Indian Journal of Production and Thermal Engineering (IJPTE)
ISSN: 2582-8029 (Online), Volume-5 Issue-4, June 2025

Research on the Effect of Air Speed on the Condensation Process on the Air-Water Separator

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Abstract: ***Atmospheric water recovery (AWH) is a promising solution to overcome the shortage of clean water in arid regions, especially highland and desertified areas. There are many solutions to recover water from the atmosphere, such as absorption, adsorption, and various condensation-based technologies (condense and recover water), such as fog nets. These nets will retain water droplets when fog passes through, and using good hygroscopic materials, they will then recover water in the moisture-retaining materials. The solution of direct condensation of water vapour by creating cold surfaces with low temperatures also emerges as a promising option for energy savings. This paper presents the calculation process for selecting suitable equipment to build a model of an air-water separator with a compressor power of 1 HP. The study focuses on the influence of air velocity on the water condensation process on the surface of an evaporator with a vertical, smooth-tube condensing surface. The system's test results were obtained under different operating modes, including the surface temperature of the evaporator changing in response to the speed of change in air humidity conditions, which were approximately 45% in Hanoi, Vietnam. The experiment demonstrates that the system can operate effectively and separate water efficiently in a relative humidity condition of roughly 45%, which is a limitation of other systems. The results of this study also serve as the basis for future research into building larger-scale systems.***

Keywords: ***AWH, Water Condensation Process, Vertical Cylindrical Evaporator, Low Temperatures.***

Abbreviations:
AWH: Atmospheric Water Recovery

I. INTRODUCTION

The issue of clean water becomes urgent when the rate of pollution of groundwater and surface water sources, especially in remote areas and islands where water is often scarce, especially in arid regions [1]. Many researchers around the world have been studying water filtration technologies, including distillation from polluted water sources and the desalination of seawater into freshwater using solar energy [2]. However, these methods are only suitable for coastal areas and islands.

The atmosphere contains an abundant source of fresh water, accounting for approximately 10% of the total water content, regardless of geographical or hydrological conditions [3]. Therefore, the production of clean water separated from the air is an effective solution to provide clean water [4]. Separating water from the air is also of interest to many scientists in the world, and there are many solutions to separate water from the air by absorption.

Method or adsorption method, using materials such as silica gel, zeolite [5], desiccant salt and MOF material. The limitation of this method is finding a suitable moisture-absorbing material [6], even in conditions of low humidity below 45%. Separating water from the adsorbent still consumes a large amount of energy to supply the heat pump system [7], which is necessary for its operation [8]. Through practical observations from a cup of ice water after being left outside the environment, we all see that water from the air will condense outside the cup and flow down. In theory, when the temperature of the outer surface of the cup is less than or equal to the dew point temperature of the air at the same time, the water in the air will condense on the surface of the cup. The lower the temperature on the surface of the cup, the faster the condensation of water vapour in the air occurs, and the more water condenses.

Based on this idea, there are numerous research topics for developing a refrigeration system utilising the Carnot cycle to create a low-temperature surface. In the world, the group of authors Kiara Pontious, Brad Weidner, Nima Guerin, Andrew Dates, Olga Pierrakos, and Karim Altaii, James Madison University, pontiokb, weidnebv, guerinnn, datesam (@dukes.jmu.edu), pierraox, altaiikx (@jmu.edu) have researched and tested the system at 85°F temperature and 60% humidity [9]. The authors Omar Abdelqader, Kabbir Ali, Rashid K. Abu Al-Rub, and Mohamed I. Hassan Ali have researched and compared the efficiency of water separation using heat exchangers with different tube shapes and orientations, including smooth and finned surfaces [10]. In Vietnam, there are research topics to manufacture a machine to separate water directly from the air without using desiccant materials, such as the HAUI Institute of Technology, Hanoi University of Industry [11], Dang Pham Phu Linh and his friends in the Faculty of Mechatronics, Institute of Mechanics, Hanoi University of Science and Technology [12]. These systems all share the common feature of utilising a copper tube condenser with aluminium fins and a convection fan operating at a specific speed. Water separation systems on the market include Aqua Air and AD5pro of AT [13]. These systems are all limited in their operating parameters when the ambient temperature drops below 15°C and the humidity is below 50%. Therefore, the question is "How to separate water effectively in low ambient temperature and humidity conditions?"

In this research, we focus on evaluating the level of condensation of water vapour on the surface of vertical pipes when the air movement speed changes, thereby providing solutions for system operation, optimal water separation, and energy saving.

Manuscript received on 29 April 2025 | First Revised Manuscript received on 23 May 2025 | Second Revised Manuscript received on 30 May 2025 | Manuscript Accepted on 15 June 2025 | Manuscript published on 30 June 2025.
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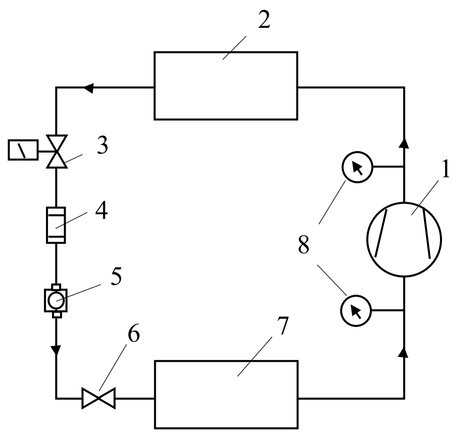
II. AIR-WATER SEPARATION SYSTEM

A. Air Water Separation System Structure

The compressor compresses the R22 refrigerant in the condenser to high pressure and high temperature. The refrigerant releases heat to the cooling environment and condenses into a liquid. The refrigerant continues to be supplied to the evaporator by the solenoid valve and passes through the throttle. After passing through the throttle, the refrigerant reduces the pressure to the designed evaporation pressure, receives heat from the air, evaporates, and is then sucked back by the compressor, completing the cycle. In the evaporator, the surface must be cooled below the dew point of the air so that the air passing through the evaporator will condense on the surface and flow down to the tray below.



1 - Compressor	5 - Gas eye
2 - Condenser	6 - Throttle
3 - Solenoid valve	7 - Evaporator
4 - Dryer, filter	8 - Pressure gauge

[Fig.1: Schematic Diagram of Water Separation System]

B. Cooling Capacity and Basic Parameters of the Condenser

i. Cooling Capacity

The experimental model uses a piston compressor with an electric capacity of 1 HP. Using a 1-stage cycle with superheat by a thermal expansion valve, refrigerant Gas R22.

ii. Condensing Temperature:

The test system is in Hanoi, where the average temperature during the hottest month reaches 37.2°C. An air-cooled condenser is selected; therefore, the condensing temperature is set at 50°C [14].

iii. Evaporation Temperature:

Based on the air dew point temperature, during winter, the ambient temperature often drops significantly, accompanied by low humidity. To ensure system operation, the average evaporation temperature is selected as 5°C [15].

Parameters of the cycle:

- Specific compression work:

$$l = h2 - h1, \frac{\text{kJ}}{\text{kg}} \ \dots \ (1)$$

- Adiabatic compression capacity:

$$\varepsilon_s = \left(\frac{S_1}{S_2}\right)^{\frac{1}{6}} \ \dots \ (2)$$

- Refrigerant Flow Rate:

$$m = \frac{N_s}{l}, \frac{\text{kg}}{\text{s}} \ \dots \ (3)$$

- Heat Dissipation Capacity of the System:

$$Q_k = mh_2 - h_3, \text{kW} \ \dots \ (4)$$

- Cooling Capacity of the System:

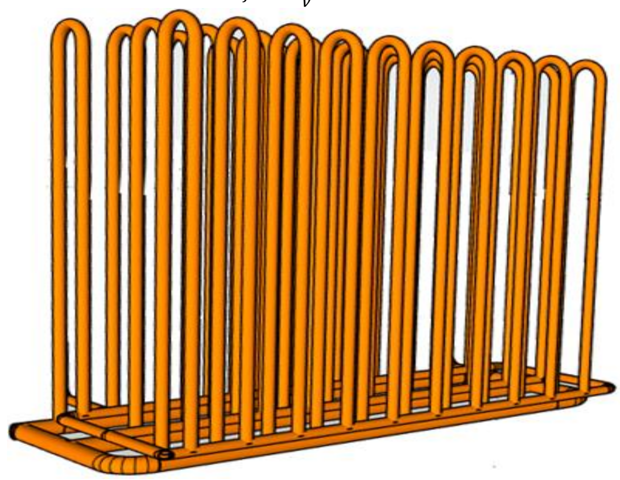
$$Qo = m.(h1' - h4), \text{kW} \ \dots \ (5)$$

iv. Condenser Design

A vertical smooth tube evaporator facilitates the flow of water from the condensate to the drain pan. The rows of tubes are arranged alternately. The condensate will condense on the surface of the evaporator; the flow rate is larger when the heat exchange area is larger. Therefore, a convection type with an average air velocity of v=2 m/s entering the evaporator is selected [16]. Copper is chosen as the tube material, with a nominal diameter of d=10 mm. The heat transfer coefficient on the surface of the evaporator is determined based on the average speed in the rows of tubes, according to the assumption.

The average velocity in the assumed pipe rows determines the heat transfer coefficient on the evaporator surface.

Re number: $$Re_f = \frac{\omega.d}{\nu} \ \dots \ (6)$$



[Fig.2: Structure of the Condenser]

The pipe base has S_1, a horizontal pipe, and S_2, a vertical pipe. The cutting line is perpendicular to the copper pipe, choose step $S_1 = S_2 = 2d$. With the pipe base [16]:

Assuming the pipe pitch ratio:

$$\frac{S_1}{S_2} = \frac{2d}{2d} = 1 < 2; \quad \varepsilon_s = \left(\frac{S_1}{S_2}\right)^{\frac{1}{6}} \ \dots \ (7)$$

The air:

$$Nu_f = 0{,}37.Re_f 0{,}6.\varepsilon_\varphi.\varepsilon_s \ \dots \ (8)$$

The equation determines the air side heat transfer coefficient:

$$\alpha_1 = \frac{Nu_f.\lambda}{d}, \frac{\text{W}}{\text{m2.K}} \ \dots \ (9)$$

The air side heat transfer coefficient is determined by the equation from 10 to 15:

Foaming mode: foaming is generated and separates from the heated tube surface.

$$\alpha_{R22} = A_0 . q^{0,7} \qquad (10)$$

According to the empirical formula: when R22 refrigerant boils, $\alpha_{R22} > (20 \div 30\%)$ compared to R12

General formula [2]:

$$\alpha_{R22} = 1{,}824 . q^{0,7} \ \ldots \ (11)$$

Heat dissipation coefficient:

$$q = 6{,}24 . \alpha_2 \, q \ = \ 6{,}24 . \alpha 2 \ \ldots \ (12)$$

$$\Rightarrow \alpha_2 = 1{,}842 . (6{,}34 . \alpha_2)^{0,7} \ \ldots \ (13)$$

Based on the heat transfer coefficient on the air side and the refrigerant side, the material used to manufacture the condenser determines the heat transfer coefficient of the condenser, k.

Surface area of the tubes:

$$F = \frac{Q_0}{k . \Delta t}, \text{m2} \ \ldots \ (14)$$

Choose the length of one tube and determine the total number of tubes n:

$$n = \frac{F}{\pi . d . l} \text{ống} \ \ldots \ (15)$$

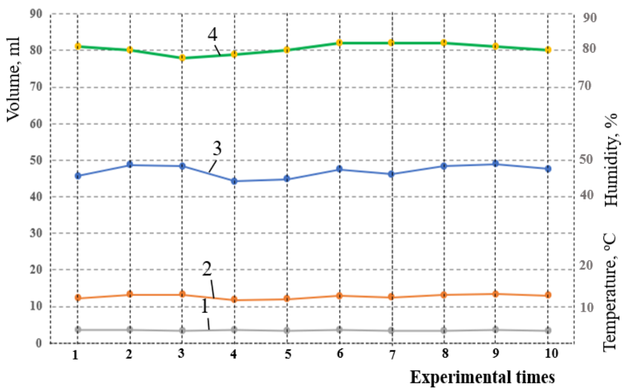
III. RESULTS AND DISCUSSION

A. Operating Mode and Separated Water Amount

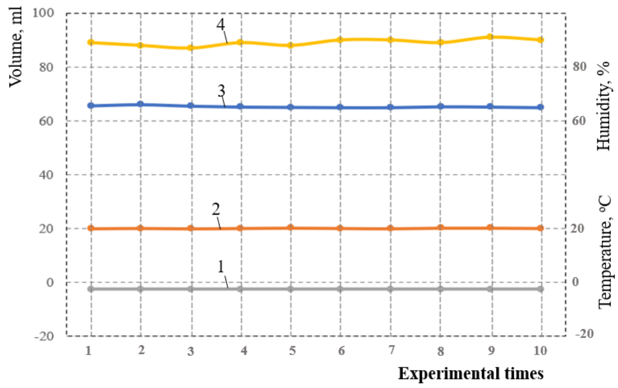
The cooling system is designed with a natural convection evaporator located on its outer surface. Consequently, the evaporator is considered to have the most significant heat exchange area. The evaporator is arranged into three clusters, and each operating mode corresponds to a specific heat exchange area. The operating modes were repeatedly tested with machine running times of 10 minutes at different time intervals.

i. Operating Mode with Natural Convection Heat Exchange Evaporator

The condensation process of water vapour from the air is also a heat dissipation process; this heat flow is used to create the boiling process of the refrigerant gas in the evaporator. On the other hand, the slow movement of air on the cooling surface increases the contact time of water vapour with the cooling surface, making the condensation process occur more easily. However, the evaporation process of the cold gas of the Carnot cycle is a continuous process, so there must be continuous heat exchange. The movement of the outside air is too slow, affecting the convection process on the outer surface, causing slow heat exchange.



(a) Surface Temperature Ranging from 3.3°C to 3.5°C



(b) Surface Temperature Ranging from -2.5°C

[Fig.3: Operating Mode with Natural Convection Evaporator]

1 - Evaporator surface temperature;
2 - Dew point temperature of air;
3 - Relative humidity of air;
4 - Amount of water obtained

The diagrams in Figure 3(a) and (b) show the operating results for the natural convection heat exchange evaporator state. Figure 3(a) presents the evaporator surface temperature ranging from 3.3 °C to 3.5 °C; Figure 3(b) operates with the evaporator surface temperature mode of -2.5 °C. If we compare the amount of condensed water in the experiments, we see that: The amount of condensed water in Figure 3(b) has a higher average amount than in Figure 3(a). This result can be explained as follows:

Figure 3(a) shows a higher surface temperature and poor heat exchange. At the same time, the relative humidity and dew point temperature of the air are low, so the condensation process of water vapour on the surface is slow. We also conducted experiments under environmental humidity conditions with a dew point temperature of 12 °C and a surface temperature of the evaporator of -2 °C, with an average humidity level below 45%. The result was that the amount of water collected increased slightly, with an average of 82 mL per measurement.

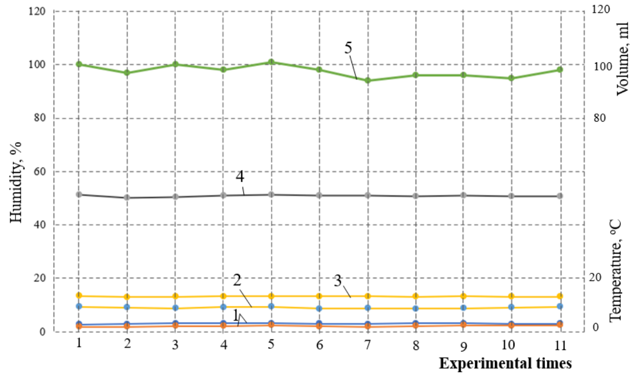
In Figure 3(b), the evaporator surface temperature is lower, so the temperature difference between the evaporator surface and the environment temperature is significant, increasing the heat exchange process. The water molecules lose heat and condense faster, so the amount of condensed water is more.

From Figure 3(b), it can be seen that the air humidity and dew point temperature are higher; the quantity of condensed water collected increases when the evaporator surface temperature is lower.

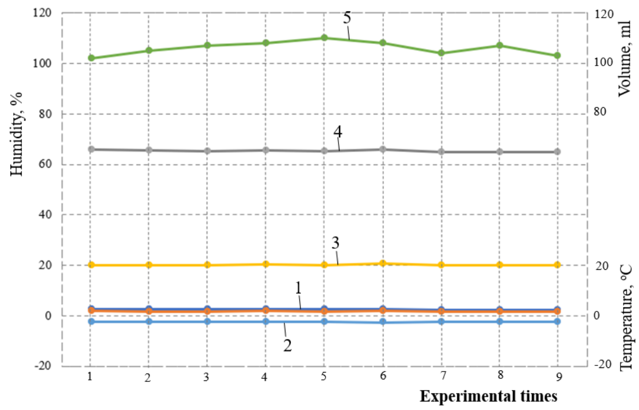
ii. Operating Mode with Forced Convection Heat Exchange Evaporator

When changing the air speed to the evaporator surface, the convection heat exchange process occurs more strongly, resulting in a larger heat dissipation coefficient on the evaporator surface. Consequently, the heat exchange area will change accordingly. In this research, we have placed four ball valves to isolate the evaporator pipe rows. Therefore, in each operating mode, the valves will be opened and closed in correspondence with the air speed at the surface of the pipe rows.

Looking at Figure 3.2(a), we can compare the two operating modes under the same dew point temperature and relative humidity conditions as those in Figure 3.1(a) (12 °C, 46%). When the evaporator is equipped with a fan running at an average air speed of 3m/s on the evaporator surface, the resulting amount of condensate collected is greater than when the evaporator does not run a fan. This indicates that the convection process on the evaporator surface is more effective, resulting in faster heat transfer and easier water condensation. However, when operating, we see that the first row of pipes is affected by higher speeds than the second and third rows, but the amount of condensate in the first row is less than in the following two rows. The operating mode of Figure 3.2(b) is similar to the operating mode of 3.2(a), but the temperature on the evaporator surface is negative on average (-2.5 °C). If we compare the results between Figure 3.2(a) and 3.2(b), the operating mode of 3.2(b) yields a higher amount of separated water than that of 3.2(a). However, the humidity of the environment in the experiments in Figure 3.2(b) is higher than that in the experiments in Figure 3.2(a).



a) Dew Point Temperature of 12 °C and Relative Humidity of 46%



b) Dew Point Temperature of -2.5 °C and Relative Humidity of 46%

[Fig.4: Operating Mode with Natural Convection Evaporator]

1 - Air velocity in 1st and 2nd row of pipes;
2 - Evaporator surface temperature;
3 - Dew point temperature of air;
4 - Relative humidity of air;
5 - Amount of water obtained

Through the above analysis, we can see that:

- The higher the humidity and dew point of the air, the greater the amount of separated water.
- The lower the surface temperature of the evaporator, the easier it is for the water in the air to condense, especially if the evaporator surface has a negative temperature, the amount of separated water will increase.
- The airspeed to the evaporator surface significantly affects the condensation process. When the evaporator surface speed is too high, the convective heat exchange process occurs quickly, causing the temperature on the evaporator surface to increase and the amount of condensed water on the surface to decrease. If the speed is too slow or the fan does not function properly, it will affect the cooling system, resulting in inadequate air movement. Consequently, the humidity in the space between the coils decreases, thereby affecting the condensation process. - The speed of air movement around the surface of the evaporator depends on the contact time of the water vapour elements with the surface of the evaporator, thereby significantly affecting the condensation process on the surface of the evaporator.

B. Efficiency of Water Separation System

To evaluate the efficiency of water separation, we evaluate it through the ratio between the amount of collected water and the amount of consumed electricity as follows:

$$\eta = \frac{V}{N} \quad \ldots \quad (16)$$

Where: V - Volume of collected water, l/s; N - Power consumption, W.

The power of the test system is 800 W The average amount of collected water at different temperatures and humidity is listed in Table I.

Table-I: Name of the Table that Justifies the Values

Temperatures/ Humidity	45%	50%	65%
15°C	9,8	12,5	14,7
25 °C	10,9	13,2	15,8

Technical specifications of the ATC water separator have the code AD5pro2, power consumption 280W in the working range with air humidity below 50% the machine does not work, from 50% to 60% corresponding to the ambient temperature of 20oC, the amount of condensed water collected is from 5.2 - 5.8 liters/day.

When comparing the experimental model with the AD5pro2 machine, we observe that the experimental model's efficiency is slightly lower. The reason is that the system is not yet operating optimally. The cooling system is handmade and rudimentary, and the operating process has not been optimised, especially at air humidity levels below 50%.

IV. CONCLUSIONS

This paper presents the design of a direct steam condenser by creating cold surfaces with low temperatures. Some results showing the influence of air velocity and structure of the device on the ability to separate water are analysed as follows:

- The process of separating water on the surface of the evaporator depends a lot on the humidity of the air.
- The air velocity on the outer surface of the evaporator

Retrieval Number: 100.1/ijpte.D202705040625
DOI: 10.54105/ijpte.D2027.05040625
Journal Website: www.ijpte.latticescipub.com

Published By:
Lattice Science Publication (LSP)

significantly affects the condensation process of water vapour; the condensation process of water on the surface of the evaporator is not uniform.

- The structure of the evaporator still has some unreasonable points, causing the condensation process to be uneven in the pipe rows.

- Optimal operating system, suitable for environmental conditions, energy saving, simple installation and O&M, and low cost.

ACKNOWLEDGMENT

Thanks to the editors and reviewers for their support and comments on my article.

DECLARATION STATEMENT

I must verify the accuracy of the following information as the article's author.

- **Conflicts of Interest/ Competing Interests:** Based on my understanding, this article has no conflicts of interest.
- **Funding Support:** This article has not been funded by any organizations or agencies. This independence ensures that the research is conducted with objectivity and without any external influence.
- **Ethical Approval and Consent to Participate:** The content of this article does not necessitate ethical approval or consent to participate with supporting documentation.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Authors Contributions:** The authorship of this article is contributed solely.

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Nguyen Xuan Binh, born on July 24, 1978, in Hanoi, Vietnam, graduated with an engineering degree in 2002 and a Master's degree in 2008 from Hanoi University of Science and Technology. I work at the Department of Energy, School of Electrical and Electronics Engineering, Hanoi University of Industry. I have been teaching and researching at the school since 2002. My major is in the field of thermal engineering technology. I have researched and collaborated with research groups in areas such as evaluating the replacement of refrigerants in refrigeration systems with banned refrigerants using environmentally friendly alternatives; adsorption refrigeration systems utilising solar energy; and heat pump drying systems with integrated solar energy. I have written reference books on topics such as Air conditioning systems, Industrial refrigeration systems, and Heat transfer to support learners in their studies and research.