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# Magnetic influence on water evaporation rate: an empirical triadic model

J.A. Dueñas [a,*], C. Weiland [b], I. García-Selfa [c], F.J. Ruíz-Rodríguez [d]

[a] Departamento de Ingeniería Eléctrica y Centro de Estudios Avanzados en Física, Matemáticas y Computación, Universidad de Huelva, 21007 Huelva, Spain
[b] Departamento de Ciencias Agroforestales, ETSI Universidad de Huelva, 21007 Huelva, Spain
[c] Departamento de Ciencias Integradas, ETSI Universidad de Huelva, 21007 Huelva, Spain
[d] Departamento de Ingeniería Eléctrica y Térmica, de Diseño y Proyectos, ETSI Universidad de Huelva, 21007 Huelva, Spain

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ABSTRACT

Over the past decades researchers have described what happens to the water when a polarizing external field is applied to it and changes the bonding forces existing in it. Water evaporation, an essential process in nature, has been targeted in a great number of studies. In this paper, static magnetic fields ranging from 30-to-200 mT were applied to circulating purified water to study their effect on how the evaporation rate changed under different ambient conditions. A statistical approach was employed to verify the significance of the magnetically induced effect. Our results showed that by applying a static magnetic field to the water, the evaporation rate increased at lower temperatures, yielding an evaporation increase for magnetized water of up to 20% at 6 °C. We found too that the circulation of the water did not contribute significantly to the evaporation rate. We used an empirical triadic model to correlate the applied magnetic field with the ambient parameters of temperature and humidity.

## 1. Introduction

Many works have been published demonstrating the fact that both the optical and the mechanical properties of water change under the influence of a static magnetic field [1–7].The different approaches taken by the scientific community to expand the limited understanding of these effects, have made the water undergo magnetic strengths ranging from tenths of milli Teslas, employing permanent magnets, to the Teslas domain where superconducting magnets are needed, and also within very different scenarios or setups. Therefore, it is not surprising that some interpretations or general statements can be misleading and/or misunderstood. It is for this reason that the authors would like to suggest that the reader think of the evaporation process as one of the most "tangible" phenomena influenced by a static magnetic field. Not surprisingly, there is unanimous agreement that magnetized water evaporates faster than non-magnetized, and that the weakening of the hydrogen-bonds due to the stress caused by a magnetic field affects the evaporation rate.

However, the water evaporation mechanism not only involves the state of the molecules in the liquid, but also the surrounding medium that will condition the experimental approach in many cases. Key factors such as the diffusion of water molecules from an open water surface to air; the relative humidity, which it increases as the temperature of the air decreases, with the result that the evaporation rate may decrease; and net radiation, or the amount of radiant energy captured by the water, will all affect the evaporation rate. In addition, the rate is affected by an applied magnetic field. For instance, Nakagwa et al. [8] employed a setup for water evaporation under externally forced carrier gas flow, monitoring the water vaporization rate by a humidity sensor placed in the outlet gas, and applying a static magnetic field that employed superconducting solenoid magnets to provide up to 8 T. A similar type of magnet was used by Otsuka & Ozeki [9] to produce 6 T. They did not evaluate the evaporation rate but some other properties by means of contact angle, and stated that magnetization of pure water requires $O_2$ or air, and the relative motion of water against a magnetic flux. Guo et al. [10] also made use of a superconducting magnet reaching up to 16.12 T. They placed the water samples at different heights within the magnet, and obtained the amount of water evaporated by weighting. A simpler approach was used by Amor et al. [11] whose magnetic devices varied from 90-to-500 mT, using an evaporation bath (at 50° & 80 °C) and then measuring the corresponding weights. Seyfi et al. [12] and Chibowski et al. [13] performed their experiments at room temperature with ferrite (55 mT) and neodymium ring magnets (0.65 T) respectively.

Notwithstanding, very few works studying water properties deal with circulating [9] and evaporating [14,15] water at the same time. Most studies involving liquid flow are related to scale prevention or ion cluster formation. Recently, Yang et al. [16] have explored the potential of enhancing tap water evaporation by combining dynamic and static

* Corresponding author.

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treatment of magnetic fields, employing NdFeB magnets ranging from 100-to-300 mT, at 20 °C.

In our approach to studying the influence of a low intensity static magnetic field on the evaporation rate of water, we applied magnetic fields ranging from 30-to-200 mT to circulating water. Unlike other works, we have been through a deep statistical process of gathering enough data to strongly support our finding, dealing with a range of temperatures between 6 and 70 °C, which to the best of our knowledge, that have not been reported before. We also developed an empirical triadic model, also not previously reported, correlating the applied magnetic field with the ambient parameters of temperature and humidity.

The motivation of this work was to explore the ongoing research of magnetic field interaction with water. For this, the aims of this research were the following: (i) to quantify the evaporation rate as a function of the applied magnetic field and the ambient parameters, (ii) to find out the contribution of the kinetic effect and (iii) to come up with an empirical model. This paper is organized as follows. Section 2 describes both the experimental framework and the statistical approach employed. Section 3 then combines the results and evaluates their the statistical significance, presents the circulating effect on the evaporation rate, and the resulting empirical model. Finally, Section 4 presents our conclusions.

## 2. Materials and methods

In the following subsections we explain: how the water samples were prepared, the calculation of the evaporation rate for each sample, and the statistical analysis method employed.

### 2.1. Sample preparation

We employed 150 mL of type II water (analytical grade) according to ASTMD1193 and ISO 3696 standards with a conductivity of 0.1$\mu$S/cm. The water was left to circulate for 15 min at a flow rate of $2.93 \times 10^{-5}$ $m^3$/s (1.76 L/min) without magnetic treatment, see closed circuit system in Fig. 1. Then, three reference (control) samples of 25 ml each were poured into petri dishes (⌀90 mm). Next, we emptied the circuit and refilled it with another 150 mL and repeated the process, but this time the magnetic field generator was inserted in the circuit so that the direction of the magnetic force is perpendicular to that of the water flow. More details about the generator can be found at [17]. The final six samples (i.e. three non-magnetized + three magnetized) were weighed and taken to the thermal chamber, which dimensions in cm are 50 × 50 × 40. The chamber has a circular hole (⌀25 mm) at the back to maintain atmospheric pressure.

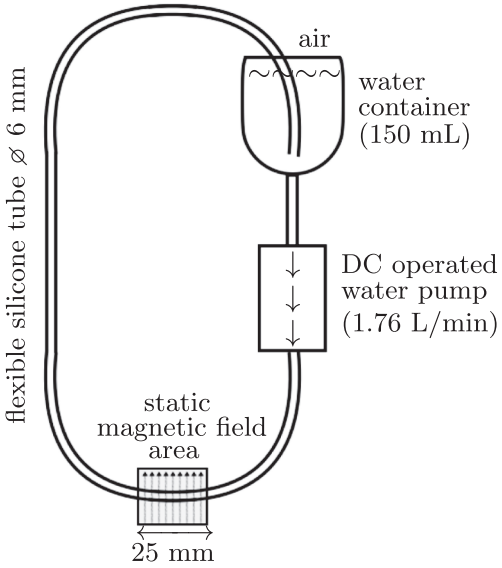


**Fig. 1.** Not to scale drawing of the closed circuit water system. 150 mL of purified water (type II, < 0.1$\mu$S/cm) is recirculated within the water pump and through a magnetic field area 25 mm in length. Direction of the magnetic force perpendicular to the water flow. The total length of the circuit is 119 cm.

### 2.2. Indirect measurement of evaporation rate

The thermal chamber was set to a given temperature and the samples were weighed at 20–25 min intervals. To calculate the evaporation rate in mg/min units, the collected weight and time (heating time) per sample were employed to obtain the trend line equation. From the slope or gradient we got the evaporation rate. Fig. 2 shows an example of the sample weight vs the heating time correlation for magnetized (circles) and non-magnetized (squares) water samples. The trend lines (solid lines) clearly exhibit different slopes, which in terms of evaporation rates yield values of 58 mg/min for the magnetized sample and 51.4 mg/min for the non-magnetized. All the trend lines obtained had coefficient of determination (i.e. degree of linear correlation) equal to or greater than 0.99.

We chose the magnetic field range 30-to-200 mT because that was the working range of the magnetic field generator, and because that range is used by other researchers in the field. This allows comparison between our results and the results of others. Because high temperature has such as profound effect on the evaporation rate, we also decided to study the effect of magnetic field at low temperature 6 °C were the effect of high temperature would be reduced.

### 2.3. Statistical analysis

Correlations are powerful tools for understanding data that often reveal important interrelations. In this work the R-software environment for statistical computing and graphics [18] has been employed. The main interrelation in which this work is interested, is that an applied static magnetic field $B$ (mT) has on the evaporation rate $R$ (mg/min) of water. Bearing this in mind, our null hypothesis is that there will not be an effect or difference in the evaporation rate when applying a magnetic field to the water samples. Among these two variables, both the

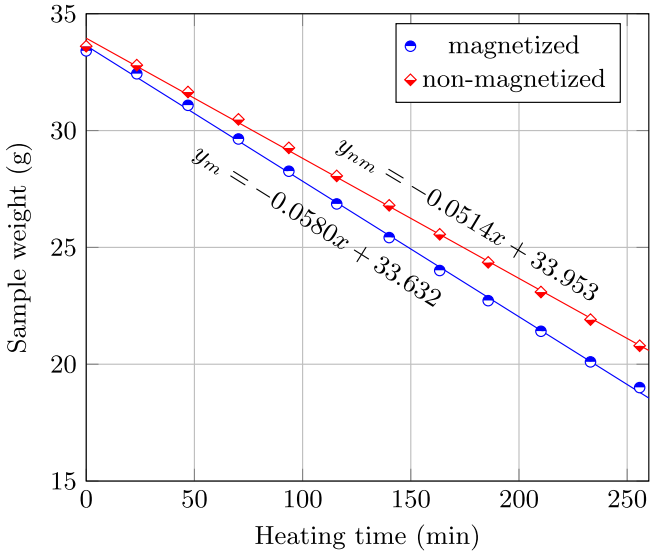


**Fig. 2.** Example of how to calculate the evaporation rate using the linear correlation between the sample weight and the heating time. The slopes of the trend lines yield the evaporation rates. The line equations for both the magnetized ($y_m$) and non-magnetized ($y_{nm}$) samples are shown.

temperature $T$ (°C) and the humidity $H$ (%) in the chamber were also taken into account to construct our correlation matrix. Therefore, for a given temperature and different values of applied magnetic fields, the correlation matrix will take the following form:

$$\begin{array}{c} \\ B \\ R \\ T \\ H \end{array} \begin{array}{c} \begin{array}{cccc} B & R & T & H \end{array} \\ \begin{pmatrix} r_{BB} & r_{BR} & r_{BT} & r_{BH} \\ r_{RB} & r_{RR} & r_{RT} & r_{RH} \\ r_{TB} & r_{TR} & r_{TT} & r_{TH} \\ r_{HB} & r_{HR} & r_{HT} & r_{HH} \end{pmatrix} \end{array} \tag{1}$$

where the correlation coefficient values will be $r_{XX} = 1$ (i.e. self correlated) and also $-1 < r_{XY} < 1$. We calculated the Pearson correlation and the two-sided $p$-value matrices for each given temperature. The input parameters ($B, R, T$ and $H$) are the average values obtained from 6 different samples, which were done in two runs. In the first run 3 magnetized + 3 non-magnetized samples were placed in the thermal chamber. Once the measurements were finished, a second run with another 6 samples, was placed in the chamber. Since it took about 5 h to perform a 12 point trend line in order to calculate the evaporation rate, most of the runs were performed on different days. Fig. 3 shows the plot of the correlation matrix for a chamber set at a temperature of 6.2 °C, using the "R-corrplot" function.

## 3. Results & discussion

### 3.1. Statistical significance

Table 1 summarises the Pearson correlation coefficients between the evaporation rate, the applied static magnetic field ($r_{RB}$) with its $p$-values ($p_{RB}$), along with the temperature and humidity coefficients ($r_{TH}$) and its $p$-values ($p_{TH}$). It is clear, as evidenced by the correlation coefficient $r_{RB}$, that the relationship between the evaporation rate and the applied magnetic field at each of the set temperatures is a linear one. Moreover, the significance of this effect is supported by the yielded $p$-values ($p_{RB}$), which are small enough to reject the null hypothesis. Therefore, the first general conclusion that can be drawn is that a significant increase in water evaporation can be achieved by having it circulate across a static magnetic field. A closer look at the values of $r_{RB}$ reveals that it decreases as temperature increases (from 0.8 at 6.2 °C to 0.6 at 70.4 °C); in other words, the effect of the magnetic field over the evaporation rate had been diminished. This is also signalled by their $p$-values, which reach their highest at 70.4 °C. The "overpowering" effect of the temperature on the influence of the applied magnetic field is caused by the higher kinetic energy of the water molecules, which makes the hydrogen bonds break, allowing the molecule to escape into the air. Specifically, it can be said that the relation between the evaporation rate and the applied magnetic is more pronounced with reducing temperatures. We can also conclude that the magnetization effect diminishes with increasing temperatures above 70.4 °C and is likely to be removed entirely at the boiling point. As expected, the temperature and humidity coefficients ($r_{TH}$) yield values close to unity (the negative sign indicates the obvious inverse relationship) reaching the best results at 70.4 °C. We interpret this as an indicator of stable conditions during our experiments.

**Table 1**
Summary of the Pearson correlation coefficients and their $p$-values. Average temperature and humidity values are also indicated.

| T (°C) | H (%) | $r_{RB}$ | $p_{RB}$ | $r_{TH}$ | $p_{TH}$ |
|---|---|---|---|---|---|
| $6.2 \pm 0.3$ | $64.9 \pm 3.3$ | 0.8 | $< 0.001$ | −0.7 | 0.006 |
| $30.8 \pm 0.5$ | $42.1 \pm 3.7$ | 0.8 | $< 0.001$ | −0.7 | 0.009 |
| $50.0 \pm 0.7$ | $22.6 \pm 1.7$ | 0.7 | 0.002 | −0.8 | $< 0.001$ |
| $70.4 \pm 1.2$ | $11.7 \pm 1.0$ | 0.6 | 0.015 | −0.9 | $< 0.001$ |

To quantify the observed magnetization effect on the evaporation rate, the increase of this rate, or enhancement, was calculated following the general percentage increase formula:

$$\Delta R(\%) = \frac{R_M - R_{NM}}{R_{NM}} \cdot 100 \tag{2}$$

where $R_M$ is the evaporation rate of the magnetized sample and $R_{NM}$ the evaporation rate of its control sample or non-magnetized "counterpart". Fig. 4 shows the percentage increase of the evaporation rate as a function of the applied static magnetic field. The lower curve presents the smallest increase of the evaporation rates, which happened at 70 °C (temperature values rounded to the nearest 1). On the other hand, the evaporation rate reached up to 20% for a set temperature of 6 °C, upper curve. This behaviour is consistent with the previously observed values of the correlation coefficient $r_{RB}$, i.e. greater at lower than at higher temperatures, and can be modelled by Eq. 3:

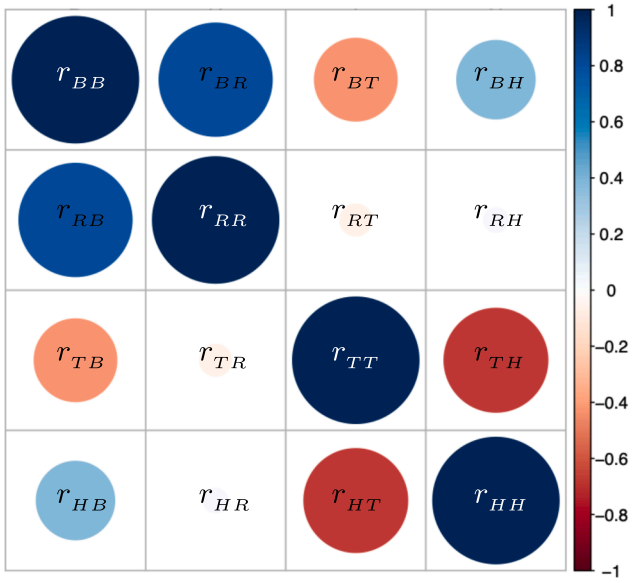


**Fig. 3.** Visualizing the correlation matrix. Positive correlations are displayed in blue and negative correlations in red color. Color intensity and the size of the circle are proportional to the correlation coefficients. This output corresponds to a set temperature of 6 °C.

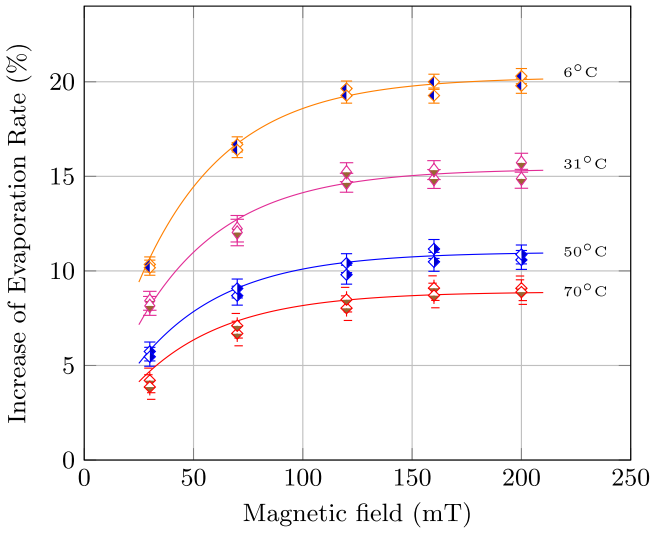


**Fig. 4.** Increase of the evaporation rate ($\Delta R$) vs applied magnetic field ($B$) at different temperature ($T$). Experimental values, depicted as symbols and solid lines, portray the fitted mathematical function. Temperature values rounded to the nearest 1.

$$\Delta R(\%) = (-0.21T + 21.85)\cdot(1 - e^{-0.025B}) \quad (3)$$

where $\Delta R(\%)$ is the percentage of the increase in the evaporation rate as a function of the temperature ($T$) and the applied magnetic field ($B$) in units of °C and mT respectively. The first factor on the right-hand side of Eq. 3 is influenced by temperature and yields the asymptotic part of the curve, while the second factor has the magnetic field parameter that controls the rate of growth of the evaporation percentage. In general terms, it can be said that applying a magnetic field of 150 mT ensured the maximum increase on the evaporation rate. This value of 150 mT was also found to be an asymptotic one in our previous contact angle studies [17], which revealed the effect of the magnetic field on the distribution and clustering structure of water molecules i.e. increase in the number of monomer and dimmer water molecules [4] which, in turn will facilitate the evaporation process. Nevertheless, magnetic field values of 35 mT may significantly increase the evaporation rate by up to 10% at 6 °C. Although rising temperature and falling humidity are the dominant factors affecting the evaporation rate of water; nevertheless, a static magnetic field has an increasing influence as the temperature drops.

### 3.2. Circulating effect on the evaporation rate

We wondered if the continuous motion of the circulating water caused a sufficient increase in the kinetic energy of the water molecules to make the water evaporate more quickly. To assess the effect of the circulation on the evaporation rate of non-magnetized water, we added an extra control petri dish containing water, which was not introduced into our closed circuit water system. From now on, we refer to it as static water. By comparison between the evaporation rate of both circulating and static water one can quantify the contribution of water motion to the evaporation rate. We highlight again the absence of magnetic field in this study. Fig. 5 shows the circulating vs the static evaporation rate ($R$) for our four sets of temperatures at a flow rate of 1.76 L/min. The experimental data sets fell in an almost a perfect straight line with a slope of 1.007. Furthermore, when the flow rate was increased up to 3.53 L/min the obtained slope was 1.008, and for a flow rate of 0.75 L/min the slope value was 1.005. From these slope values we established

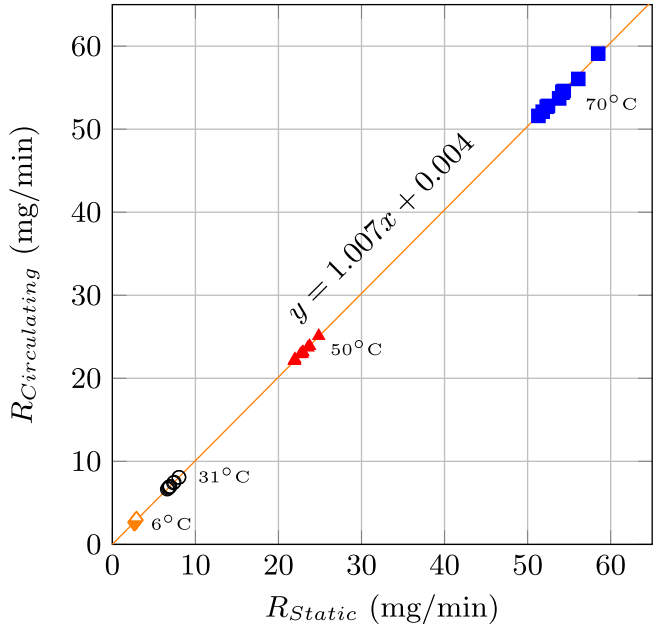


**Fig. 5.** Correlation of the circulating vs static water evaporation rate for a flow rate of 1.76 L/min, none magnetic field applied. Temperature values rounded to the nearest 1.

that the circulating effect contributed less than 1% to the evaporation rate. We concluded that for flow rate ⩽3.53 L/min, the water motion does not contribute greatly to the evaporation rate. This is in agreement with some other works [19,20] where the fluid velocity exerted no significant influence on solubles particles like $CaCO_3$ when applying magnetic treatment ⩾710 mT i.e. the water structure is not sufficiently modified to accommodate the solute. In some other work [14] the flow rate was correlated to the evaporation rate in terms of exposure time i.e. the product of the applied magnetic field and the exposure time per unit of volume, where authors claimed that the evaporation rate is proportional to the flow rate for magnetic field ⩾270 mT.

### 3.3. Empirical model

From the calculated evaporation rates, obtained from our experimental data, it is clear that the correlation with the temperature is not linear but rather an exponential-like function as shown in Fig. 6. We therefore propose this model:

$$R = kB^{\alpha}T^{\beta}H^{-\gamma} \pm \xi \quad (4)$$

where $k$ is a constant, $\alpha$-$\beta$-$\gamma$ are the model parameters ($> 0$) and $\xi$ the associated error. In order to determine the non-linear least-squares estimates of the parameters, we obtained initial parameter values by linearization through a change of variables:

$$ln(R) = ln(k) + \alpha ln(B) + \beta ln(T) - \gamma ln(H) \pm \xi' \quad (5)$$

Then we proceeded, by using these initial values, to perform the non-linear adjustment. For this we employed the "nls" function of the R-software. The final proposed model for the evaporation rate take the form of the following formula:

$$R = 363.8712\cdot\frac{B^{0.0154}T^{0.2962}}{H^{1.2815}} \pm \xi \quad (6)$$

As expected, the atmospheric parameters of temperature ($T$) and humidity ($H$) condition the evaporation rate, the later having the greatest impact. We acknowledge the limitations of our empirical model, which were due to our laboratory setup, and therefore other parameters such us the flow rate of air, atmospheric pressure and surface area were not accounted for. Nevertheless, the proposed empirical model can reproduce quite well the behaviour of the evaporation rate for all the applied static magnetic fields to the set temperatures and the measured humidity, as shown in Fig. 6. We have also interpolated the values of $R$ at 20, 40 and 60 °C. The area delimited by the two exponential dashed curves gives the confident interval, accounting for the deviations shown in Table 1.

### 3.4. Discussion

The evidence of the increase in water evaporation rate with magnetic treatment implies also an increase in the breaking or weakening of the intermolecular forces, hydrogen bonds being the strongest in the case of water molecules. This rupture of the hydrogen bonds is primarily temperature dependent, as we have seen, but also in a lesser way, pressure dependent [21,22]. The external force contributing to this breaking is the Lorentz force, which in the case of only magnetic treatment, can be reduced to just a single magnetic force i.e. no electric force term included, $\vec{F_m} = q\vec{v} \times \vec{B}$, where $q$ is the electric charge and $v$ its velocity. The magnetic force reaches its maximum for a charge moving perpendicular to the magnetic field, while the magnetic force is zero for a charge moving parallel to the magnetic field i.e. $F_m = qvBsin(\theta)$, where $\theta$ is the angle between the velocity and the magnetic field. As shown (see Fig. 4), the percentage enhancement values of the evaporation rate as a function of the applied magnetic field became higher as we approached the maximum density of water at ≈ 4 °C i.e. water molecule move slower and closer together. Since the magnetic force was removed prior

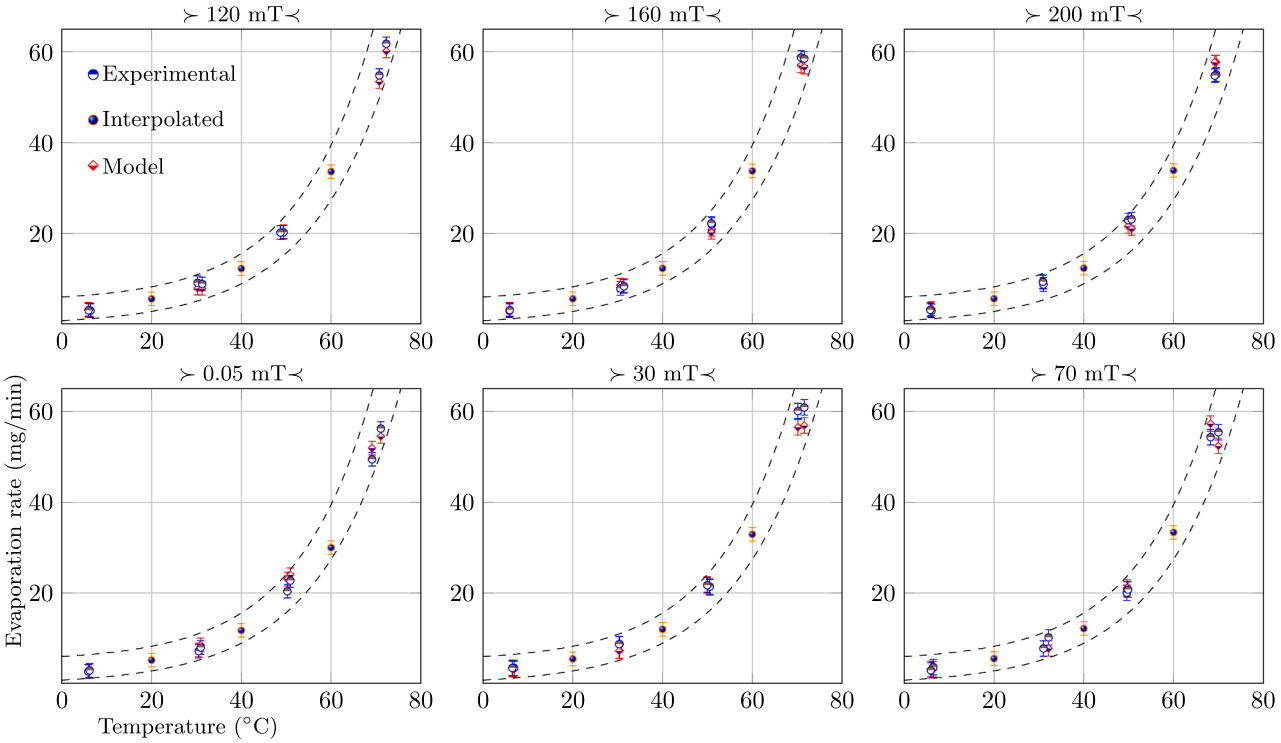


**Fig. 6.** Evaporation rate $R$ vs temperature $T$ for different applied magnetic fields. Experimental values, depicted as circles and rhombi, portray the generated by the empirical model, while solid balls show the interpolated ones. The area delimited by the two exponential dashed curves gives the confident interval.

to the temperature treatment, the remaining monomer molecules and/or smaller clusters recently created by the magnetic treatment will greatly contribute to the evaporation process. This, in turn, will benefit from the low internal kinetic energy at low temperatures, where random motion of molecules and clusters, due to the internal kinetic energy of the water, will eventually cause the "recombination" of these molecules and clusters. In other words, it takes longer for water molecules and cluster to form new hydrogen bonds.

Very few works have combined the effect of magnetic field into a coherent water evaporation empirical model. For instance, Guo et al. [10] suggested an enhancement of water evaporation as a function of the area in the water/air interface and the magnetic field gradient. Meanwhile, Amor et al. [11] produced a linear model of evaporation as a function of the temperature and the magnetic field. However, our model also considers the humidity factor; therefore, by also knowing the temperature and the applied static magnetic field, the model should be able to yield the evaporation rate in mg/min units. For comparison, we have extracted from Yang et al. [16] their evaporation rate after 6 h (heating time similar to ours) under applied magnetic fields of 100, 200 and 300 mT, at $20 \pm 1$ °C with a humidity of $65 \pm 5$ %. If we calculate the percentage difference (i.e. the difference between our model and their value divided by the average, shown as a percentage) the results are: $< 10$ % for 100 mT, $< 8$ % for 200 mT and $< 6$ % for 300 mT. Although the experimental conditions and setup were different in that Yang et al. employed tap water and we used distilled water, the two experiments gave very similar water evaporation rates. Therefore, we concluded that our model can be used to forecast the evaporation rate of water within the above-mentioned range of temperature and magnetic field.

## 4. Conclusions

We employed a statistical approach to study the influence of low intensity static mangnetic fields on the evaporation rate of circulating water. For this purpose, static magnetic fields ranging from 30-to-200 mT were applied to purified water circulating under temperatures between 6° and 70 °C. Results have shown that although rising temperature and falling humidity are the dominant factors affecting the evaporation rate of water; nevertheless, a static magnetic field has an increasing influence as the temperature drops. Therefore, the authors suggest that future studies regarding water intermolecular forces influenced by magnetic field should be addressed at low temperature i.e. between 5°-to-10 °C. We also concluded that for a flow rate $\leqslant$3.53 L/min, the water motion does not contribute greatly to the evaporation rate i.e. less than 1%. We have finally proposed an empirical triadic model that correlates the applied magnetic field with the ambient parameters of temperature and humidity. Future works contemplate a more complex setup to account for the above mentioned parameters not included in our model: air flow, atmospheric pressure and surface area. Some computational work will be needed to come up with a theoretical molecular model that will help us to understand the magnetically induced effect on water molecules.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

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