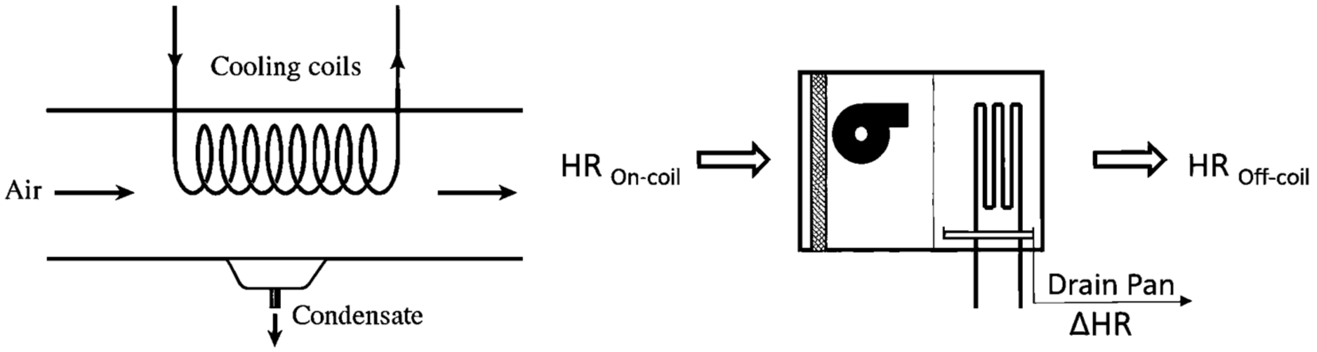
Journal of Applied Research in Water and Wastewater
E-ISSN: 2476-6283
Journal homepage: https://arww.razi.ac.ir

Potential of condensate as a water source from air conditioning systems: A thermodynamic analysis

Koorosh Goudarzi

Department of Mechanical Engineering, Faculty of Engineering, Yasouj University, Yasouj, Iran.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article type:
Research Article

Article history:
Received 5 July 2024
Received in revised form 10 October 2024
Accepted 14 October 2024
Available online 16 October 2024

Keywords:
Air conditioning systems
Cooling coils
Condensates
Water
Thermodynamic analysis

ABSTRACT

A considerable amount of water condensate produced through the cooling coils of air conditioning systems is usually directed to municipal sewage systems and wasted along with the energy it contains. This energy can instead be utilized to increase the efficiency of air conditioning systems and refrigeration systems in cold storage facilities, save energy consumption, reduce the carbon footprint, and also meet some of the water consumption needs. Since the choice of how to use condensate energy depends on its potential, i.e., the amount of collected water, this thermodynamics study estimates the amount of collected water and investigates the effects of various parameters such as ambient temperature, relative humidity (RH), coil temperature, etc., on the amount of water produced. The research results indicate that RH and air flow rate over the cooling coil have the greatest impact on the amount of water produced.

1. Introduction

The amount of water produced from condensates in air conditioning units and colling plants has very high potential in areas with warm and humid climates (Oki and Kanae, 2006). Therefore, in many cities in Iran such as Bushehr and Bandar Abbas, this potential can be utilized. Data obtained from the meteorological organization indicate and confirm that in these areas, the outside air humidity levels are high during the mornings, evenings, and nights throughout the year (Shiklomanov and Rodda, 2003). As mentioned, many cities in Iran have warm and humid climates and almost use air conditioning units throughout the year. As a result, a considerable amount of condensate water is produced through the cooling coils of air conditioning units. This relatively low-temperature condensate water can be collected and recycled using appropriate methods. This free source of cold energy can be used to reduce mechanical system costs, decrease cooling demand, enable the selection of smaller air conditioning equipment, maximize energy efficiency, reduce carbon footprint, and enhance the thermal comfort of occupants.

Historically, the world's water reservoirs and their limitations for extraction and use by researchers have been identified. Among them, water vapor in the atmosphere is considered as a complementary source of fresh water (Shiklomanov and Rodda, 2003; Oki and Kanae, 2006). This is because the atmosphere contains a large amount of vapor, about 1.29×10^{13} m^3, which is ubiquitous and can be obtained without geographical or hydrological restrictions. This allows households to access clean water without additional purification stages (Zhou *et al*., 2021; Humphrey *et al*., 2020; Jiao *et al*., 2020).

In the cooling systems used in buildings, air passes over the cooling coils in the air conditioning units before entering the desired space, converting moisture into water. In the past, water was directed into a channel and sent to the sewer. Today, especially in areas where water is rare and the rate of water production is high, many building owners collect this water for various uses. For example, at the Cancer Institute, 900,000 gallons of water are collected annually from HVAC systems and directed to reduce the cost of tower feed water of cooling towers. Similarly, at Rice University, a few percent of the total water consumption per year is obtained from the condensation of water vapor,

*Corresponding author Email: kgoudarzi@yu.ac.ir

Cite this article: K. Goodarzi, Potential of condensate as a water source from air conditioning systems, a thermodynamic analysis, *Journal of Applied Research in Water and Wastewater*, 11 (2), 2024, 90-94. doi: https://doi.org/10.22126/arww.2024.10740.1334

and used for the water needed by the condenser. Assuming that Houston combined (freshwater and wastewater) cost of $8 per 1,000 liters, the university saves 96,000$ per year. Other researches and projects have demonstrated economic feasibility, prompting engineers to closely examine fluid recovery systems (EPA, 2007; Hernandez, 2011). The mass flow rate of water produced in HVAC systems is variable. Its value depends on parameters such as the power and capacity of HVAC equipment, the temperature range at which the HVAC system operates, RH and the temperature of the air, among others (Cunha *et al*., 2015). A system for integrated water recycling in a sample building was studied and designed (Gasseling *et al*., 2012). This type of building was chosen because hotels require both HVAC and a large amount of water. Additionally, hotels are significant for local water management, especially in terms of their impact on urban water usage. In fact, the water consumption footprint of tourism is a fundamental issue at the local level, as daily water consumption in hotels, is almost always higher than residential consumption.

In Bangladesh, almost all modern buildings use HVAC cooling systems. These cooling systems produce a noteworthy and underutilized source of fresh water. This water source is mostly discharged into the sewage systems and streets. Considering the water scarcity in Bangladesh, wastewater can be considered an alternative water source, playing a dynamic role in water supply when fresh water is inadequate. The highest water flow rate was observed in the Panasonic brand (3.64 liters per hour) compared to other brands used in Bangladesh (Uddin *et al*., 2019).

A study is conducted on a two-story concrete building with an area of 32,500 m^2, which is the central campus of a university (John and Ahmed, 2008). The HVAC system of this building is provided through 25 separate air conditioning units. These units receive cold water from a cold-water production facility. All air conditioners are installed on the ceiling. It was found that wastewater collection in this building is done through external piping from the air conditioner to the ceiling overflow drain. They used two air conditioning systems for monitoring and collecting wastewater. Air conditioner number 6 mainly served classrooms and administrative areas, while air conditioner number 23 served the chemistry, physics, and biology areas. The results presented by them covered a four-week period from August 5th to 8th. During this period, wastewater collection varied from zero to the maximum amount for the 100% outdoor air unit. The results showed a corresponding increase in the collected wastewater amount with an increase in the average dew point temperature. During the four-week period, 4,075 gallons (15,443 liters) of wastewater were collected in air.

In line with efforts for water sustainability, water conservation, and the production of environmentally friendly technologies, as well as the development of water resources, a study on the recovery of condensate from HVAC systems is presented by Algharni and colleagues (2018). They discussed advancements in condensate recovery systems, quality limitations, and potential applications. They also described the issues, challenges, and future directions for research. Given the current water crisis and the push for clean energy sources, this topic provides a significant opportunity for study and advancement in order to develop practical condensate recycling systems for buildings and other applications. Therefore, if planned during the design phase of buildings, the collection, storage, and reuse of condensate will be easier. Although the cost of condensate recovery systems is about 3 to 5 percent of the total mechanical system costs for new buildings, it is entirely justifiable due to the potential significant applications of condensate.

A study on the chemical and physical properties of produced condensate was conducted that the existence of heavy metals was examined (Matarnah and colleagues, 2024). To confirm that the water quality meets the standards set by the Jordanian standards (JS) for consumption water and FAO guidelines for irrigation purposes, the experimental results of water quality were evaluated. Their study provided interdisciplinary approaches to understanding the feasibility and acceptance of reusing condensate, thus paving the way for sustainable water practices.

A study focused on the humid and hot climate of the United Arab Emirates (UAE) over five years is presented (Khan and colleagues, 2014). They provided information that can be used to estimate the amount of cold condensate during the cooling and dehumidification process in HVAC systems, especially through fresh air handling units, for the preservation of drinking water.

Despite the relatively good studies conducted on the water production capacity from condensate in HVAC systems and the investigations carried out to recycle the energy from this condensate and utilize it in different parts, it seems that the study of the possible factors affecting the amount of water produced from condensate in HVAC systems has not been conducted so far. Therefore, this study focuses on the thermodynamic analysis of the impact of various parameters such as air flow rate, RH, etc. on the amount of water produced from condensate.

2. Estimation and calculation of water production from HVAC

In order to evaluate the economics, engineers first need to estimate the annual amount of condensate water obtained from HVAC systems. Factors affecting the collection of this water include: weather conditions, the percentage of incoming air to the cooling coil, the RH of the environment, and the number of operating hours of the HVAC system per year. The maximum amount of vapor is related to the vapor present in the air that enters through open doors and infiltrates the interior. There are several methods for calculating the mass flow rate of water produced from vapor condensation in the air. Some methods are easy and approximate, while others are very precise but require extensive time and experience in mass flow analysis. In this paper, we use a simple method for determining the amount of condensate water from the cooling coils.

The flow rate of condensate water in an HVAC unit can be determined by the amount of vapor that the cooling coil can remove from the air at a given time. Fig. 1 shows a schematic of a cooling coil.

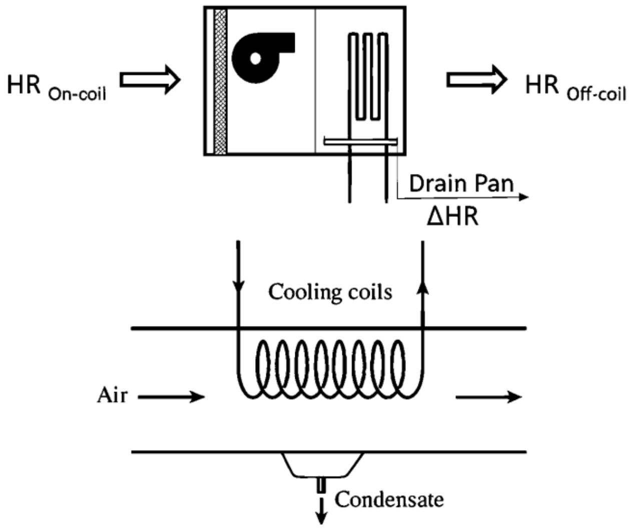


Fig. 1. Schematic of a coiling coil in an HVAC system.

The mass flow rate of the air passing through the cooling coil depends on the type of HVAC, the capacity of the refrigeration system, the type of use and the ambient air conditions. In the present study, it is assumed that the mass flow rate of the air flow passing through the cooling coil is steady, and the ambient air conditions are assumed to be constant.

To calculate the mass flow rate of the condensate water, the following steps must be performed. At first, the difference in humidity ratio (HR) between the incoming air (near the coil) and the outgoing air (away from the coil) is calculated. This difference indicates how much humidity has been removed from the incoming air by passing through the cooling coil.

$$\Delta HR = HR_{on-coil} - HR_{off-coil} \quad (1)$$

$HR_{on-coil}$ represents the HR of the arriving air, and $HR_{off-coil}$ represents the HR of the outgoing air.

Then, from the volumetric flow rate of air ($\dot{V}$), the mass flow rate of air ($\dot{m}_{Air}$) passing through the cooling coil at a given time is determined by Eq. 2.

$$\dot{m}_{Air} = \rho_a \, \dot{V} = \frac{\dot{V}}{v_a} = \frac{V\left(\frac{m^3}{change}\right) ACH\left(\frac{change}{s}\right)}{v_a} \quad (2)$$

where, $\rho_a$is the density of the air, which depends on temperature and pressure, can be obtained from the specific volume of wet air per unit mass of dry air, using a psychrometric chart or any online psychrometric calculator. V is the air volume and ACH is number of air changes. v_a is volumetric density of air. Therefore, the mass flow rate of condensate water can be calculated using the following equation:

$$\dot{m}_{cond} = \dot{m}_{Air} \Delta HR \quad (3)$$

The amount of produced water is related to the HR of the air, the amount of air passing through the cooling coil, and the times of air changes in the refrigeration system.

3. Results and discussion

The results examine the volume of water produced in air conditioning systems and the mass flow rate of water produced from the condensation of water vapor in the air. The impact of various parameters on the amount of condensate water, such as the percentage of incoming air (percentage of total circulating airflow) that brings water vapor to the cooling coil, ambient temperature, RH, and the operating hours of the air conditioning system per year, is investigated. For example, in accordance with Fig. 2, an air conditioning system is selected that uses a compression refrigeration system for space cooling.

Initially, it is assumed that the mass flow rate of air through the cooling coil of the refrigeration system depicted in Fig. 2 is 4.21 m^3/h. The effect of the RH of the incoming air to the cooling coil is shown in Fig. 3 for three values of the RH of the air leaving the cooling coil. Similarly, the impact of the RH of outlet air from the cooling coil on the volume flow rate of the produced water is shown in Fig. 4.

As shown in Figs. 3 and 4, the highest amount of water is produced when the RH of the incoming air is high and the RH of the outlet air from the coil is low. As it is known in equation 3, the amount of condensed water depends on the difference between the humidity ratio of the incoming and outgoing air from the coil. The difference in humidity ratio also directly depends on the difference in RH of the air passing through the coil. Therefore, as this relative humidity difference increases, the amount of water produced also increases.

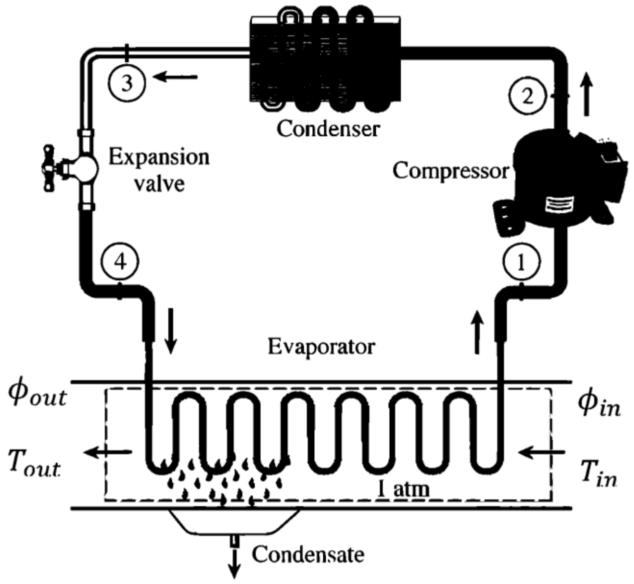


Fig. 2. Schematic of a coil in a vapor compression refrigeration system.

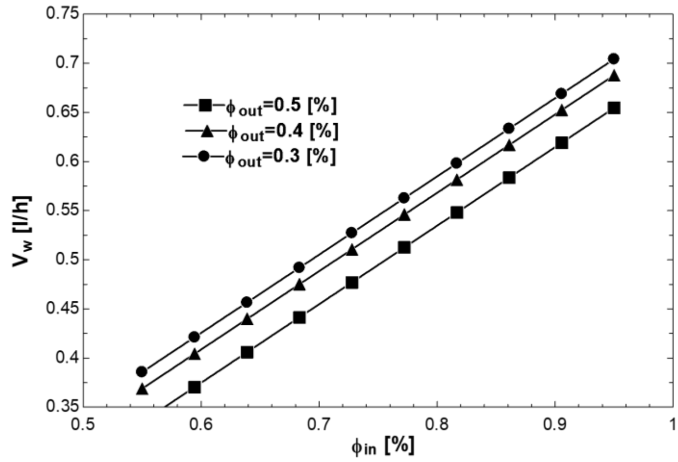


Fig. 3. Effect of the RH on the volumetric flow rate of the produced water.

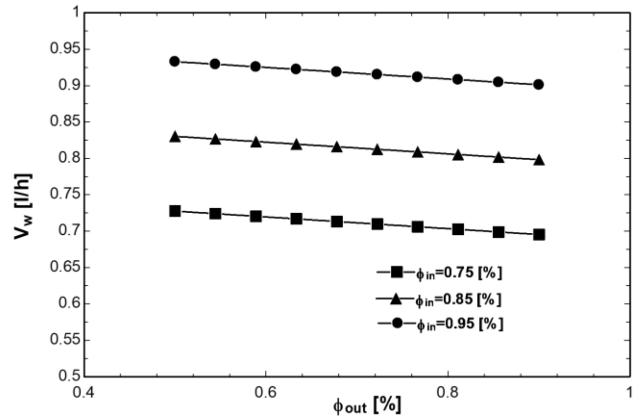


Fig. 4. Effect of the RH on the volumetric flow rate of the produced water.

Fig. 5 shows the effect of the temperature of the incoming air on the volume flow rate of the produced water at different dew temperatures. The RH of the incoming air is 95.0 % and the RH of the outlet air from the coil is 50.0 %. The outlet temperature from the coil is also 0 ºC. The results shown in Fig. 5 indicate that at a specific dew higher increase with higher temperatures of incoming air to the cooling coil. Additionally, the amount of water produced is greater when the dew temperature of the air is lower.

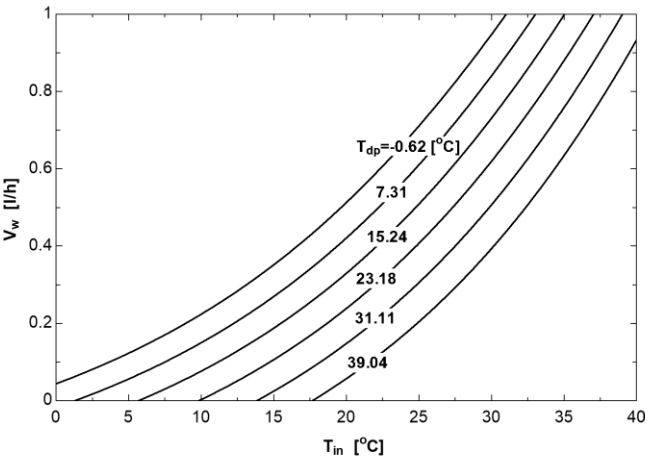


Fig. 5. Effect of the temperature of the incoming air on the volume flow rate of the produced water at different dew temperatures.

Fig. 6 shows the effect of the temperature of the outlet air from the coil on the volume flow rate of produced water for three values of the incoming air temperature (20, 25, and 30 ºC). The mass flow rate of air through the coil is 4.21 cubic meters per hour, and the RH at the inlet and outlet is 95.0% and 50.0% respectively. The highest amount of water is produced for the highest incoming air temperature, and the volume of produced water increases with a decrease in the temperature of the outlet air from the coil at a constant incoming air temperature.

Fig. 7 shows the effect of the temperature of the incoming air to the cooling coil on the volume flow rate of produced water for four values of the RH of the incoming air (65.0%, 75.0%, 85.0%, and 95.0%). The results presented in the Fig., show that as the RH of the incoming air and the temperature of the incoming air to the coil increase, a greater amount of water vapor in the air is condensed into liquid water.

One of the important factors influencing water production in cooling coils is the volume of fresh air passing through the coil. This factor is significant across most air conditioning systems, with particular important in refrigeration systems. Therefore, the volume of fresh air passing through the coil plays a critical role in determining the amount of water produced.

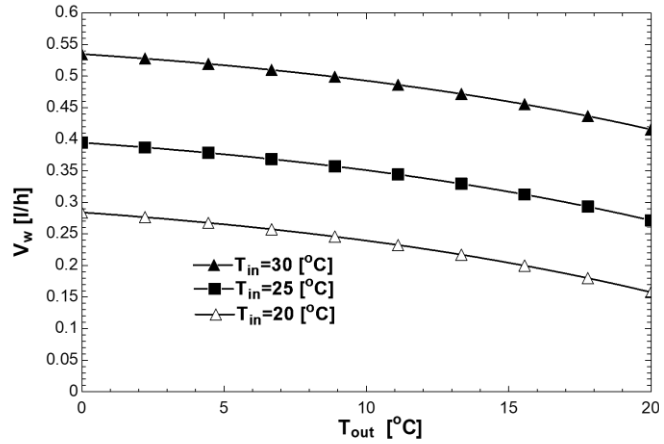


Fig. 6. Effect of the temperature on the volumetric flow rate of the produced water.

Fig. 8 illustrates the effect of the mass flow rate of air passing through the cooling coil on the amount of water produced for three different outlet temperatures from the coil (0, 5, and 10 ºC). The temperature of the incoming air to the coil is 30 °C, and the RH at the inlet and outlet is 95.0 % and 50.0 % respectively. As shown in the Fig., the amount of water produced increases significantly with an increase in the mass flow rate of air through the coil.

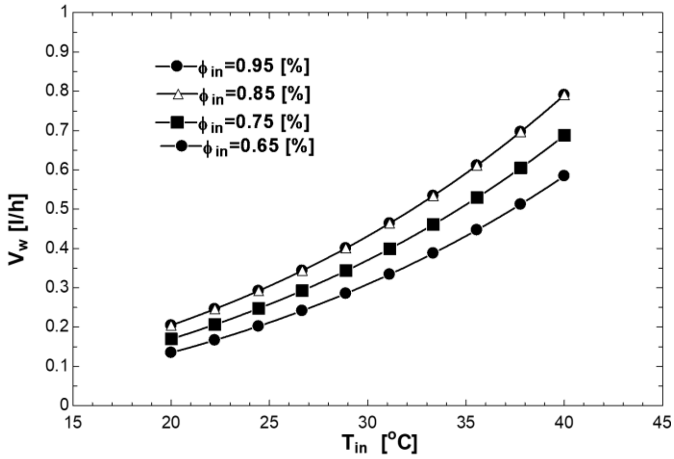


Fig. 7. Effect of the temperature on the volumetric flow rate of the produced water.

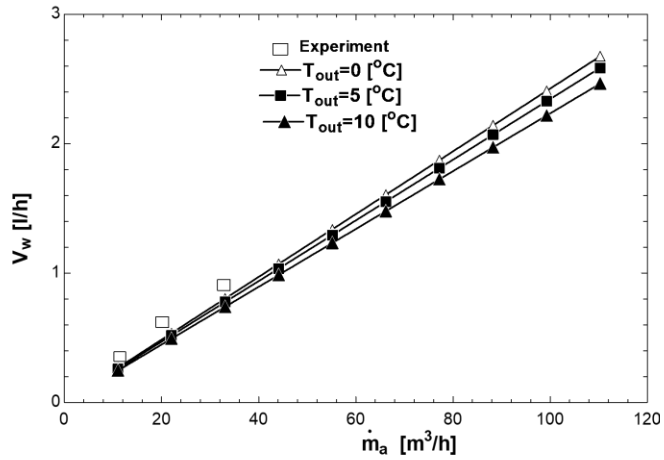


Fig. 8. Effect of the mass flow rate on the volumetric flow rate of the produced water.

In order to validate the analysis results, the amount of condensate from a home air conditioner was collected in a 30-liter tank and its volume was measured within 24 h. This test was performed on three consecutive days for three slow, medium and fast fan speeds, i.e. three volume flow rates of air passing through the coil. The volume of water produced in three low, medium and high flows is 8.3, 14.8 and 21.6 L/day, respectively. Therefore, as seen in Fig. 8, the results obtained from the analytical solution are in good agreement with the experimental results. The effect of the mass flow rate of air through the cooling coil on the amount of water produced at different inlet air temperatures is shown in Fig. 9. Additionally, the Fig., shows the energy required for water production at different inlet temperatures. In both cases, the outlet temperature from the coil is 10 ºC.

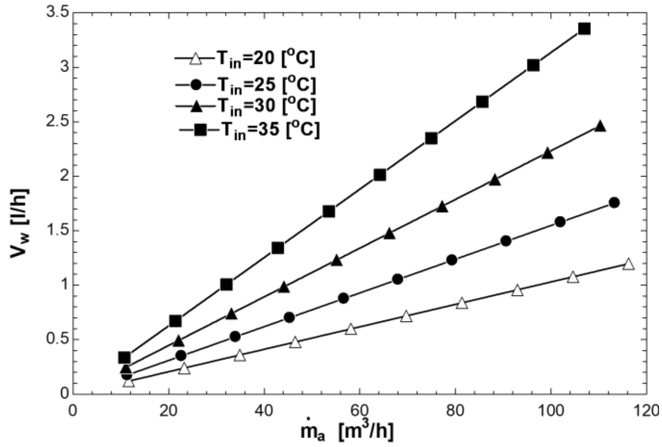


Fig. 9. Effect of the mass flow rate of air through the cooling coil on the amount of water produced.

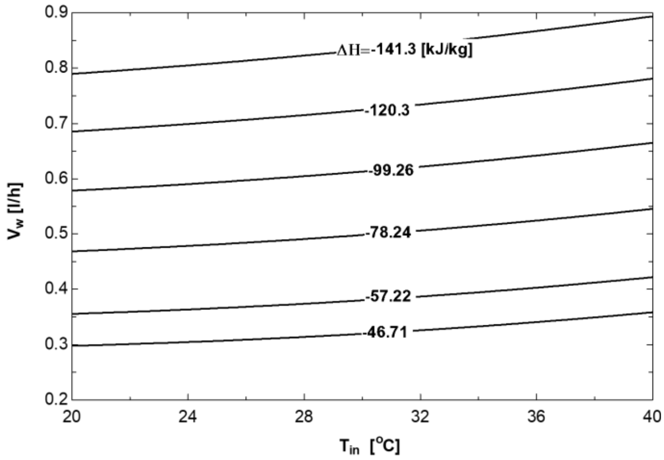


Fig. 10. Effect of the mass flow rate of air through the cooling coil on the amount of water produced.

4. Conclusions

The potential for condensate water production from air conditioning systems and cold rooms is particularly high in regions with warm and humid climates, such as many cities like Bushehr and Bandar Abbas. To assess the economic viability of condensate recovery projects, it is crucial to first estimate the annual amount of water extracted from building air conditioning systems. Factors influencing water collection include weather conditions, the percentage of inlet air passing through the coil, ambient relative humidity (RH), and the annual operating hours of the air conditioning system.

There are several methods for calculating the mass flow rate of water produced from water vapor in the air. this paper employs a simplified approach to estimate the amount of water extracted from the cooling coils. Key findings from the study include:

1- The highest water production occurs when the incoming air has high RH and the air leaving the coil has low RH.

2- At a specific dew point temperature, water production increases with higher inlet air temperatures entering the cooling coil.

3- Higher RH and inlet air temperatures lead to increased condensate production from water vapor in the air.

Author Contributions

Koorosh Goudarzi: Review & editing, data curation, investigation, formal analysis, validation, conceptualization, methodology, writing original draft, writing - review & editing.

Acknowledgement

This work is based upon research funded by Iran National Science Foundation (INSF) under project No.4025456.

Conflict of Interest

The author declares no conflict of interest.

Data Availability Statement

Data will be available on request due to privacy and ethical restrictions.

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