Can water evaporation rates be enhanced 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. Since the conventional methods of increasing evaporation viz. increasing temperature, surface area etc. may not be always practically feasible or economical, novel methods of evaporation enhancement are necessary. The current study explores the possibility of evaporation enhancement by introducing a Tetrafluoroethane gas ambient under different conditions of heating and circulation. Depending upon the temperature and circulation conditions, as enhancement of 58 to 375% in evaporation rate has been measured and physical explanations into the underlying mechanism have been suggested.

Keywords: *Evaporation rate; Dipole Moment; Tetrafluoroethane; Hydrogen bond; R134a*

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, drying, electronics cooling etc.¹. Evaporation is clearly a surface phenomenon, and is governed largely by surface area and temperature, the latter being a most commonly used strategy for drying in household or laboratory conditions, although it may be impractical and uneconomical to do so in many situations. Several different approaches have been implemented by researchers in the past, to enhance evaporation rates of water such as the addition of a foreign molecule to be adsorbed on the surface², the addition of nanoparticles³, injection of bubble nuclei created by electrolysis in a flash evaporator⁴, using air ions created by corona discharge⁵, and removal of vapor above the surface continuously can significantly enhance the evaporation rate⁶. However, till date, no study has been reported regarding the effect of the presence of a different ambient (other than that of vapor of polar liquid) on the rate of evaporation. Clearly, the evaporation phenomenon is quite poorly understood³ and there are still a host of unresolved issues surrounding evaporation physics that need to be explained⁷. We are thus prompted to question as to whether a different polar gas ambient can cause a faster evaporation of water. The answer to this question 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 etc.

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 the several factors that have an important bearing on the evaporation rates, including surface area, liquid temperature and gas circulation (if any). Although a variety of polar gas ambient can be chosen for experimentation, it is expected that the effect of the dipole moment interaction at gas-liquid interface can be effectively captured if the dipole moment of the gas molecules are similar to that of water. Difluoromethane ($C_2H_2F_2$) is ideally suited to our experiments with water, however it is regulated as a greenhouse gas and is largely unavailable in market. So, Tetrafluoroethane ($C_2H_2F_4$), largely sold as a refrigerant R134a which has a dipole moment of 2.45D, close to the water's dipole moment of 1.83 D, 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. The four sets of experiments have been abbreviated by the acronyms – NHNC (No heating, No Circulation), NHC (No Heating with Circulation), HNC (Heating but No Circulation) and HC (Both Heating and Circulation), respectively.

Figure 1 shows the experimental setup used in this study for carrying out all the 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 4mm tubing to create a flow rate of 7.5 LPM. Pressurized Tetrafluoroethane (R134a) can pass through a needle valve, a regulator, 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. Repeated checks were made at all the connections with soap bubbles to ensure there was no leakage anywhere. 200 g of Silica gel was used as a 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. Silica Gel was thoroughly dried and the water in the chamber was replaced after each experiment, and a total of eight experiments were conducted, spanning four hours each. 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 nm⁸. 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 0.92nm, suggesting negligible absorption by the Silica Gel⁹.

Figure 1: A 3D schematic showing (a) outside view, and (b) inside view of the experimental setup

The results of the weight gain in these experiments at different conditions is depicted in Table 2 below. As presented in Table 1, the water uptake of Silica gel, $\Delta W_t (= W_{\text{final}} - W_{\text{initial}})$ over a span of four hours represents 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/hr.). In the presence of air ambient, the evaporation rates were found to be 1, 3.75, 5.5 and 8.5 g/hr. for NHNC, NHC, HNC and HC cases, respectively. In contrast, the introduction of R134a ambient showed an evaporation rate of 4.75, 9.25, 10.75 and 13.5 g/hr for the corresponding cases, respectively.

Table 1. Evaporation of water in the presence of different gas ambient

Case	Experiment	Ambient	T (°C)	W_{init} (g)	W_{final} (g)	ΔW_t (g)	t (hrs)	$\Delta W_t / t$ (g/hr)
1	NHNC	Air	21	200	204	4	4	1.00
2	NHC	Air	21	200	215	15	4	3.75
3	HNC	Air	35	200	222	22	4	5.50
4	HC	Air	35	200	234	34	4	8.50
5	NHNC	R-134a	21	200	219	19	4	4.75
6	NHC	R-134a	21	200	237	37	4	9.25
7	HNC	R-134a	35	200	243	43	4	10.75
8	HC	R-134a	35	200	254	54	4	13.50

Figure 2 shows a comparison of the evaporation rate for the four sets of experiments in the two ambient. It is clearly observed that the introduction of a polar ambient drastically enhances the evaporation rates irrespective of the circulation and the temperature (i.e. for all the four cases). This clearly suggests the role of the dipole moment of the ambient in enhancing the evaporation rates. Yet, there are admittedly many factors that could lead

to enhancement in evaporation rates, and it is worth taking a stock of the underlying factors behind the responsible mechanism.

Figure 2: A bar plot showing the water uptake by the Silica gel for all the eight experiments

Theoretically speaking, the maximum evaporation rate would be attained, when the temperature of water is kept constant and all the vapor is taken away constantly, not allowing a single molecule from returning back to the liquid. Thus, the theoretically maximum rate of evaporation of water ($\text{g}/\text{cm}^2\cdot\text{sec}$) is expressed as $j_{max} = 0.0583P\sqrt{18/T}$, where P is saturation pressure and T is absolute temperature⁶. However, in such a case, at a temperature of 20 °C, water would evaporate at a rate of 9 m/ hr., 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 2m/year, or even lesser around 50 cm/year. 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. 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^{1,6}. For this diffusion-limited evaporation, the value of diffusion constant of water depends upon the surrounding gas ambient, since it is determined by intermolecular forces of attraction². Among the different types of intermolecular forces of attraction, the evaporation of water molecules are primarily controlled by the hydrogen bonds between them². The water molecules, which are held together by short range van der Waals type forces in the liquid, are free to move in the vapor phase. 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 its effect is so profound for the water molecule that the physical properties of the water molecule are determined predominantly by the H-bond⁷.

As shown in Figure 3b, the situation becomes more intricate with the introduction of a polar ambient over water surface such as $\text{C}_2\text{H}_2\text{F}_4$, facilitating the dipole-dipole interactions, i.e. H-bonds. According to Stropkin (2011), 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. $\text{C}_2\text{H}_2\text{F}_4$ with highly electronegative F atoms forms strong H-bonds with H-atom of H_2O molecule, and the interlinking of its H atom with O atom of 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 $\text{C}_2\text{H}_2\text{F}_4$ 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.

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. The Pink arrow indicates that some water molecules are pulled out of the Knudsen layer because of advection currents in the presence of circulation.

Finally, a close look at the percent increment in evaporation rate upon introduction of R134a ambient for all the four sets of experiment reveals some interesting insights. Figure 4 presents the corresponding data for each set of experiment, with $\Delta W = W_{R134a} - W_{air}$. Although evaporation rate is a cumulative effect of many factors in our experiments, it is expected that the role of H-bonds between polar molecules in the enhancement of evaporation will be most prominent when there is no heating or advection. On the other hand, at an increased temperature, H-bonds 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 when the gas is stationary over water. Figure 4 clearly attests to this suggestion, since the increment in evaporation rate is around 375% for NHNC case, as compared to a mere 58.8% for HC case. The increment in two intermediate cases are a result of the competing factors of advection vis-à-vis temperature increment.

Figure 4: Percent increment observed in evaporation rate by the introduction of a polar ambient. Red dotted line shows the case of no improvement in evaporation rate because of polar ambient.

In summary, the current study explores the possibility of enhancing 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. It is expected that if a means and mechanism be found for creating an artificial ambient around a water surface, it should be possible to significantly enhance the evaporation rate of water in many applications such as desalination of water.

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