RESEARCH ARTICLE

# On the enormous enhancement in water evaporation rates obtained by employing a different polar ambient

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**Abstract**
Enhancing evaporation rates are of great practical interest in many technological applications, such as water desalination or drying in industry. Evaporation mass flux is a function of ambient temperature, relative humidity, and velocity of the air passing over it. Since the conventional methods of increasing evaporation, namely increasing temperature, surface area, and so on, may not be always practically feasible or economical, novel methods of evaporation enhancement are necessary. The current study proposes that the introduction of a polar gas ambient above an evaporating liquid can drastically enhance its evaporation rate when the dipole moments of the evaporating liquid and the ambient gas are comparable. Thus, we explore the possibility of evaporation enhancement of water by introducing a polar Tetrafluoroethane gas ambient. The weight loss of water due to evaporation as well as the ambient temperature and air circulation conditions were measured. For each case, a companion experiment was carried out simultaneously under the same ambient conditions but without the presence of polar gas ambient. Each experiment lasted for 4 h. The evaporation rate has been found to be crucially dependent upon the polar gas ambient, the temperature as well as circulation

conditions. Depending upon the temperature and circulation conditions, an enhancement of 59%–373% in evaporation rate has been recorded by the introduction of tetrafluoroethane gas ambient over the water surface. Some insights into the underlying mechanisms have been suggested in light of the physics of the evaporation process. Finally, some comparisons in the measured enhancement in evaporation rates under different experimental conditions are observed to concur with the suggested physical mechanism.

## 1 | INTRODUCTION

Evaporation, a ubiquitous phenomenon in nature, is also employed for a wide array of technological applications, such as desalination of seawater, treatment of polluted water, steam generation, electronics cooling, and so on.[1] Apart from the evaporation of bulk liquids, evaporation is also studied on a droplet level for applications, such as the combustion of liquid fuels in automotive engines.[2] Another instance where evaporation has recently been utilized is the production of the microparticle drugs, whereby regulated evaporation of microdroplets using spray-drying yields a structured microparticle.[3,4] The study of evaporation also assumes considerable importance since it can underscore the contribution and role of short-term evaporation events in the total seasonal evaporation from water bodies, such as lakes and hydropower impoundments.[5] Evaporation is clearly a surface phenomenon and is governed largely by surface area and temperature. In fact, increasing the temperature or surface area is a very common strategy for drying or evaporation enhancement in household or laboratory conditions, although it may be impractical and uneconomical to do so in many situations. Such a phenomenon can be clearly observed in natural events, such as the augmentation of the evaporation rate from a large Northern lake due to the entrainment of warm, dry air over the lake surface.[5] Apart from this, several different approaches have been implemented by researchers to enhance the evaporation rate of water in the past, such as the addition of a foreign molecule to be adsorbed on the surface,[6] the addition of nanoparticles,[7] injection of bubble nuclei created by electrolysis in a flash evaporator,[8] using air ions created by corona discharge,[9] and removal of vapor above the surface continuously.[10] Other notable strategies employed to enhance water evaporation rate include the application of an electrostatic field[11] (i.e., corona wind), the magnetic field,[12] or even an infrared laser.[13] It has been reported that with the application of an electric field, the evaporation rate increases with the applied voltage, and with the introduction of cross-flow such an enhancement is found to be independent with the applied voltage and is nearly equal to that obtained with cross-flow alone.[11] Similarly,

Nakagawa et al. reported the increment in evaporation rate of pure water in a gradient magnetic field as a function of the magnitude of the magnetic field and attributed this effect to the magnetization-driven convection in the water.[12]

However, to date, no study has reported the effect of the presence of a different ambient (other than that of vapor of the polar liquid) on its rate of evaporation. Clearly, the evaporation phenomenon is quite poorly understood[7] and there are still a host of unresolved issues surrounding evaporation physics that need to be explained.[14] We are thus prompted to investigate whether a different polar gas ambient above the liquid surface can cause faster evaporation of water. In addition, we also wish to explore if such an enhancement in evaporation rate is contingent upon the liquid temperature or the circulation caused inside the liquid. The answer to these questions can possibly provide clues and critical insights into the development of systems and strategies for both suppression and enhancement of water evaporation, which is important in a number of applications, such as desalination, treatment of polluted water, and so on.

To test our hypothesis regarding the possible effect of the dipole moment on the evaporation rates of water, it is important to keep in mind several other factors that have an important bearing on the evaporation rates, including surface area, liquid temperature, and gas circulation. As far as the choice of the gas ambient is concerned, although a variety of polar gas ambient can be chosen for experimentation, it is expected that the effect of the dipole moment interaction at the gas–liquid interface can be effectively captured if the dipole moment of the gas molecules is similar to that of water. Water has a dipole moment of 1.83D and many gases could be suggested with similar dipole moment values, such as Hydrogen Fluoride (1.82D), Pyrrole (1.84D), Fluoromethane, Ethylene Sulfide or Trimethylene Sulfide (1.85D), and so on. In general, hydrofluorocarbons are promising since the larger molecular size of the polar molecule can aid in easy separation using molecular sieve or swing absorption technique once they are dissolved in water. However, the toxicity of the gas to humans as well as its impact on the environment must also be considered. For instance, Difluoromethane ($C_2H_2F_2$) is ideally suited to our experiments with water, but since it is regulated as a greenhouse gas and is largely unavailable in the market, it could not be selected for experimentation. Finally, Tetrafluoroethane gas ($C_2H_2F_4$), which is largely sold as a refrigerant R134a and which has a dipole moment of 2.45D, close to the water's dipole moment of 1.83D, is selected for our experiments. Further, to study the cumulative effects of different factors, a set of four experiments were conducted, with both air and Tetrafluoroethane as the ambient at different conditions of heating and gas circulation.

## 2 | EXPERIMENTAL SETUP

Figure 1 shows the outside and the inside views of the experimental setup used in this study for carrying out all four sets of experiments. A stainless steel chamber with a tightly sealed (with rubber) cap is employed, with two ports attached to the top of the cap. These ports are essentially one-way screw valves, intended to allow for gas recirculation. For the purpose of causing gas circulation, a simple battery-operated aquarium pump is used with a 4 mm tubing to create a flow rate of 7.5 standard liters per minute (SLPM). Pressurized Tetrafluoroethane ($C_2H_2F_4$) passes through a needle valve, a regulator, and a tube before it enters the chamber. For the purpose of temperature control, a heating coil (1500 W) is used along with a thermostat to maintain a steady liquid temperature of 35°C. Two hundred grams of silica gel was used as a
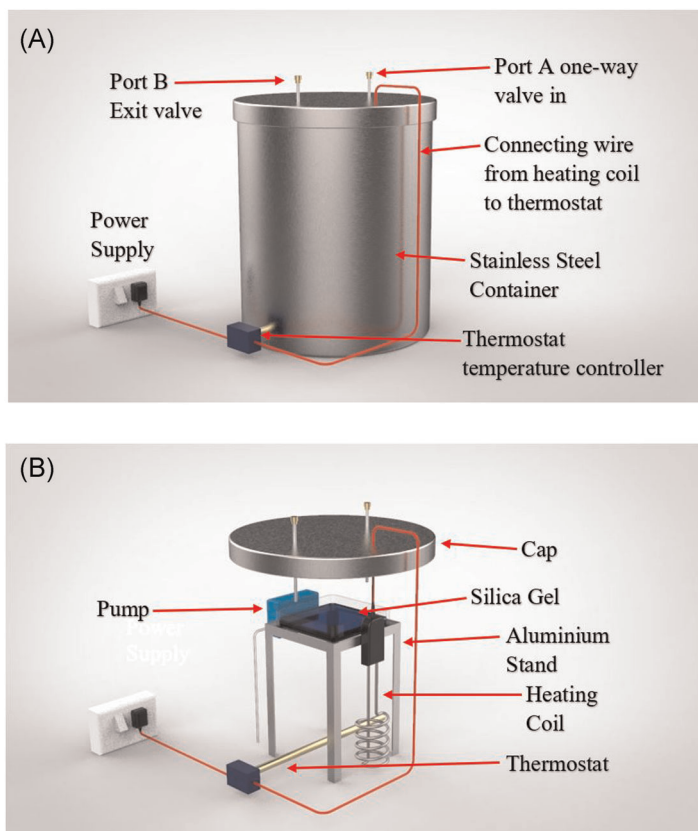
**FIGURE 1** A 3D schematic showing (A) outside view, and (B) inside view of the experimental setup [Color figure can be viewed at wileyonlinelibrary.com]

desiccant to absorb water, and the weight of silica gel along with the glass container was measured using a SAMURAI precision electronic balance before and after each experiment. It is worth noting that the minimum pore size in the Silica gel can be as small as 0.8 nm, whereas the average size of a water molecule is 0.2 nm.[15] Moreover, Tetrafluoroethane, with a molecule volume of 0.07262 nm³, a molecular surface area of 0.9528 nm², and an ovality of 1.22 yields a maximum axis length of 0.92 nm, suggesting negligible absorption by the Silica Gel.[16]

The uncertainty in the measurement of weight by the SAMURAI electronic balance is 0.01 g, while the flow rate measurement by the rotameter can be done with an uncertainty of 0.1 SLPM. The temperature measurements involve an uncertainty of $\pm 1°C$, whereas the measurements of time are up to an accuracy of $\pm 1$ ms. Overall, these variabilities lead to a maximum uncertainty of 6.0%-9.5% in the measurement of evaporation rate across all eight sets of experiments.

## 3 | EXPERIMENTAL METHODOLOGY

A total of four sets of experiments were conducted, which were named as following—no heating, no circulation (NHNC), no heating with circulation (NHC), heating but no circulation (HNC), and both heating and circulation (HC), respectively. To capture the evaporation rates

under different conditions of temperature, circulation ambient, an experimental setup as shown in Figure 1, was designed. To explore the effect of the presence of a polar ambient, water is kept at a fixed temperature of 21°C and 35°C, respectively, for no-heating and heating experiments, and the gas circulation flow rate is governed by the aquarium pump and is fixed at 7.5 SLPM. A heating coil (1500 W) is used along with a thermostat to keep the water temperature steady during the heating experiments. The four sets of experiments were repeated for both air and the $C_2H_2F_4$ polar gas ambient. Repeated checks were made at all the connections with soap bubbles to ensure that there was no leakage anywhere in the experimental setup. First, NHNC experiments were conducted with the air ambient without any heating or circulation. Two hundred grams of silica gel was taken as a desiccant to absorb water and put in the experimental setup for 4 h. After a duration of 4 h, the silica gel container was taken out and the weight of silica gel was immediately recorded. NHC experiments were similarly carried out in the air ambient, except that the circulation pump was turned on. In the HNC experiment, the circulation pump was stopped and the heating coil and thermostat setup were turned on. Finally, in the HC experiment, both the heating coil and the circulation pump were kept turned on. Each of these experiments was repeated three times and an average of the three readings was taken to ensure the accuracy of the collected results. Next, the experiments were conducted with the polar gas ambient. To replace the air ambient with the Tetrafluoroethane gas inside the stainless steel container, the inlet (Port-A) and exit valves (Port-B) were employed. The pressurized tetrafluoroethane container was connected through the valve and tubing to the one-way inlet valve Port-A and was allowed to fill in the empty space above the water surface. Since the tetrafluoroethane gas is heavier than air, it settled at the bottom near the water surface, displacing the air toward the top and pushing it through the exit valve (Port-B). The pressurized flow was left to occur for over 2 min until the entire gas exiting out of port-B consisted solely of tetrafluoroethane gas. The fact that the container above the water surface is entirely filled with polar gas was ascertained as follows. A soap solution kept in a Petri dish was kept near the exit port when the air or the air-polar gas mixture was being flushed out. The exiting gas produced soap bubbles, the transparency of which reduced significantly with the tetrafluoroethane gas and the bubbles became translucent to milky opaque when the gas concerned was pure tetrafluoroethane. Again, NHNC experiments were conducted first and before NHC, HNC, and HC experiments, the container was filled with the polar gas each time. On average, each set of these experiments required 750 ml of tetrafluoroethane gas. Finally, a total of 24 experiments were conducted, three at each experimental condition. The average of the three readings for each experiment was taken and hence a total of eight data points were obtained.

## 4 | RESULTS AND DISCUSSION

### 4.1 | Measurements of evaporation rates under different conditions

The results of the weight gain in the Silica gel in these experiments at different conditions are depicted in Table 1. As presented in Table 1, the water uptake of Silica gel, $\Delta W_t (= W_{\text{final}} - W_{\text{initial}})$ over a span of 4 h represents the net amount of water evaporated from the steel chamber. Thus, a representative rate of evaporation was obtained by calculation of $\Delta W_t / t$ (g/h). In the presence of air ambient, the evaporation rates were found to be 1.005, 3.718, 5.413, and 8.520 g/h for NHNC, NHC, HNC, and HC cases, respectively. In contrast, the introduction of

**TABLE 1** Evaporation of water in the presence of different gas ambient.

| Case | Experiment | Ambient | $T$ (°C) | $W_{init}$ (g) | $W_{final}$ (g) | $\Delta W_t$ (g) | $t$ (h) | $\Delta W_t/t$ (g/h) |
|------|-----------|---------|----------|----------------|-----------------|------------------|---------|----------------------|
| I | NHNC | Air | 21 | 200 | 204.02 | 4.02 | 4 | 1.005 |
| II | NHC | Air | 21 | 200 | 214.87 | 14.87 | 4 | 3.718 |
| III | HNC | Air | 35 | 200 | 221.65 | 21.65 | 4 | 5.413 |
| IV | HC | Air | 35 | 200 | 234.08 | 34.08 | 4 | 8.520 |
| V | NHNC | $C_2H_2F_4$ | 21 | 200 | 219.02 | 19.02 | 4 | 4.754 |
| VI | NHC | $C_2H_2F_4$ | 21 | 200 | 236.97 | 36.97 | 4 | 9.243 |
| VII | HNC | $C_2H_2F_4$ | 35 | 200 | 243.32 | 43.32 | 4 | 10.829 |
| VIII | HC | $C_2H_2F_4$ | 35 | 200 | 254.19 | 54.19 | 4 | 13.548 |

Abbreviations: HC, both heating and circulation; HNC, heating but no circulation; NHC, no heating with circulation; NHNC, no heating, no circulation.
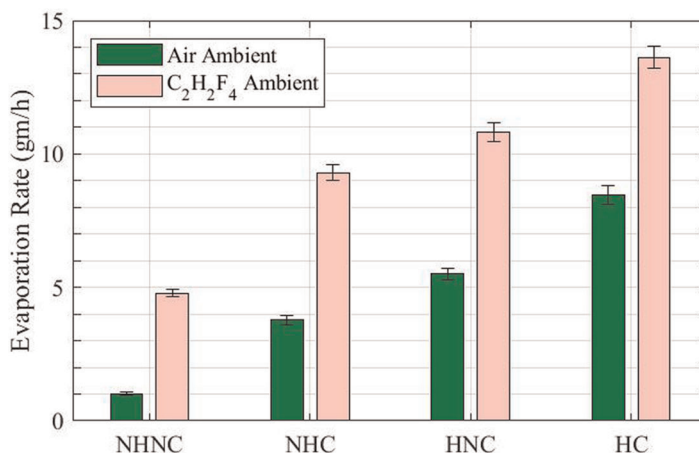


**FIGURE 2** A bar plot showing the water uptake by the Silica gel for all eight experiments. HC, both heating and circulation; HNC, heating but no circulation; NHC, no heating with circulation; NHNC, no heating, no circulation [Color figure can be viewed at wileyonlinelibrary.com]

$C_2H_2F_4$ ambient showed an evaporation rate of 4.754, 9.243, 10.829, and 13.548 g/h for the corresponding cases, respectively, indicating clearly that evaporation rate is augmented by the introduction of $C_2H_2F_4$ ambient. A comparison between the evaporation rates computed for Case I and Case II in the air ambient indicates solely the effect of circulation and a threefold increment in evaporation rate is obtained. A similar trend is noted for the $C_2H_2F_4$ ambient (Case V and Case VI), but only an increase of 1.9 times in evaporation rate is attained. Another interesting trend could be drawn by a comparison of Case II and Case IV (or Case I and Case III), whereby the temperature effects could be extricated. In general, in the absence of circulation, the temperature increment from 21°C to 35°C yields a much greater enhancement in evaporation rate as compared to the case when circulation is present, in the air or the polar ambient.

Figure 2 shows a comparison of the evaporation rate for the four sets of experiments in the two ambients. Many observations can be made regarding the recorded data. First, the evaporation rates increased in the order of NHNC, NHC, HNC, and HC for both air and the polar ambient. Second, in all the cases, the evaporation rate obtained upon the introduction of a polar ambient is significantly greater as compared to the air ambient. It is thus amply clear that the introduction of a polar ambient drastically enhances the evaporation rates irrespective of the circulation and the temperature (i.e., for all four cases). This discovery indeed substantiates the role of the dipole moment of the ambient in enhancing the evaporation rates. However, there are admittedly many other factors that could contribute to enhancement in evaporation rates, and thus it is worth taking a stock of the underlying factors behind the responsible mechanism to fully explain the underlying reasons behind such trends and explain the competing influence of heating and gas circulation.

## 4.2 | The underlying physics of evaporation behind the experimental observations

The physics of the evaporation process can be understood from the molecular perspective as enunciated by the kinetic theory whereby molecules at the liquid surface are emitted and transitioned into the vapor phase (evaporation), and conversely, vapor molecules strike the surface and change into the liquid phase (condensation).[17] Thus, at a state of thermal equilibrium between liquid and its saturated vapor, the microscopic evaporation rate, and microscopic condensation rates are identical, and no net evaporation occurs. Therefore, the macroscopic evaporation process must be a nonequilibrium process and a greater net evaporation rate essentially implies that the vapor evaporating from the liquid surface will deviate more from the equilibrium state.[18] A more practical estimate of the evaporation mass flux is conventionally obtained by the classical Hertz–Knudsen relation, although an active controversy has been existing in the scientific community regarding its accuracy. In fact, a conclusive review recently established that the Hertz–Knudsen relation is incomplete since it misses out on an important physical concept of the coupling between the liquid and vapor phases during evaporation.[19]

Theoretically speaking, the maximum evaporation rate would be attained, when the temperature of the water is kept constant and all the vapor is taken away constantly, not allowing a single molecule from returning back to the liquid.[20] Thus, the maximum rate of evaporation of water (g/cm$^2$ s) is expressed as $j_{max} = 0.0583 P \sqrt{18/T}$, where $P$ is saturation vapor pressure expressed in millimeter of mercury and $T$ is the absolute temperature in K.[10] However, in such a case, at a temperature of 20°C, water would evaporate at a rate of 9 m/h, which is about $10^5$–$10^6$ times greater than what is observed in reality. Actually, a tropical sea evaporates at a rate of about 2 m/year, or even lesser, around 50 cm/year.[10] The reason behind this huge discrepancy can be attributed to the existence of a thin gas layer over the liquid, called as Knudsen layer, which is a few mean-free paths thick as presented in Figure 3A. The region out of the Knudsen layer is often referred to as the region of gas-dynamic flow.[18] In this thin layer, water vapor pressure is near saturation, and the vapor concentration gradient between the Knudsen layer and the far-field drives the interfacial flux, with the overall transport being governed by the diffusion process.[1,10] For this diffusion-limited evaporation, the value of the diffusion constant of water depends upon the surrounding gas ambient since it is determined by intermolecular forces of attraction.[6] Among the different types of intermolecular forces of
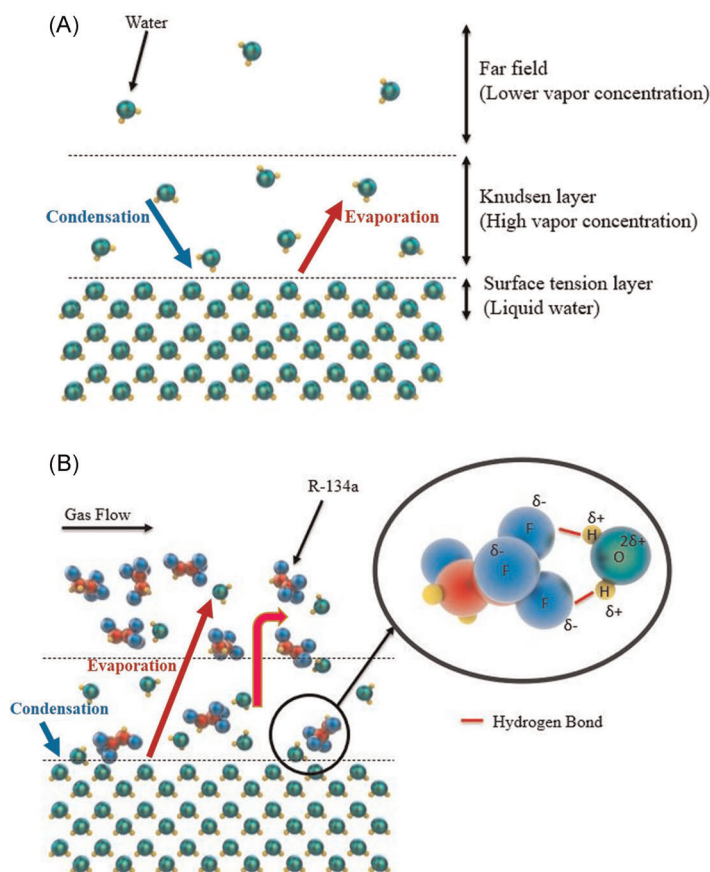
**FIGURE 3**  (A) Schematic showing the distribution of water molecules in the different layers in diffusion-limited evaporation, and (B) the effect of the presence of a polar ambient on the evaporation and condensation rates and the role of H-bond. Pink arrow indicates that some water molecules are pulled out of the Knudsen layer because of advection currents in the presence of circulation [Color figure can be viewed at wileyonlinelibrary.com]

attraction, the evaporation of water molecules is primarily controlled by the hydrogen bonds between them since evaporation must involve the breaking of such bonds.[6] Typically, since the $H_2O$ molecule has two H-atoms, the more electronegative oxygen can usually get a partial negative charge and can interlink with two other H-atoms. Conversely, both the H-atoms with partial positive charges can form multiple hydrogen bonds. These bonds fluctuate rapidly, depending upon temperature, yet their effect is so profound for the water molecule that the physical properties of the water molecule are determined predominantly by the H-bond.[14] In addition, short-range Van der Waals forces between the water molecules hold them together in the liquid state, although these are free to move in the vapor phase. However, such van der Waals forces are weaker than Hydrogen bonds, but an attenuation in their magnitudes may yield an augmentation in evaporation rates.

As shown in Figure 3B, the situation becomes more intricate with the introduction of a polar ambient over the water surface, such as $C_2H_2F_4$, facilitating the dipole–dipole interactions, that is, H-bonds. According to Stiopkin,[21] although a majority of the water molecules in the surface layer are hydrogen-bonded to each other, a fraction of molecules with unbounded

hydrogens protrude in the vapor phase. Such dangling bonds are free to interact with other water molecules in the vapor through hydrogen bonds. Tetrafluoroethane with its highly electronegative F atoms forms strong H-bonds with H-atom of $H_2O$ molecule, and the inter-linking of its H atom with O atom of the water molecule is equally likely. Further, these H-bond interactions are possible at the surface layer as well as in the Knudsen layer and beyond. Not only $C_2H_2F_4$ molecules can pull away $H_2O$ from the surface, but also denude the Knudsen layer by drawing the $H_2O$ molecules in the far-field, thus leading to an increased net flux across the interface. Furthermore, polar molecules have an ordered surface and the impinging gas molecules have to be oriented in a particular way, for the condensation to take place. Hence, the ratio of the actual evaporation rate and the expected evaporation rate (also called condensation coefficient) is much lesser than unity for molecules with large dipole moments.[22]

## 4.3 | Some preliminary validation of the proposed physical mechanism

Finally, a close look at the percent increment in evaporation rate upon introduction of tetra-fluoroethane ambient for all four sets of experiments reveals some interesting insights. Figure 4 presents the corresponding data for each set of experiments, with $\Delta W = W_{polar} - W_{air}$, where $W_{polar}$ and $W_{air}$ denote the evaporation rate in tetrafluoroethane and air ambient, respectively, at a chosen experimental condition. Hence, $\Delta W$ when normalized with $W_{air}$ represents relative evaporation increment solely due to the ambient change. While trying to understand and explain the role that the polar gas may play in the evaporation process, a firsthand intuition leads us to conjecture that the role of H-bonds between polar molecules in the enhancement of evaporation will be most markedly prominent in the absence of heating or advection. On the other hand, at an increased temperature, H-bonds and Van der Waals forces are weakened because of the increased kinetic energy of the molecules. Similarly, advection does not allow for as much enhancement in evaporation rate due to dipole interactions, as compared to the case
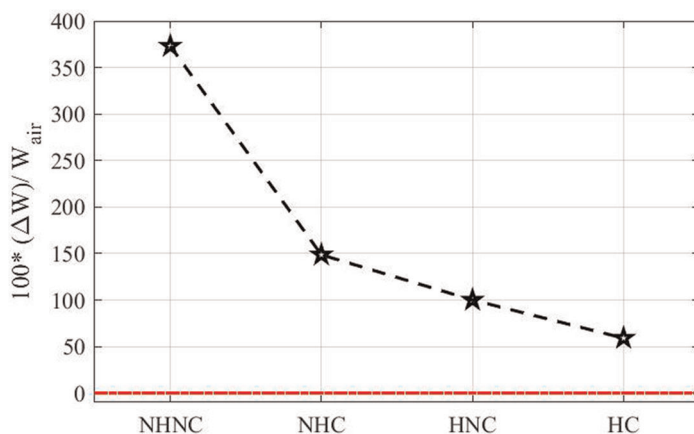


**FIGURE 4** Percent increment observed in evaporation rate by the introduction of polar ambient. Red dotted line indicates no improvement in evaporation rate because of the presence of polar ambient. HC, both heating and circulation; HNC, heating but no circulation; NHC, no heating with circulation; NHNC, no heating, no circulation [Color figure can be viewed at wileyonlinelibrary.com]

when the ambient gas is stationary over water. Figure 4 clearly attests to this suggestion, since the increment in evaporation rate is around 373% for the NHNC case, as compared to a mere 59% for the HC case. The increment in two intermediate cases is a result of the competing factors of advection vis-à-vis the temperature increment.

Evidently, it is clear that the increase in evaporation rate is maximum for the NHNC case, while such an effect is much less prominent in the presence of heating and advection. It can also be mentioned that the enhancement in the evaporation rate due to such a "dipole–dipole" interaction effect is significantly attenuated in the event of the occurrence of heating. This explains the 50% more increase in evaporation rate in the case of the NHC case in contrast to the HNC case. Thus, the hypothesis proposed regarding the enhancement of evaporation due to the dipole stands affirmed, validated by the experimental measurements, which further corroborate the underlying mechanisms suggested behind such an increment in evaporation rates. These preliminary measurements on evaporation rates can be further substantiated by advanced measurements or numerical/molecular dynamics simulations to arrive at an integrated understanding of the evaporation process and the role that dipole moment of the ambient gas in it. It is hoped that the current study may serve as a befitting precursor to such advanced scientific studies on evaporation enhancement using a polar gas ambient. It must be admitted, however, that before such a technique could be put to technological applications, such as desalination or drying, investigations should be done to explore the possibility of using different nontoxic environment-friendly polar gases, which are either insoluble in water or can be easily separated from it in an energy-efficient way. The current research when supplemented with such a finding may pave a breakthrough for desalination and drying technology in the future.

## 5 | CONCLUSIONS

In summary, the current study explores the possibility of enhancing the evaporation rates of water by the introduction of ambient gas, which has a dipole moment close to that of water. The current study provides sufficient experimental data and a possible physical mechanism to suggest the influence that a different polar ambient can have in enhancing the evaporation rate of water. To test the abovementioned hypothesis, a suitable experimental setup was designed to capture evaporation rate measurements. Then, four sets of experiments were conducted: NHNC, NHC, HNC, and HC. In all four cases, an enhancement in evaporation was observed, between 59% and 373%. However, the comparative increment in the four cases seems to indicate the relative influence of advection, temperature rise, and its consequent effect on H-bonds, which are responsible for increasing the evaporation rate. Since the maximum rise in evaporation rate is observed for the NHNC case, it is obvious that the dipole–dipole interactions responsible for evaporation enhancement have been facilitated. Conversely, the minimum augmentation of evaporation rate for HC case accounts for the least effectiveness of such physics in raising evaporation rate. The underlying reason behind this observation is attributed to the weakening of H-bonds as well as a limited time of interaction in the Knudsen layer. Thus, this study hopefully provides a novel way of increasing evaporation for polar liquids. It is expected that if a means and mechanism be found for creating an artificial ambient around water surface, it should be possible to significantly enhance the evaporation rate of water in many applications, such as the desalination of water or in industrial drying applications.

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## DATA ACCESSIBILITY STATEMENT

The data that supports the findings of this study are available in the Supporting Information Material of this article.

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## REFERENCES

1. Lu Z, Kinefuchi I, Wilke KL, et al. A unified relationship for evaporation kinetics at low Mach numbers. *Nat Commun*. 2019;10(1):1-8.
2. Kitano T, Nishio J, Kurose R, Komori S. Evaporation and combustion of multicomponent fuel droplets. *Fuel*. 2014;136:219-225.
3. Baldelli A, Boraey MA, Nobes DS, Vehring R. Analysis of the particle formation process of structured microparticles. *Mol Pharmaceutics*. 2015;12(8):2562-2573.
4. Baldelli A, Power RM, Miles REH, Reid JP, Vehring J. Effect of crystallization kinetics on the properties of spray dried microparticles. *Aerosol Sci Technol*. 2016;50(7):693-704.
5. Blanken PD, Rouse WR, Schertzer WM. Enhancement of evaporation from a large northern lake by the entrainment of warm, dry air. *J Hydrometeorol*. 2003;4(4):680-693.
6. Kingdon KH. Enhancement of the evaporation of water by foreign molecules adsorbed on the surface. *J Phys Chem*. 1963;67(12):2732-2737.
7. Zhang W, Shen R, Lu K, Ji A, Cao Z. Nanoparticle enhanced evaporation of liquids: a case study of silicone oil and water. *AIP Adv*. 2012;2(4):042119.
8. Miyatake O, Tomimura T, Ide Y. Enhancement of spray flash evaporation by means of the injection of bubble nuclei. *J Sol Energy Eng*. 1985;107:163-167.
9. Barthakur N, Bhartendu S. Enhancement of evaporation rates from thin layers of liquids exposed to air ions. *Int J Biometeorol*. 1988;32(3):163-167.
10. Jones FE. *Evaporation of Water with Emphasis on Applications and Measurements*. Boca Raton, FL: CRC Press; 2018.
11. Lai F, Huang M, Wong D. EHD-enhanced water evaporation. *Drying Technol*. 2004;22(3):597-608.
12. Nakagawa J. Magnetic field enhancement of water vaporization. *J Appl Phys*. 1999;86(5):2923-2925.
13. Ferraz-Albani LA, Baldelli A, Knapp CJ, et al. Enhanced evaporation of microscale droplets with an infrared laser. *J Heat Transfer*. 2017;139(1).
14. Almenas K. *Evaporation/Condensation of Water. Unresolved Issues. I. Phase Change At Low Pressure, Laminar Conditions*. Vilnius: Vytautus Magnus University/Versus Aureus; 2015.
15. Wallace S, Brinker CJ, Smith DM. *The Minimum Pore Size Obtainable in a Silica Gel During Drying*. Albuquerque, NM: Sandia National Labs; 1994.
16. Cousins DS, Laesecke A. Sealed gravitational capillary viscometry of dimethyl ether and two next-generation alternative refrigerants. *J Res Natl Inst Stand Technol*. 2012;117:231.
17. Kundsen M. *Kinetic Theory of Gases*. 3rd ed. London: London Methuene; 1950.
18. Bird E, Liang Z. Transport phenomena in the Knudsen layer near an evaporating surface. *Phys Rev E*. 2019; 100(4):043108.
19. Persad AH, Ward CA. Expressions for the evaporation and condensation coefficients in the Hertz-Knudsen relation. *Chem Rev*. 2016;116(14):7727-7767.
20. Deboer JH. *The Dynamical Character of Adsorption*. London: Clarendon at the University Press; 1953.

21. Stiopkin IV, et al. Hydrogen bonding at the water surface revealed by isotopic dilution spectroscopy. *Nature.* 2011;474(7350):192-195.
22. Wyllie G. Evaporation and surface structure of liquids. *Proc R Soc London Ser A.* 1949;197(1050):383-395.

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