 500 LPH is more. So it is better to choose optimum mass flow rate according to inlet temperature available.

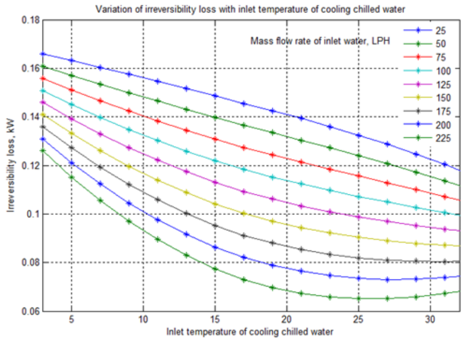


**Fig.5. Variation of irreversibility loss with inlet chilled water temperature**

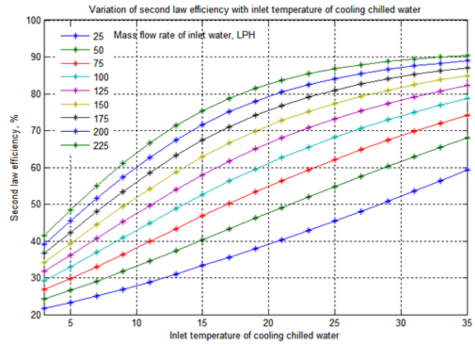


**Fig.6. Variation of exergy efficiency with inlet chilled water temperature.**

The Fig.5 shows the variation of irreversibility loss with change in chilled water inlet temperature for different chilled water mass flow rate. With increase in mass flow rate at given temperature irreversibility loss decreases. There is a maximum mass flow rate limit for every temperature, after which irreversibility loss will be negative.

The irreversibility loss decreases with increase in temperature for low mass flow rate of inlet chilled water. For high mass flow rate irreversibility first decreases with increase in temperature upto an optimum temperature after that its start decreasing. It is observed that at low temperature loss is high, but in order to obtain high fresh water output the dehumidifier can be run at lower temperature.

It is observed from the Fig.6, for a given temperature, with increase in water mass flow rate exergy efficiency of the dehumidifier is increasing as irreversibility loss is decreasing. For a given mass flow rate, the second law efficiency of the dehumidifier is increasing with increase in inlet temperature of the chilled cooling water as irreversibility loss is observed decreasing.

After second law analysis of both dehumidifiers it can be observed that, for the designed dehumidifier 25˚C - 30˚C is optimum temperature range of inlet cooling water in order to maximize the energy utilization and minimize the irreversibility loss for a given mass flow rate. But to get high yield of fresh water it can be operated at lower temperature of inlet cooling water. Also at lower temperature low mass flow rate of water is required so at pump load will be lower.

Improvement in fresh water production is one of the objectives. Production of fresh water has been observed for whole day for 10 days. Average fresh water produced from both dehumidifiers has been plotted to observe the increment in the production with respect of hours of the day.

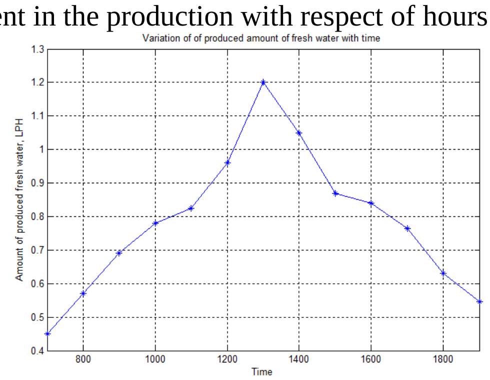


**Fig.7. Average amount of produced water from first dehumidifier with different time of the day**

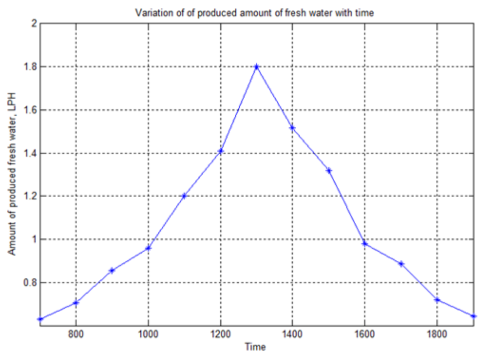


**Fig.8. Average amount of produced water from 2nd dehumidifier with different time of the day**

The Fig.7 shows the average amount of water produced from 1st dehumidifier with different hours of the day. It can be observed that maximum water produced is in afternoon time specially 12 PM to 2 PM. The reason can be understood as the solar radiation is high at the time due to which humidifier humidifies the air at higher level.

From the Fig.8 it is observed that the second dehumidifier also follows the same behavior as of first dehumidifier. The only difference is the amount of water produced from second dehumidifier is more than the first dehumidifier at a given time.

The increase in amount of fresh water yield leads for an increase in Gained Output Ratio (GOR) of the plant and Energy Utilizing Factor (EUF) of plant will increase with the production of more fresh water and the cooling effect from chilled water.

## 4. CONCLUSION

Exergy analysis is carried out on dehumidifier for optimum operating conditions to get a maximum yield of fresh water and cooling effect from chilled water. Cooling system has been integrated with the dehumidifier results in increased dehumidifier effectiveness. The yield of fresh water is maximum at 1 PM as the solar radiation is high for the day. During this time the difference in average amount of fresh water produced is 0.6 LPH. The temperature of cooled air obtained was in the range of 13˚C to 26˚C. Due to production of more fresh water and cool air it can be concluded that integration of cooling system can increase the EUF and GOR of the plant. The second law analysis for the dehumidifier gives optimum operating conditions for dehumidifier to run between temperature range of 25˚C to 32˚C.

## 5. ACKNOWLEDGMENT

The authors acknowledge the project grant of the Council of Scientific and Industrial Research (CSIR), New Delhi, India (22(0627)/13/EMR-II).

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