



Water Vapor Uptake and Microwave Heating of Magnetite / Aluminum Fumarate Composites

Tatsiana G. Shutava¹ , Alina S. Tsimanenkava², Denis S. Martsinkevich¹, Kanstantsin S. Livanovich¹  and Vladimir V. Pankov^{2,*} 

¹Institute of Chemistry of New Materials, National Academy of Sciences of Belarus, 36 F. Skaryna St., Minsk 220084, Belarus

²Faculty of Chemistry, Belarusian State University, 4 Nezavisimosti Av., Minsk 220030, Belarus

Abstract:

Aim: This study aims to obtain new desiccant materials based on magnetic nanoparticles and metal-organic framework (MOF) that are regenerable by microwave heating.

Background: Among the nanoparticles/MOF composites, the magnetic ones are especially interesting as sorbents with stimuli-triggered release of adsorbate and separation/concentration in an external magnetic field.

Methods: The composites were obtained by adding pre-synthesized magnetite nanoparticles to the solution of fumaric acid used to synthesize the porous aluminum fumarate (Al-fum) matrix. The mass fraction of Fe_3O_4 in the composites was evaluated by an o-phenanthroline-based assay, and their structure was characterized by XRD and FTIR. The magnetic properties and humidity-dependent water vapor uptake were measured.

Results: The broad X-ray diffraction signals of magnetite, decreased Curie temperature, and increased water uptake by the composites with a low magnetite content reflect the escalation of microdefects at the interphase boundary. Higher temperatures and pressures were reached in a shorter period of time upon the microwave heating of water-enriched powders and aqueous dispersions of Fe_3O_4 /Al-fum composites as compared with pure water.

Conclusion: The absorption of microwave radiation by Al-fum saturated with water is improved to a degree that allows one to overcome the decrease in dielectric losses and tangent of pure water with increasing temperature. The presence of magnetite in the amount of 0.04 g g^{-1} or more accelerates the heating of aqueous dispersions of the composites to the same extent as pure magnetite nanoparticles.

Keywords: Metal-organic framework, Magnetite, Nanoparticles, Composites, Desiccant, Microwave thermal effects.

© 2025 The Author(s). Published by Bentham Open.

This is an open access article distributed under the terms of the Creative Commons Attribution 4.0 International Public License (CC-BY 4.0), a copy of which is available at: <https://creativecommons.org/licenses/by/4.0/legalcode>. This license permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

*Address correspondence to this author at the Faculty of Chemistry, Belarusian State University, 4 Nezavisimosti Av., Minsk 220030, Belarus; E-mail: pankovbsu@gmail.com

Cite as: Shutava T, Tsimanenkava A, Martsinkevich D, Livanovich K, Pankov V. Water Vapor Uptake and Microwave Heating of Magnetite / Aluminum Fumarate Composites. Open Chem Eng J, 2025; 19: e18741231366263. <http://dx.doi.org/10.2174/0118741231366263250214112601>



CrossMark

Received: October 29, 2024

Revised: December 5, 2024

Accepted: January 1, 2025

Published: February 24, 2025



Send Orders for Reprints to
reprints@benthamscience.net

1. INTRODUCTION

Metal-organic frameworks (MOFs) are of great interest due to their periodic 3D structure with interconnecting system of voids accessible for selective filling with small molecules and related extraordinary porosity that manifests itself in a high specific surface area and adsorbate uptake. The possibility of synthesis from block compounds and flexible use of aqueous and non-aqueous solvents, temperature, and modulators allow one to obtain MOFs with precisely specified structure and physicochemical properties, often as a layer on the template surface [1-4]. By embedding metal, metal oxide, ceramic, and polymeric nanoparticles into the bulk porous matrix or surrounding them with a shell of MOF, new composites with a unique set of properties are obtained. As expected, they consolidate tailorable porosity and adsorption selectivity of MOF with the catalytic activity of nanoparticles into new functional material with enhanced performance. Possible applications of such composites cover catalysis, adsorption, storage, and separation of gases, plasmonic sensing, sequestration of pollutants, molecular drug delivery, etc [5-9].

Among the nanoparticles/MOF composites, the magnetic ones are especially interesting since they can be recollected by applying an external magnetic field to separate/concentrate the sorbent with inorganic pollutants or target organic compounds [7, 10, 11]. Furthermore, they become sensitive to alternating magnetic fields or microwaves to stimuli-trigger the release of adsorbate molecules (water, CO₂, H₂, therapeutics) [6, 12-16].

The physico-chemical effects related to the absorption of microwave radiation (heating, water desorption, catalytic performance, etc.) have been reported for a limited number of pure MOFs and MOF-based composites [9, 13-17]. As broadband microwave-absorbing materials, they are inferior to MOF-derived carbon-based composites. The latter obtained by pyrolysis of MOFs or metal-enriched MOFs in air or inert atmosphere keep high specific surface area and porosity inherent in MOF and demonstrate effective electromagnetic wave absorption in the range of 3.5 to 8 GHz as a few millimeter coating, while relatively few MOF-derived coatings absorb below 3 GHz [18].

We report here on the synthesis of magnetic nanoparticles/MOF composites with different magnetite to aluminum fumarate (Al-fum) ratios, in which magnetite nanoparticles are incorporated into a porous MOF matrix, the study of their composition and structure, including the mutual influence of the two phases, as well as water vapor uptake by the composites and influence of the water saturation on the 2.45 GHz microwave heating.

Magnetic iron oxides are thermally stable in air up to temperatures of 750 K, which ensures their wide application in many industries. Fe₃O₄ nanoparticles have unique characteristics: chemical stability, low cost and biocompatibility, proven by their applications in such fields as cell labeling and drug delivery, as contrast agents for MRI or magnetic heating mediators [19, 20]. Aluminum fumarate MOF is considered as a promising environmentally friendly adsorbent for a high variety of applications with exceptionally high hydrothermal stability [21-24]. Preliminary

evaluation showed the good reproducibility of water uptake by selected Fe₃O₄/Al-fum composites under humid conditions [25]. The magnetite nanoparticles included in the MOF matrix are expected to improve the water absorption properties of the composites and enhance their sensitivity to microwave heating.

2. MATERIALS AND METHODS

2.1. Materials

Al₂(SO₄)₃·18H₂O (97%, Sigma-Aldrich), fumaric acid (98%, Sigma-Aldrich), FeCl₃·6H₂O (98%, Sigma-Aldrich), FeSO₄·7H₂O (99%, Sigma-Aldrich), NaOH (99%, Sigma-Aldrich), toluene (Sigma) were used as received. Distilled water was obtained one day prior to the experiments using a laboratory distiller.

2.2. Synthesis of Magnetite

Magnetite was synthesized from an aqueous solution of iron salts [26]. In a typical experiment, 100 mL of a 0.125 M FeCl₃ solution and 50 mL of a 0.069 M FeSO₄ solution were combined and stirred for 3 min, then the mixture was added to a 0.338 M sodium hydroxide solution (200 mL), further stirred for half an hour under constantly monitored pH of 11. The particles were washed by magnetic decantation to neutral pH and brought to a ca. 21.5 g L⁻¹ concentration in terms of solid matter by adding distilled water. The hydrodynamic diameter of the obtained magnetite nanoparticles measured by dynamic light scattering is approximately 30 nm.

2.3. Synthesis of Fe₃O₄/Al-fum Composites

In order to incorporate the freshly synthesized magnetite nanoparticles into porous aluminum fumarate matrix the synthetic method was modified [3]. A predetermined volume of the magnetite dispersion was taken to achieve a given theoretical ratio of magnetite to Al-fum, namely 1:x, where x = 1, 5, 10, 20, 50, in the composites and admixed to a solution obtained from fumaric acid (1.05 M, 200 mL) and sodium hydroxide (3.94 M, 160 mL). The resulting mixture was added to 300 mL of a 0.35 M aluminum sulfate solution for 10 min with constant stirring. The dark to light brown precipitates were separated by vacuum filtration through a paper filter. They were dried at 100°C in the air for 24 h followed by activation in a vacuum oven at 130°C for 24 h [27]. The composites were fine ground in a mortar.

2.4. Characterization of Fe₃O₄/Al-fum Composites

The mass fraction of magnetite in the composites (ω) after their dissolution in HCl was determined by an o-phenanthroline-based assay for total iron [28] using a CM 2203 Solar spectrofluorimeter. FTIR spectra of the Fe₃O₄/Al-fum composites were recorded on a Tensor 27 Bruker spectrometer after pressing them into KBr tablets. A scanning electron microscope LEO 1420 was used to characterize the morphology of composites. X-ray diffraction analysis (XRD) was performed on an X-ray diffractometer DRON-3 using a Co Kα1 (α = 1.79021 Å) radiation source. The water uptake by the powders was

measured using a MAX 50 Radwag moisture analyzer. The powder under investigation was placed into a cell with controlled relative humidity (RH) and temperature for 24 h, then quickly poured onto the analyzer weighing pan and heated at 80 °C until a constant mass was achieved.

The temperature dependence of specific magnetization (σ) was measured in the range of 77 – 900 K by the Faraday method in a magnetic field of 0.86 T. The error in magnetization measuring is $\pm 0.005 \text{ emu g}^{-1}$.

The interaction of the $\text{Fe}_3\text{O}_4/\text{Al-fum}$ composites with microwave radiation was evaluated using a MonoWave 300 Anton Paar instrument operating at a frequency of 2.45 GHz. The composite under study was dispersed in either toluene (8.5 mg mL^{-1}) or water (8.5 and 250 mg mL^{-1}) and a 5.5 mL aliquot of the dispersion was irradiated at a 30 W power in a sealed microwave vial under constant steering. The irradiation of solvent-free composite powders ($5.5 \pm 0.1 \text{ g}$) was carried out after drying them over KOH flakes. Otherwise, the composites were kept at a relative humidity of 90% in a sealed container for 12 h at $20 \pm 1^\circ\text{C}$ prior to microwave heating. The pressure (P) and temperatures of the wall (T_{IR}) and internal content (T_{R}) of a microwave vial were measured with a time interval of 1 s. The microwave heating was automatically stopped after reaching one of the preset upper limits (200°C and 16 (30) bar for temperature and pressure, respectively) or manually interrupted after no perceptible increase in temperature occurred within 60 s.

The standard deviations of triply determined time of heating to 200°C of saturated with water vapor powders of Al-fum (sample-to-sample) and a 0.06 g g^{-1} composite (trial-to-trial) were ca. 42 and 28 s, respectively. For aqueous composite dispersions, good reproducibility in microwave heating experiments was also observed; the standard deviation in a series of three heating time measurements does not typically exceed 30 s.

3. RESULTS AND DISCUSSION

By admixing various amounts of Fe_3O_4 nanoparticles to a sodium fumarate solution before adding the latter to

aluminum sulfate, the $\text{Fe}_3\text{O}_4/\text{Al-fum}$ composites with the different ratios of Fe_3O_4 to Al-fum were prepared (Table 1). The mass fractions of magnetite in the composite particles were determined by an o-phenanthroline assay and also calculated as the ratio of specific magnetization of the composites to that of magnetite nanoparticles as prepared. The obtained values are in good agreement with each other. The experimental values of ω in the composites appear to be approximately 30% lower than the theoretically calculated magnetite fractions. However, the calculations did not take into account water that the Al-fum-based composites absorb at ambient temperature and relative humidity, leading to overestimated values of ω . Meanwhile, the water uptake by such a composite, as shown below, can reach 300 mg g^{-1} .

The microphotograph of a $\text{Fe}_3\text{O}_4/\text{Al-fum}$ composite powder in Fig. (1a) shows highly polydispersed aggregates with pronounced edges. They consist of small MOF crystals that are responsible for rough surface appearance, as can be seen at larger magnification Fig. (1b). Magnetite nanoparticles appear to be evenly distributed throughout the Al-fum matrix and embedded into the porous material; no bulk phase of iron oxide was visualized.

Table 1. Composition and magnetic properties of $\text{Fe}_3\text{O}_4/\text{Al-fum}$ composites.

Composition 1:x	$\omega, \text{ g g}^{-1*}$			$T_{\text{Curie}}, \text{ K}$	$\sigma, \text{ emu g}^{-1}$
	Theory	Experiment			
		o-phen. assay	magn.		
Fe ₃ O ₄	1.00	0.982±0.035	1.00	805	23.0
1:1	0.50	0.341±0.007	0.326	800	7.5
1:5	0.17	0.114±0.015	0.109	790	2.5
1:10	0.09	0.057±0.003	0.057	760	1.3
1:20	0.05	0.039±0.009	0.035	750	0.8
1:50	0.02	0.013±0.004	0.011	730	0.3
Al-fum	0.00	0.000±0.002	-	-	-

Note: * round to two decimal places hereafter.

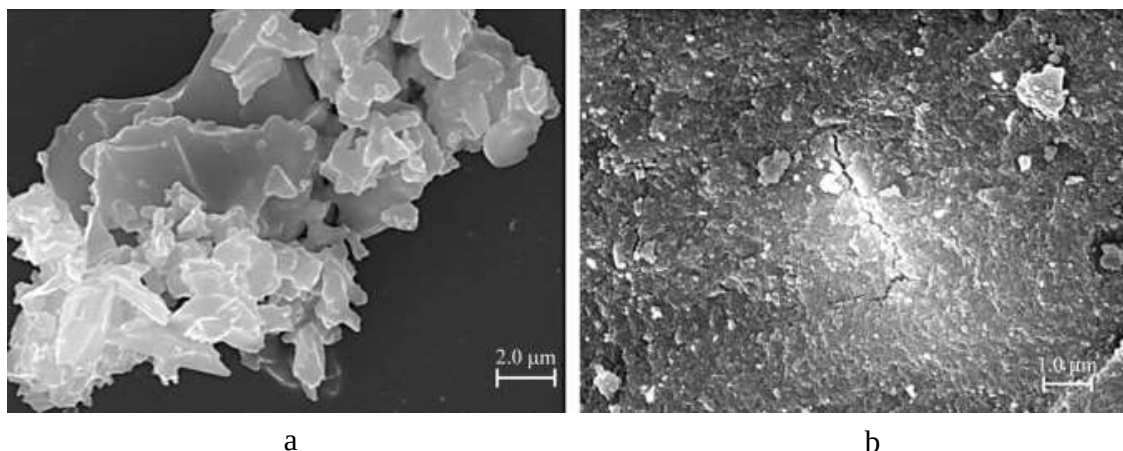


Fig. (1). SEM of $\text{Fe}_3\text{O}_4/\text{Al-fum}$, $\omega = 0.34 \text{ g g}^{-1}$ composite powder as prepared (a) and surface of a dried agglomerate of particles (b).

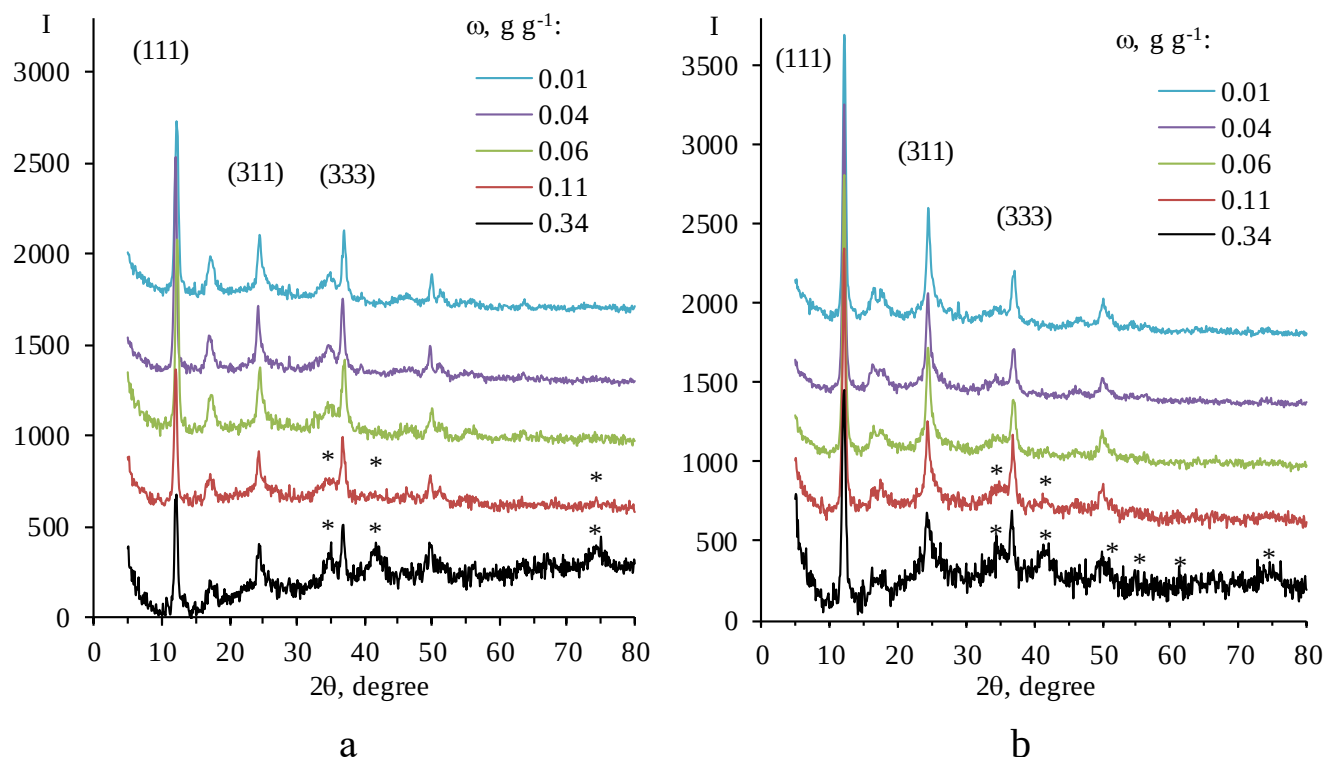


Fig. (2). XRD spectra of $\text{Fe}_3\text{O}_4/\text{Al-Fum}$ composites with different magnetite mass fractions before (a) and after (b) drying in a vacuum oven. The diffraction peaks that correspond to the reflection planes of aluminum fumarate are indexed. The diffraction reflexes of Fe_3O_4 are marked with an asterisk.

The X-ray diffraction spectra of $\text{Fe}_3\text{O}_4/\text{Al-fum}$ composites are shown in Fig. (2). The positions and relative intensities of the peaks in the spectrum of Al-fum coincide with those reported for the MOF in [29, 30]. The spectrum of a composite with $\omega=0.34 \text{ g g}^{-1}$ additionally contains broad peaks centered at 2θ of 35.5 and 42.0 that are typical for magnetite {311} and {400} reflection planes [31, 32]. In the spectra of the composites, some diffraction peaks of magnetite overlap with those of Al-fum and appear as broadening or shouldering of a main strong peak, such as one at $2\theta \sim 35.5$. The magnetite diffractions are barely noticeable in the XRD spectra of a composite with the magnetite mass fraction of 0.11 g g^{-1} and do not appear at lower ω despite other methods confirming the presence of magnetic phase.

It is worth mentioning that the intensity of X-ray reflections increases after drying the composites in a vacuum oven for 24 h. It is accompanied by some changes in the relative intensity of the peaks while their positions remain unchanged.

In contrast to the X-ray reflections of aluminum fumarate, the peaks of the iron oxide phase are greatly broadened and, regardless of ω are of low intensity. This well-known side effect is associated with the incompleteness of the processes of phase formation and crystallization of the spinel structure, the existence of defects in

large quantities and disruption of the distribution of cations across the sublattices of the crystal structure, as well as the existence of a surface layer with a non-collinear arrangement of spins, which is caused by fluctuations of magnetic moments due to the significantly greater influence of thermal vibrations on ions, located on the surface of magnetite nanoparticles [33, 34].

The intense characteristic adsorption bands of Al-fum appear in the FTIR spectra of all $\text{Fe}_3\text{O}_4/\text{Al-fum}$ composites Fig. (3). The detailed assignment of the peaks in the spectrum of Al-fum can be found elsewhere [31]. For pure magnetite nanoparticles, two closely situated merging peaks are observed at 592 and 632 cm^{-1} , which can be attributed to the vibration of Fe-O bonds in the spinel structure [35]. Two wide asymmetric uninformative bands at 3460 and 1628 cm^{-1} in the magnetite spectrum are related to the presence of hydroxyl groups and adsorbed water molecules (O-H stretching and H-O-H bending vibrations respectively) [36]. Despite the presence of magnetite particles in all $\text{Fe}_3\text{O}_4/\text{Al-fum}$ composites being confirmed by other methods (Table 1), only a moderate increase of absorption around 600 cm^{-1} and an asymmetric broadening of the band centered at 3487 cm^{-1} are noticeable in the spectrum of a 0.34 g g^{-1} composite because of overlapping with more intense absorption peaks of Al-fum.

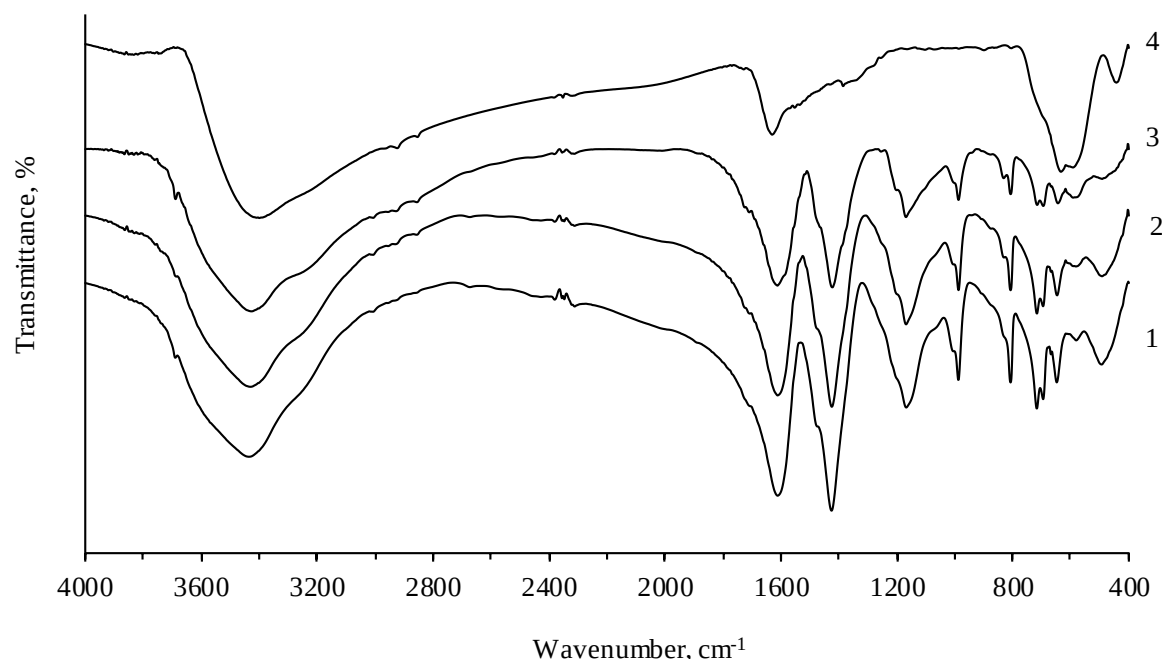


Fig. (3). FTIR spectrum of Al-fum (1), $\text{Fe}_3\text{O}_4/\text{Al-fum}$ composites (2-3, ω , g g^{-1} : 2 - 0.11; 3 - 0.34), and Fe_3O_4 nanoparticles (4).

The surface layer fraction in fine magnetite particles is expectedly large; this results in decreasing their saturation magnetization as compared to bulk material [34, 37]. The saturation magnetization of the synthesized magnetite nanoparticles used for the preparation of $\text{Fe}_3\text{O}_4/\text{Al-fum}$ composite is only 23.0 emu g^{-1} , while the values for the composites depend on their composition. By comparing the magnetization values with that of pure magnetite, the mass fraction of the latter was independently evaluated (Table 1). The values of ω for the composites obtained by two independent methods align well with each other, thus, the preservation of the magnetic properties of nanoparticles incorporated in the porous MOF matrix is confirmed. This is in good agreement with magnetic properties of particulated magnetite reported previously [32].

The dependence of magnetic properties of the composites on temperature was investigated in order to evaluate their thermal stability. The curve of specific magnetization of pure prepared Fe_3O_4 versus temperature shows that it behaves as a typical ferromagnetic Fig. (4). The Curie temperature (T_{Curie}) for magnetite nanoparticles (Table 1) turned out to be lower than the value for bulk material (858 K) [38]. This fact is known for nanoparticles and is due to the existence of a surface layer with an imperfect crystalline and magnetic structure [39, 40]. We found that a decrease in the amount of magnetite in the composites led to a further slight decrease in the Curie temperature

(Table 1). This may also indirectly reflect the influence of hydrophilic MOF matrix as magnetite surrounding the properties of the surface layer of the nanoparticles.

The water uptake by the freshly prepared $\text{Fe}_3\text{O}_4/\text{Al-fum}$ composites with different mass fractions of magnetite is shown in Fig. (5). In an arid atmosphere ($\text{RH} \sim 10\%$), the water vapor absorption by the composites is low regardless of the concentration of magnetite. As the relative humidity rises to 70%, the positive effect of small amounts of fine magnetite particles becomes visible, apparently associated with an escalation of microdefects in the Al-fum lattice structure caused by the incorporated nanoparticles. The maximum water vapor uptake of 464 mg g^{-1} was found for ω around 0.04 g g^{-1} . The increase is as high as 17% as compared with Al-fum matrix. With increasing the content of magnetite to 0.34 g g^{-1} , the water uptake by the composite drops drastically below 250 mg g^{-1} , thus approaching the value for finely ground magnetite powder (213 mg g^{-1}). At the high relative humidity ($\text{RH} = 90\%$), freshly prepared pristine Al-fum and the composites with ω lower than 0.11 g g^{-1} show a high uptake of water vapor, and the adsorption reaches up to $600\text{--}650 \text{ mg g}^{-1}$. The high water uptake value may be partially due to the condensation of vapor in the pores at high humidity [4]. A good reproducibility of water uptake by Al-fum and a 1:10 $\text{Fe}_3\text{O}_4/\text{Al-fum}$ composite has been previously shown [25]. In six consecutive cycles of relative humidity alternation from 10% to 90% the coefficient of variation was less than 7%.

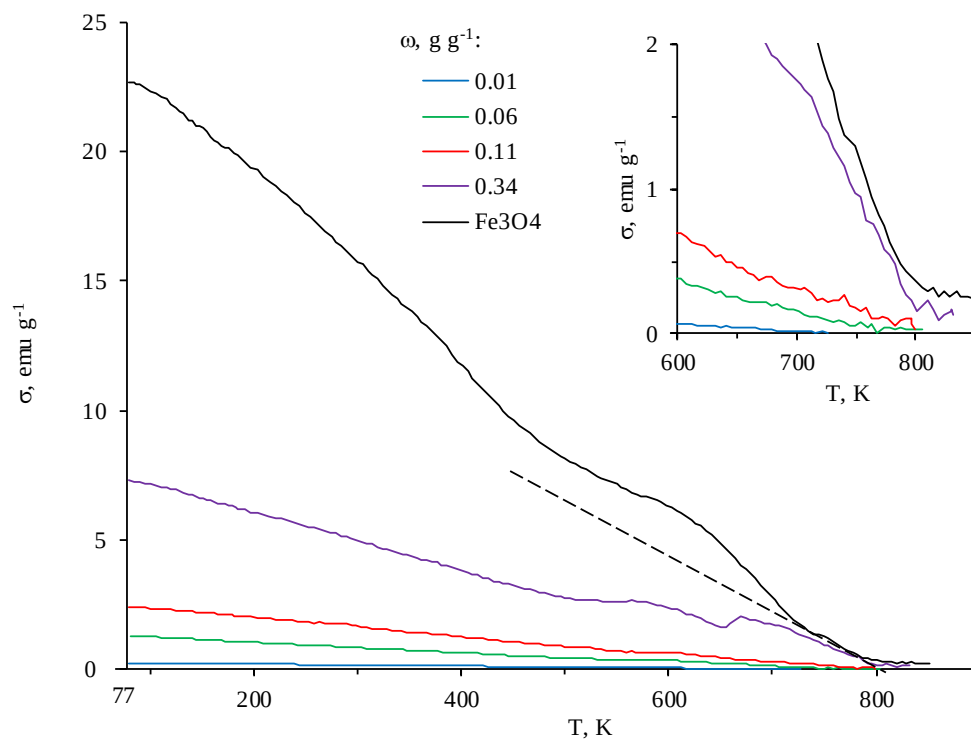


Fig. (4). Dependence of specific magnetization of Fe₃O₄/Al-fum composites and Fe₃O₄ nanoparticles as prepared on temperature. The insert shows the region near the Curie temperatures of the composites.

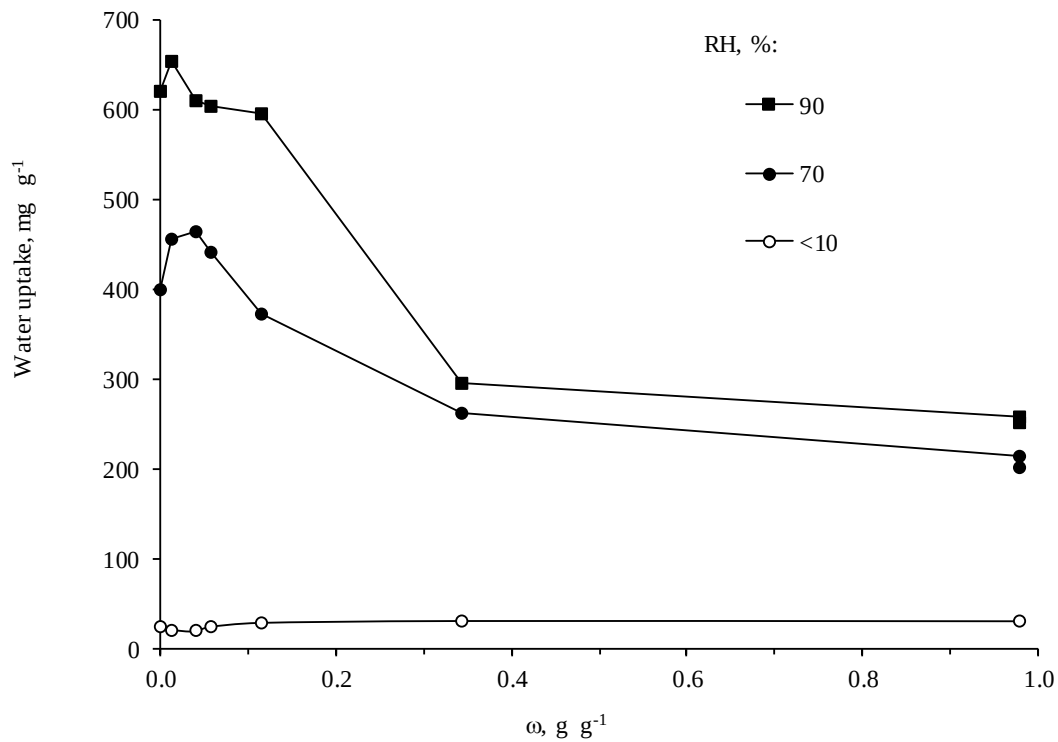


Fig. (5). Water uptake by Fe₃O₄/Al-fum composites with different mass fractions of magnetite. 24 ± 1 °C.

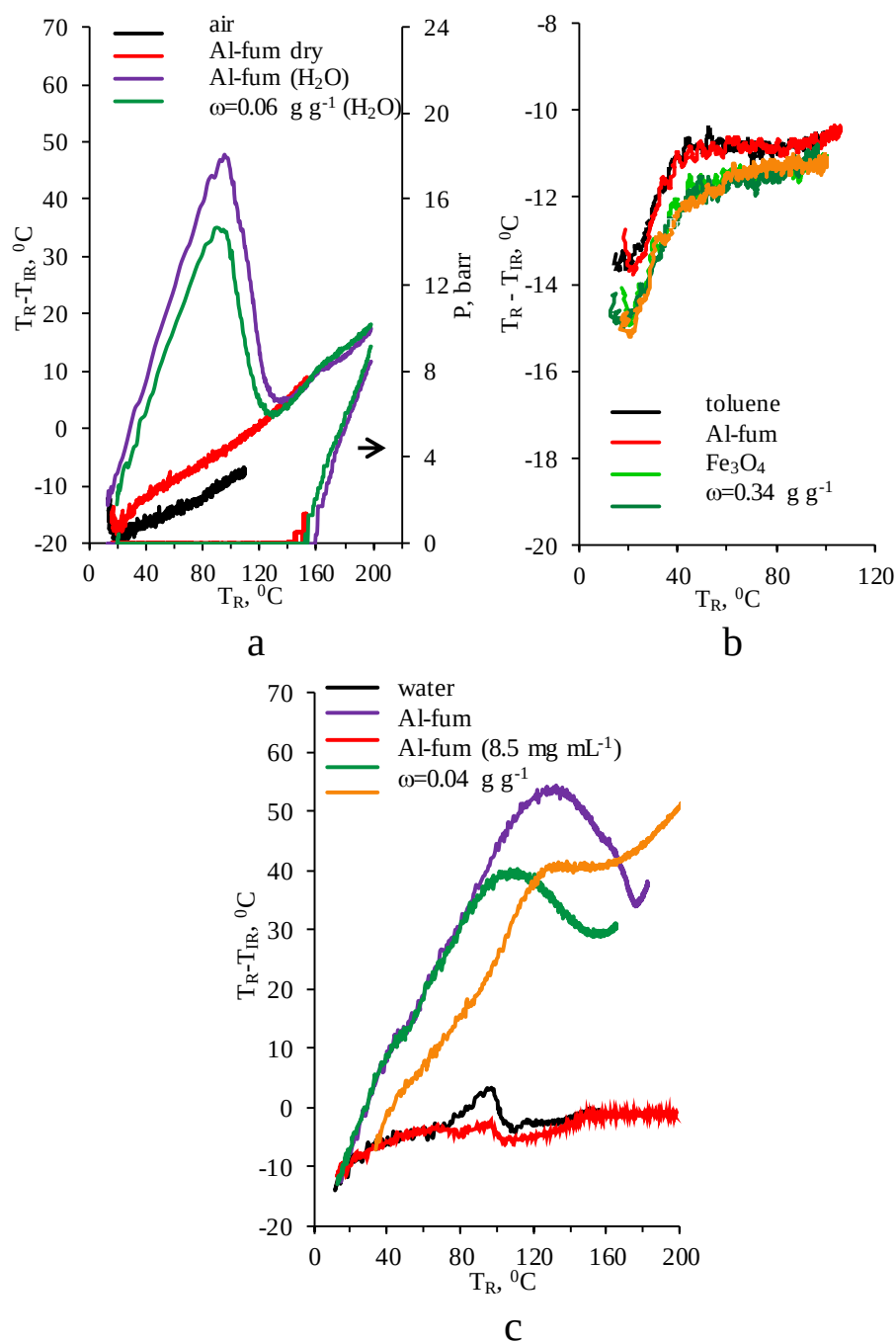


Fig. (6). $T_R - T_{IR}$ as a function of T_R for Al-fum and $\text{Fe}_3\text{O}_4/\text{Al-fum}$ composites: **a)** powder (corresponding pressure curves are shown in the left lower corner), **b)** toluene (8.5 mg mL^{-1}), **c)** water (250 mg mL^{-1}).

An analysis of temperature differences in spatially separated parts of a microwave reactor provides valuable information on the localization of materials that predominantly adsorb microwave radiation. The changes in temperature of the reactor content T_R and its wall T_{IR} and pressure P experimentally observed during microwave heating of dry and water-saturated MOFs are shown in Fig. (S1). For the vials filled with Al-fum and $\text{Fe}_3\text{O}_4/\text{Al-fum}$, the microwave heating curves are presented as $T_R - T_{IR}$ vs. T_R

plots in Fig. (6). The dry powder of Al-fum seems to be reasonably transparent to a 2.45 GHz microwave radiation at ambient temperatures up to 120 $^{\circ}\text{C}$ Fig. (6a). Under these conditions, the vial wall temperature is higher than that of Al-fum powder (negative $T_R - T_{IR}$ values). Therefore, the powder is warmed up by the heat supplied by the vial wall glass, which is apparently a more effective microwave-absorbing material in this case. A similar situation is typical for an air-filled vial. Gases, including water vapor,

are poor absorbers of microwaves, and a difference between the readings of two thermometers is expected [41]. After the microwave heating for 18 min, the value of T_R inside an air-filled vial asymptotically approaches 110 °C, being constantly 8 deg. lower than T_{IR} .

After 4-5 min radiation of pre-dried and distilled toluene which is a low microwave-adsorbing solvent ($\text{tg}\delta=0.04$) [41] T_R of approximately 100 °C is reached (Fig. S2). Over a long period of time, the temperature difference remains equal to 11-12 °C in favor of the glass walls (Fig. 6b). All dry Al-fum and magnetite/Al-fum composites do not change the T_R - T_{IR} vs. T_R curve while dispersed in toluene in a concentration of 8.5 mg mL⁻¹; the minor variations observed from sample to sample are within the experimental error.

The analysis of microwave absorption by dry Al-fum and composites in air and toluene suggests that in the absence of water, they are low microwave-absorbing materials below 100 °C, with their loss tangent apparently being comparable or lower than that of toluene. For dry Al-fum, the T_R - T_{IR} value slowly increases with increasing temperature and becomes positive above 120 °C (Fig. 6a). This is presumably explained by changing dielectric permeability or loss of Al-fum at elevated temperatures. However, the available studies on dielectric properties of MOF cover so far only a few individual MOFs in limited frequency ranges [14-17, 42-44], among which Al-fum, to the extent of our knowledge, is not included. We can refer to the temperature dependence of dielectric properties for some known microwave radiation absorbers [45, 46] and another MOF at 1 MHz frequency [47].

Unlike dry Al-fum powder, the one *saturated with water* is heated extremely efficiently by microwaves (Fig.

S1, c,d). T_R rises to 120 °C in less than 2 min of heating. Moreover, the maximum temperature difference reaches 48 and 35 °C (while T_R is equal to 90 and 95 °C) for Al-fum and a composite with $\omega=0.06$ g g⁻¹ respectively (Fig. 6a). The adsorption of microwave radiation of 2.45 GHz by a solvated Al-fum can be explained by electron delocalization induced by interactions between an adsorbate molecule and a MOF host. It leads to structural polarization, resulting in an enhancement of dielectric constant for the host-guest system as shown in the range of 1 Hz to 1 MHz for MFM-300(M) (M = Al, Sc, Cr, Fe, Ga, In) upon adsorption of Ar and NH₃ [48], HKUST-1 upon loading with H₂O, methanol, ethanol, and I₂ [49-51], and UiO-66 upon adsorption of H₂O [43].

The T_R - T_{IR} value decreases with further microwave heating, most likely due to the diffusion of heated water vapor from MOF to the walls. An almost linear increase of T_R - T_{IR} and pressure is observed over the range of elevated temperatures in which the MOF exhibits intrinsic microwave absorption.

Due to its medium value of loss tangent ($\text{tg}\delta=0.123$ at 25 °C and 2.45 GHz), liquid water is a medium microwave-absorbing solvent [41]. Under experimental conditions, it is rapidly (within a 2 min period) heated up to ~110-120 °C, followed by a slow increase of temperature for 15 min to reach 160-190 °C (Fig. 7, S3). Because the dielectric loss and loss tangent of pure water decrease with increasing temperature [41], the absorption of microwave radiation by the solvent also decreases. Due to uniform heating and constant stirring of the liquid, the T_R - T_{IR} difference is minimal (Fig. 6c). Similarly, in aqueous dispersions of Al-fum and composites with a concentration of 8.5 mg mL⁻¹ under constant intensive stirring, the temperature gradient in the vial is negligible.

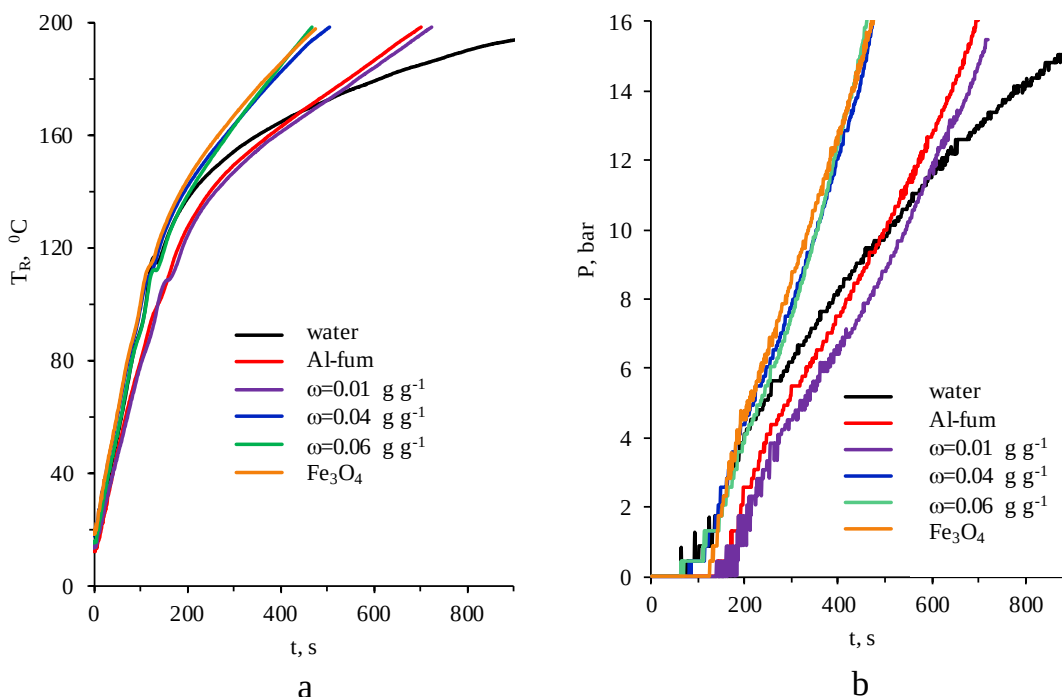


Fig. 7 contd.....

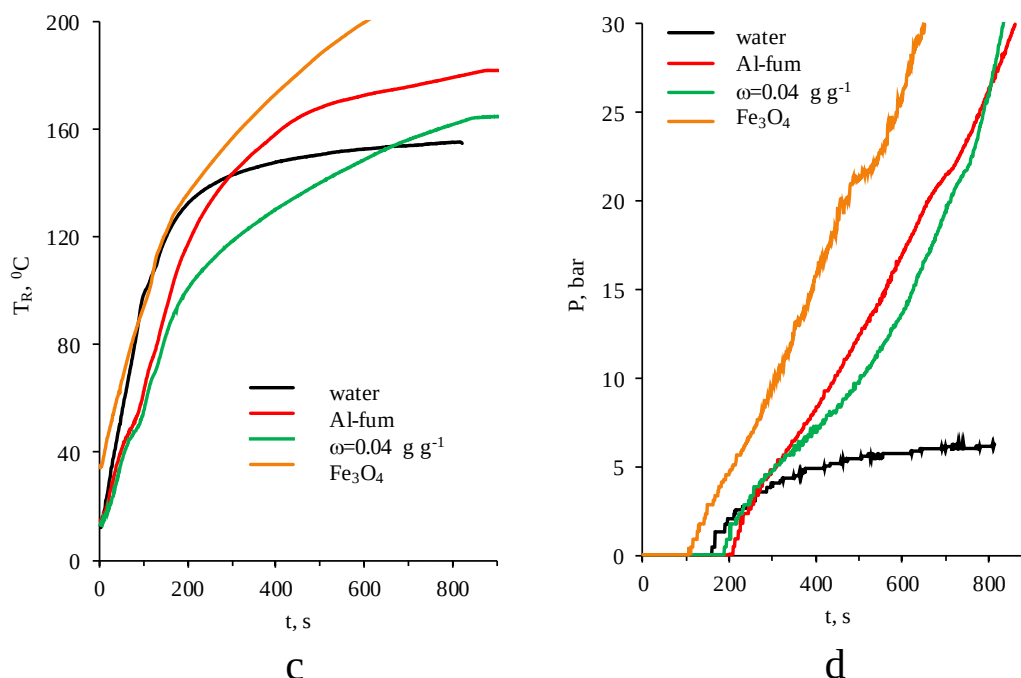


Fig. (7). Temperature (a, c) and pressure (b, d) vs. time of microwave heating of $\text{Fe}_3\text{O}_4/\text{Al-fum}$ composites at 8.5 (a, b) and 250 (c, d) mg mL^{-1} .

As mentioned previously, water adsorbed inside MOF pores becomes an effective microwave absorber. A rapid increase in temperature inside the reactor is observed when aqueous dispersions of Al-fum or composite concentrated up to 250 mg mL^{-1} are irradiated (Fig. S4). The T_R-T_{IR} difference reaches the maximum values of 53 °C (at $T_R=128$ °C) and 36 °C (at $T_R=106$ °C) for Al-fum and $\text{Fe}_3\text{O}_4/\text{Al-fum}$ dispersions accordingly Fig. (6c). The overheating of vial interior is apparently related to the low thermal conductivity (K) of aluminum fumarate due to its porous structure [52]. For Al-fum, the reported values of K vary from 0.1 to 0.3 $\text{W m}^{-1} \text{K}^{-1}$, with a light dependence on dopant, temperature, coating thickness, and particle packing [53-55]. It is two times lower than the thermal conductivity of water.

In turn, magnetite has a much higher thermal conductivity as compared to water [56, 57] but also it is a highly effective microwave absorber in a wide range of microwave frequencies [57, 58].

Due to the increasing absorption capacity of the substance with increasing temperature, when treating substances with low thermal conductivity value, local overheating usually occurs and "hot spots" are formed because the released heat does not have time to be evenly distributed over the volume. For uniform heating of the substance by microwave radiation and elimination of uneven temperature distribution in the volume of the heated body, it is necessary that the substance has a sufficiently high thermal conductivity, such as magnetite [59, 60].

The positive T_R-T_{IR} values observed for the concentrated dispersion of Fe_3O_4 nanoparticles Fig. (6c) are most likely related to extreme heat production by magnetite particles under 2.45 GHz radiation and local overheating due to the absence of proper mixing.

Regardless of the investigated concentration, magnetite dispersions heat up faster than pure water Fig. (7). The fact is in good agreement with the microwave-related properties of magnetic nanoparticles [41]. For an Al-fum dispersion, the heating curve is located lower than that of water for temperatures below ~160-170 °C.

The effect of magnetite on microwave heating of $\text{Fe}_3\text{O}_4/\text{Al-fum}$ composites depends on the mass fraction ω Fig. (8). At an 8.5 mg mL^{-1} concentration that ensures rapid redistribution of heat between parts of the reactor, only a composite with $\omega=0.013 \text{ g g}^{-1}$ shows the T_R curve in the vicinity to that of unmodified Al-fum. The rest of the investigated $\text{Fe}_3\text{O}_4/\text{Al-fum}$ composites demonstrate a rapid temperature increase, which is only a few degrees lower than that of pure magnetite dispersion. The magnetite mass fraction of 0.04 g g^{-1} is enough for accelerated heating of the dispersion, which is especially noticeable at temperatures above 160 °C. The time of microwave heating required to reach pre-set temperature of 200 °C decreases by 40-45% while using Al-fum or the composite with a low ω and by 60-65% if the mass fraction of magnetite is above 0.04 g g^{-1} (Fig. 8).

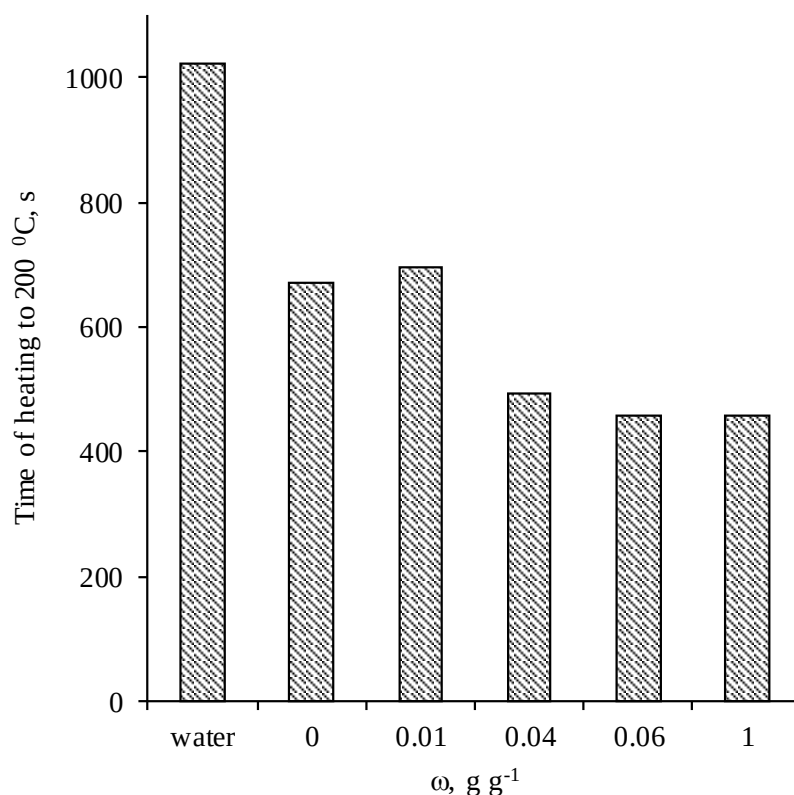


Fig. (8). Time of heating to 200 °C for the $\text{Fe}_3\text{O}_4/\text{Al-fum}$ composites with different ω .

In the $\text{Fe}_3\text{O}_4/\text{Al-fum}$ composites obtained using pre-synthesized magnetite nanoparticles with a diameter of about 30 nm the magnetic phase is enclosed in the porous hydrophilic matrix of MOF. The mass fraction of magnetite in the composite varies from 0.01 to 0.34 g g^{-1} depending on the initial mass ratio of magnetite nanoparticles and aluminum salts in the reaction mixture. Both the synthesis of magnetic materials and metal-organic frameworks are implemented in industry. The proposed here synthetic approach to the magnetic MOF-based composites is believed to be fully scalable. The only scaling issue might be the preparation of magnetic particles of specified sizes from commercially available powders and long term stability of their aqueous dispersions, which imposes certain restrictions on the choice of magnetic phase for composites. Some aspects of this problem can apparently be solved by combining the stages of magnetic nanoparticle preparation and composite synthesis within one production facility.

It is shown that in such a composite magnetite completely retains its magnetic properties, but the Curie temperature decreases with decreasing the mass fraction of magnetic phase. A slight decrease in the Curie temperature by a maximum of 70 K occurs in this case, most likely due to the influence of hydrophilic Al fumarate matrix on the structure and properties of the surface layer of magnetite at the interface. It lies in the temperature

range of more than 800 K, which is significantly higher than the temperature range of use of this composite - less than 500 K, which is limited by the temperature of its decomposition of aluminum fumarate (570 K). Therefore, this phenomenon will not affect the consumer properties of the material.

Moreover, it was shown that the temperature decrease usually occurs as a result of the formation of a thin layer (one nanometer) on the surface of particles that practically does not change their magnetization. For example, for a particle with a diameter of 30 nm, the volume of such a layer is only about 7% of the total volume of the particle. In the same limit, there is also a slight decrease in magnetization.

It was found that the measurement of the change in the Curie temperature of Fe_3O_4 in the composite is a sensitive marker indicating the interaction of the metal-organic framework matrix with the magnetic phase and can serve as a factor that will help in the future to characterize in detail the influence of MOFs on the magnetic properties of nanoparticles with which they form composites.

The broaden signals of the crystalline phase of magnetite in the X-ray spectra of the $\text{Fe}_3\text{O}_4/\text{Al-fum}$ composites apparently can be associated with a large share of disordered magnetite crystal structure at the boundary of

two phases. The mutual influence of two phases also appears as an increase in water uptake by a 0.04 g g^{-1} composite as compared with Al-fum matrix due to the escalation of microdefects in the MOF lattice structure caused by incorporated magnetite nanoparticles.

Among possible applications of magnetic MOF-based adsorbents, the magnetic separation must be mentioned first, with a drastically increasing rate of MOF removal after the adsorption of the target substance. Recently, an innovative proposal has been made to cool microchips using a MOF-based coating [61]. The use of the magnetite/Al-fum composites with enhanced and reproducible water vapor uptake and environmental stability will allow, in this case, to implement the thermal management of electronics through effects associated with the sorption/desorption of water vapor by MOF.

Conventional 2.45 GHz microwave equipment can be used to heat the Fe_3O_4 /Al-fum composites while observing all standard safety precautions. No additional precautions are needed regardless of elevated pressures that are only encountered in a sealed container in the laboratory setting. However, if the magnetic MOF-based composites are intended to be used as a substitute for magnetite at significantly lower microwave frequencies, their ability to be heated up needs to be additionally investigated.

Dry Al-fum and the composites are poor microwave absorbers at temperatures below 120°C , with slightly improved absorption at elevated temperatures. At the same time, due to the guest-host interaction between water molecules and the porous MOF matrix, the absorption of microwave radiation by Al-fum saturated with water is improved to a degree that allows one to overcome the decrease in dielectric losses and tangent of pure water with increasing temperature. As a result, water-enriched powders and aqueous dispersions of Al-fum and the Fe_3O_4 /Al-fum composites are heated more evenly, almost linear in time, and allow for higher temperatures and pressures in a shorter period of time. The presence of magnetite in the composite in the amount of 0.04 g g^{-1} or more accelerates the heating of aqueous dispersions to 200°C .

The use of induction heating with magnetite/MOF composite can have extensive practical applications in a large variety of processes where accelerated desorption is required. Magnetic nanoparticles, when exposed to a high-frequency magnetic field, heat up instantly, and when present within a MOF, this localized heating is enough to drive the release of adsorbed molecules.

There are three main mechanisms by which a substance transforms a microwave field into thermal energy. Dielectric heating refers to heating by the electric component of high-frequency electromagnetic radiation [59]. In addition to this, there are other types of microwave heating, such as magnetic loss heating, Joule heating caused by conductive losses, *etc.* Since MOFs have a fairly high resistance and are not magnetic, energy dissipation for them occurs only by the first mechanism [62].

Magnetite, being a magnetic material, is capable of releasing heat via all three mechanisms. It exhibits magnetic losses due to hysteresis, domain wall resonance, and, inherent to it, electron spin resonance - FMR (resonance mode of energy absorption) [63]. All these factors significantly increase the efficiency of heating the composite containing the magnetic phase since heat will be generated in this case under the influence of high-frequency electromagnetic radiation inside the material itself.

For example, in the process of oxygen separation from air using MOFs, owing to their thermally insulating nature and often favorable binding of guest species, controlled desorption of the adsorbed molecules from such frameworks can be challenging and energy intensive [64]. In this case, the use of the microwave heating effect of magnetic nanoparticles to achieve the desorption can improve the process.

CONCLUSION

Our finding on the effect of Fe_3O_4 /Al-fum composites on the time of heating of aqueous suspensions allows them to be considered as additives which, while introduced into a given spatial area, can be heated locally to achieve a significant temperature difference, for example, in microwave-assisted 3D printing.

AUTHORS' CONTRIBUTIONS

T. G. S.: Conceptualization, investigation, methodology, visualization, and writing – original draft, review and editing; A. S. T.: Investigation, formal analysis, and data curation; D. S. M.: investigation and formal analysis. K. S. L.: Data curation and writing – review & editing; V. V. P.: Conceptualization, data curation, and writing – review & editing. All authors have made a significant contribution to this work and have read and agreed to the published version of the manuscript.

LIST OF ABBREVIATIONS

XRD	=	X-ray diffraction analysis
RH	=	Relative humidity
P	=	Pressure
T^{IR}	=	Temperatures of the wall
T^{R}	=	Internal content

CONSENT FOR PUBLICATION

Not Applicable.

AVAILABILITY OF DATA AND MATERIALS

The data supporting the findings of the article will be available from the corresponding author [V.V.P.] upon reasonable request.

FUNDING

This work was supported by grants 8.1.3.5 and 8.1.3.6 from the State Program for Scientific Research “Materials Science, New Materials and Technologies” for 2021–2025, the Republic of Belarus.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

ACKNOWLEDGEMENTS

Declared none.

SUPPLEMENTARY INFORMATION

Supplementary material is available on the publisher's website along with the published article.

REFERENCES

- [1] S. Kayal, A. Chakraborty, and H.W.B. Teo, "Green synthesis and characterization of aluminium fumarate metal-organic framework for heat transformation applications", *Mater. Lett.*, vol. 221, pp. 165-167, 2018.
[<http://dx.doi.org/10.1016/j.matlet.2018.03.099>]
- [2] F. Jeremias, D. Fröhlich, C. Janiak, and S.K. Henninger, "Advancement of sorption-based heat transformation by a metal coating of highly-stable, hydrophilic aluminium fumarate MOF", *RSC Advances*, vol. 4, no. 46, pp. 24073-24082, 2014.
[<http://dx.doi.org/10.1039/C4RA03794D>]
- [3] E. Leung, U. Miller, N. Trukhan, H. Mattenheimer, G. Cox, and S. Blei, "Process for preparing porous metal-organic frameworks based on Aluminum Fumarate", Patent US 20120082864A1
- [4] T. Shutava, C. Jansen, K. Livanovich, V. Pankov, and C. Janiak, "Metal organic framework/polyelectrolyte composites for water vapor sorption applications", *Dalton Trans.*, vol. 51, no. 18, pp. 7053-7067, 2022.
[<http://dx.doi.org/10.1039/D2DT00518B>] [PMID: 35393994]
- [5] A. Hernández, *Janus-type and Molecular MOF-based Composites.*, Universitat Autònoma de Barcelona, 2017.
- [6] P. Falcaro, R. Ricco, A. Yazdi, I. Imaz, S. Furukawa, D. Maspoch, R. Ameloot, J.D. Evans, and C.J. Doonan, "Application of metal and metal oxide nanoparticles@MOFs", *Coord. Chem. Rev.*, vol. 307, pp. 237-254, 2016.
[<http://dx.doi.org/10.1016/j.ccr.2015.08.002>]
- [7] S. Zayan, A. Elshazly, and M. Elkady, "In situ polymerization of polypyrrole @ Aluminum Fumarate Metal-organic framework hybrid nanocomposites for the application of wastewater treatment", *Polymers*, vol. 12, no. 8, p. 1764, 2020.
[<http://dx.doi.org/10.3390/polym12081764>] [PMID: 32784539]
- [8] L. Zhao, W. Zhang, Q. Wu, C. Fu, X. Ren, K. Lv, T. Ma, X. Chen, L. Tan, and X. Meng, "Lanthanide europium MOF nanocomposite as the theranostic nanoplatfrom for microwave thermo-chemotherapy and fluorescence imaging", *J. Nanobiotechnology*, vol. 20, no. 1, p. 133, 2022.
[<http://dx.doi.org/10.1186/s12951-022-01335-7>] [PMID: 35292037]
- [9] H.L. Nguyen, T.T. Vu, D.K. Nguyen, C.A. Trickett, T.L.H. Doan, C.S. Diercks, V.Q. Nguyen, and K.E. Cordova, "A complex metal-organic framework catalyst for microwave-assisted radical polymerization", *Commun. Chem.*, vol. 1, no. 1, p. 70, 2018.
[<http://dx.doi.org/10.1038/s42004-018-0071-6>]
- [10] G. Zhao, N. Qin, A. Pan, X. Wu, C. Peng, F. Ke, M. Iqbal, K. Ramachandiraiah, and J. Zhu, "Magnetic Nanoparticles@Metal-organic framework composites as sustainable environment adsorbents", *J. Nanomater.*, vol. 2019, pp. 1-11, 2019.
[<http://dx.doi.org/10.1155/2019/1454358>]
- [11] A. Hamed, F. Trotta, M. Borhani Zarandi, M. Zanetti, F. Caldera, A. Anceschi, and M.R. Nateghi, "In situ synthesis of MIL-100(Fe) at the Surface of Fe₃O₄@AC as highly efficient dye adsorbing nanocomposite", *Int. J. Mol. Sci.*, vol. 20, no. 22, p. 5612, 2019.
[<http://dx.doi.org/10.3390/ijms20225612>] [PMID: 31717564]
- [12] M.R. Lohe, K. Gedrick, T. Freudenberger, E. Kockrick, T. Dellmann, and S. Kaskel, "Heating and separation using nanomagnet-functionalized metal-organic frameworks", *Chem. Commun.*, vol. 47, no. 11, pp. 3075-3077, 2011.
[<http://dx.doi.org/10.1039/c0cc05278g>] [PMID: 21293827]
- [13] W. Feng, Y. Liu, Y. Bi, X. Su, C. Lu, X. Han, Y. Ma, C. Feng, and M. Ma, "Recent advancement of magnetic MOF composites in microwave absorption", *Synth. Met.*, vol. 294, p. 117307, 2023.
[<http://dx.doi.org/10.1016/j.synthmet.2023.117307>]
- [14] H. Wei, Y. Tian, Q. Chen, D. Estevez, P. Xu, H.X. Peng, and F. Qin, "Microwave absorption performance of 2D Iron-Quinoid MOF", *Chem. Eng. J.*, vol. 405, p. 126637, 2021.
[<http://dx.doi.org/10.1016/j.cej.2020.126637>]
- [15] O. Mirzaee, I. Huynen, and M. Zareinejad, "Electromagnetic wave absorption characteristics of single and double layer absorbers based on trimetallic FeCoNi@C metal-organic framework incorporated with MWCNTs", *Synth. Met.*, vol. 271, p. 116634, 2021.
[<http://dx.doi.org/10.1016/j.synthmet.2020.116634>]
- [16] X. Zhang, X. Tian, N. Wu, S. Zhao, Y. Qin, F. Pan, S. Yue, X. Ma, J. Qiao, W. Xu, W. Liu, J. Liu, M. Zhao, K.K. Ostrikov, and Z. Zeng, "Metal-organic frameworks with fine-tuned interlayer spacing for microwave absorption", *Sci. Adv.*, vol. 10, no. 11, p. ead16498, 2024.
[<http://dx.doi.org/10.1126/sciadv.adl6498>] [PMID: 38478599]
- [17] M. Green, Z. Liu, P. Xiang, X. Tan, F. Huang, L. Liu, and X. Chen, "Ferric metal-organic framework for microwave absorption", *Mater. Today Chem.*, vol. 9, pp. 140-148, 2018.
[<http://dx.doi.org/10.1016/j.mtchem.2018.06.003>]
- [18] W. Si, Q. Liao, W. Hou, L. Chen, X. Li, Z. Zhang, M. Sun, Y. Song, and L. Qin, "Low-frequency broadband absorbing coatings based on MOFs: Design, fabrication, microstructure and properties", *Coatings*, vol. 12, no. 6, p. 766, 2022.
[<http://dx.doi.org/10.3390/coatings12060766>]
- [19] A. Pratt, "Environmental applications of magnetic nanoparticles", *Frontiers of Nanoscience*, vol. 6, pp. 259-307, 2014.
[<http://dx.doi.org/10.1016/B978-0-08-098353-0.00007-5>]
- [20] S. Mornet, S. Vasseur, F. Grasset, and E. Duguet, "Magnetic nanoparticle design for medical diagnosis and therapy", *J. Mater. Chem.*, vol. 14, no. 14, pp. 2161-2175, 2004.
[<http://dx.doi.org/10.1039/b402025a>]
- [21] J.A. Coelho, A.M. Ribeiro, A.F.P. Ferreira, S.M.P. Lucena, A.E. Rodrigues, and D.C.S. Azevedo, "Stability of an Al-Fumarate MOF and its potential for CO₂ capture from wet stream", *Ind. Eng. Chem. Res.*, vol. 55, no. 7, pp. 2134-2143, 2016.
[<http://dx.doi.org/10.1021/acs.iecr.5b03509>]
- [22] B. Han, and A. Chakraborty, "Ligand extension of aluminum fumarate metal-organic framework in transferring higher water for adsorption desalination", *Desalination*, vol. 592, p. 118135, 2024.
[<http://dx.doi.org/10.1016/j.desal.2024.118135>]
- [23] E. Moumen, L. Bazzi, and S. El Hankari, "Aluminum-fumarate based MOF: A promising environmentally friendly adsorbent for the removal of phosphate", *Process Saf. Environ. Prot.*, vol. 160, pp. 502-512, 2022.
[<http://dx.doi.org/10.1016/j.psep.2022.02.034>]
- [24] A. Velte, E. Laurenz, L. Rustam, P.P.C. Hügenell, M. Henninger, J. Seiler, and G. Fuldner, "Adsorption dynamics and hydrothermal stability of MOFs aluminium fumarate, MIL-160 (Al), and CAU-10-H, and zeotype TiAPSO for heat transformation applications", *Appl. Therm. Eng.*, vol. 227, p. 120336, 2023.
[<http://dx.doi.org/10.1016/j.applthermaleng.2023.120336>]
- [25] T.G. Shutava, V.V. Pankov, and A.S. Tsimanenkava, "Metal-organic framework / magnetite composites for water vapor sorption applications", V.M. Fedosyuk, Ed., *Scient. Conf.*, pp. 219-222 Minsk
- [26] W. Wu, Q. He, and C. Jiang, "Magnetic iron oxide nanoparticles: Synthesis and surface functionalization strategies", *Nanoscale Res. Lett.*, vol. 3, no. 11, pp. 397-415, 2008.
[<http://dx.doi.org/10.1007/s11671-008-9174-9>] [PMID: 21749733]
- [27] E. Alvarez, N. Guillou, C. Martineau, B. Bueken, B. Van de Voorde, C. Le Guillouzer, P. Fabry, F. Nour, F. Taulelle, D. de Vos, J.S. Chang, K.H. Cho, N. Ramsahye, T. Devic, M. Daturi, G. Maurin,

- and C. Serre, "The structure of the aluminum fumarate metal-organic framework A520", *Angew. Chem. Int. Ed.*, vol. 54, no. 12, pp. 3664-3668, 2015.
[<http://dx.doi.org/10.1002/anie.201410459>] [PMID: 25655768]
- [28] *Drinking water. Methods for determination of total iron*, IPC Publishing House of Standards: Moscow, 1972.
- [29] V.A.J. Silva, P.L. Andrade, M.P.C. Silva, A. Bustamante D, L. De Los Santos Valladares, and J. Albino Aguiar, "Synthesis and characterization of Fe₃O₄ nanoparticles coated with fucan polysaccharides", *J. Magn. Magn. Mater.*, vol. 343, pp. 138-143, 2013.
[<http://dx.doi.org/10.1016/j.jmmm.2013.04.062>]
- [30] R. Massart, "Preparation of aqueous magnetic liquids in alkaline and acidic media", *IEEE Trans. Magn.*, vol. 17, no. 2, pp. 1247-1248, 1981.
[<http://dx.doi.org/10.1109/TMAG.1981.1061188>]
- [31] S. karmakar, J. Dechnik, C. Janiak, and S. De, "Aluminium fumarate metal-organic framework: A super adsorbent for fluoride from water", *J. Hazard. Mater.*, vol. 303, pp. 10-20, 2016.
[<http://dx.doi.org/10.1016/j.jhazmat.2015.10.030>] [PMID: 26513559]
- [32] N. Kurnaz Yetim, F. Kurşun Baysak, M.M. Koç, and D. Nartop, "Characterization of magnetic Fe₃O₄@SiO₂ nanoparticles with fluorescent properties for potential multipurpose imaging and theranostic applications", *J. Mater. Sci. Mater. Electron.*, vol. 31, no. 20, pp. 18278-18288, 2020.
[<http://dx.doi.org/10.1007/s10854-020-04375-7>]
- [33] D.S. Negi, H. Sharona, U. Bhat, S. Palchoudhury, A. Gupta, and R. Datta, "Surface spin canting in Fe₃O₄ and CoFe₂O₄ nanoparticles probed by high-resolution electron energy loss spectroscopy", *Phys. Rev. B*, vol. 95, no. 17, p. 174444, 2017.
[<http://dx.doi.org/10.1103/PhysRevB.95.174444>]
- [34] Y. Hadadian, H. Masoomi, A. Dinari, C. Ryu, S. Hwang, S. Kim, B. Cho, J.Y. Lee, and J. Yoon, "From low to high saturation magnetization in magnetite nanoparticles: The crucial role of the molar ratios between the chemicals", *ACS Omega*, vol. 7, no. 18, pp. 15996-16012, 2022.
[<http://dx.doi.org/10.1021/acsomega.2c01136>] [PMID: 35571799]
- [35] K.D. Kim, S.S. Kim, Y.H. Choa, and H.T. Kim, "Formation and surface modification of Fe₃O₄ nanoparticles by co-precipitation and Sol-gel method", *J. Ind. Eng. Chem.*, vol. 13, pp. 1137-1141, 2007.
- [36] C. Silva, R. e Silva, A. de Figueiredo, and V. Alves, "Magnetic solid-phase microextraction for lead detection in aqueous samples using magnetite nanoparticles", *J. Braz. Chem. Soc.*, vol. 31, pp. 109-115, 2020.
[<http://dx.doi.org/10.21577/0103-5053.20190134>]
- [37] S.K. Elsaidi, M.A. Sinnwell, D. Banerjee, A. Devaraj, R.K. Kukkadapu, T.C. Droubay, Z. Nie, L. Kovarik, M. Vijayakumar, S. Manandhar, M. Nandasiri, B.P. McGrail, and P.K. Thallapally, "Reduced magnetism in core-shell Magnetite@MOF composites", *Nano Lett.*, vol. 17, no. 11, pp. 6968-6973, 2017.
[<http://dx.doi.org/10.1021/acs.nanolett.7b03451>] [PMID: 29048916]
- [38] D. Levy, R. Giustetto, and A. Hoser, "Structure of magnetite (Fe₃O₄) above the Curie temperature: A cation ordering study", *Phys. Chem. Miner.*, vol. 39, no. 2, pp. 169-176, 2012.
[<http://dx.doi.org/10.1007/s00269-011-0472-x>]
- [39] L. Cao, D. Xie, M. Guo, H.S. Park, and T. Fujita, "Size and shape effects on Curie temperature of ferromagnetic nanoparticles", *Trans. Nonferrous Met. Soc. China*, vol. 17, no. 6, pp. 1451-1455, 2007.
[[http://dx.doi.org/10.1016/S1003-6326\(07\)60293-3](http://dx.doi.org/10.1016/S1003-6326(07)60293-3)]
- [40] I. Simon, A. Savitsky, R. Mülhaupt, V. Pankov, and C. Janiak, "Nickel nanoparticle-decorated reduced graphene oxide/WO₃ nanocomposite - A promising candidate for gas sensing", *Beilstein J. Nanotechnol.*, vol. 12, pp. 343-353, 2021.
[<http://dx.doi.org/10.3762/bjnano.12.28>] [PMID: 33936923]
- [41] O. Kappe, A. Stadler, and D. Dallinger, *Microwaves in organic and medicinal chemistry*, Wiley: Weinheim, 2012.
[<http://dx.doi.org/10.1002/9783527647828>]
- [42] M.R. Ryder, Z. Zeng, Y. Sun, I. Flyagina, K. Titov, E.M. Mahdi, T.D. Bennett, B. Civalieri, C.S. Kelley, M.D. Frogley, G. Cinque, and J.C. Tan, "Dielectric properties of metal-organic frameworks probed via synchrotron infrared reflectivity", *arXiv:1802.06702*, 2018.
- [43] S. Balčiūnas, D. Pavlovaitė, M. Kinka, J.Y. Yeh, P.C. Han, F.K. Shieh, K.C.W. Wu, M. Šimėnas, R. Grigalaitis, and J. Banys, "Dielectric spectroscopy of water dynamics in functionalized UiO-66 metal-organic frameworks", *Molecules*, vol. 25, no. 8, p. 1962, 2020.
[<http://dx.doi.org/10.3390/molecules25081962>] [PMID: 32340223]
- [44] M. Usman, S. Mendiratta, and K.L. Lu, "Metal-organic frameworks: New interlayer dielectric materials", *ChemElectroChem*, vol. 2, no. 6, pp. 786-788, 2015.
[<http://dx.doi.org/10.1002/celec.201402456>]
- [45] M. Omran, T. Fabritius, G. Chen, and A. He, "Microwave absorption properties of steelmaking dusts: Effects of temperature on the dielectric constant (ϵ') and loss factor (ϵ'') at 1064 MHz and 2423 MHz", *RSC Advances*, vol. 9, no. 12, pp. 6859-6870, 2019.
[<http://dx.doi.org/10.1039/C9RA00009G>] [PMID: 35518455]
- [46] X. Li, L. Qiao, H. Shi, G. Chai, T. Wang, and J. Wang, "Temperature dependent microwave absorption properties of SrFe₁₂O₁₉ in X-band", *Front. Mater.*, vol. 9, p. 1054725, 2022.
[<http://dx.doi.org/10.3389/fmats.2022.1054725>]
- [47] A.S. Babal, L. Donà, M.R. Ryder, K. Titov, A.K. Chaudhari, Z. Zeng, C.S. Kelley, M.D. Frogley, G. Cinque, B. Civalieri, and J.C. Tan, "Impact of pressure and temperature on the broadband dielectric response of the HKUST-1 metal-organic framework", *J. Phys. Chem. C*, vol. 123, no. 48, pp. 29427-29435, 2019.
[<http://dx.doi.org/10.1021/acs.jpcc.9b08125>]
- [48] X. Chen, S. Sapchenko, W. Lu, M. Li, M. He, Y. Chen, M.D. Frogley, I. da Silva, S. Yang, and M. Schröder, "Impact of host-guest interactions on the dielectric properties of MFM-300 materials", *Inorg. Chem.*, vol. 62, no. 42, pp. 17157-17162, 2023.
[<http://dx.doi.org/10.1021/acs.inorgchem.3c02110>] [PMID: 37812797]
- [49] S. Sorbara, N. Casati, V. Colombo, F. Bossola, and P. Macchi, "The dielectric behavior of protected HKUST-1", *Chemistry*, vol. 4, no. 2, pp. 576-591, 2022.
[<http://dx.doi.org/10.3390/chemistry4020041>]
- [50] A.S. Babal, A.K. Chaudhari, H.H.M. Yeung, and J.C. Tan, "Guest-tunable dielectric sensing using a single crystal of HKUST-1", *Adv. Mater. Interfaces*, vol. 7, no. 14, p. 2000408, 2020.
[<http://dx.doi.org/10.1002/admi.202000408>]
- [51] R. Scatena, Y.T. Guntern, and P. Macchi, "Electron density and dielectric properties of highly porous MOFs: Binding and mobility of guest molecules in Cu₃(BTC) 2 and Zn₃(BTC) 2", *J. Am. Chem. Soc.*, vol. 141, no. 23, pp. 9382-9390, 2019.
[<http://dx.doi.org/10.1021/jacs.9b03643>] [PMID: 31129957]
- [52] M. Islamov, H. Babaei, R. Anderson, K.B. Sezginel, J.R. Long, A.J.H. McGaughey, D.A. Gomez-Gualdrón, and C.E. Wilmer, "High-throughput screening of hypothetical metal-organic frameworks for thermal conductivity", *npj Computational Materials*, vol. 9, no. 1, p. 11, 2023.
[<http://dx.doi.org/10.1038/s41524-022-00961-x>]
- [53] E. Elsayed, M.M. Saleh, R. AL-Dadah, S. Mahmoud, and A. Elsayed, "Aluminium fumarate metal-organic framework coating for adsorption cooling application: Experimental study", *Int. J. Refrig.*, vol. 130, pp. 288-304, 2021.
[<http://dx.doi.org/10.1016/j.jirefrig.2021.05.015>]
- [54] I. Jahan, and B.B. Saha, "Thermal conductivity enhancement of metal-organic frameworks employing mixed valence metal doping technique", *Proceedings of International Exchange and Innovation Conference on Engineering & Sciences (IEICES) 2020*, vol. 6, pp. 20-26
[<http://dx.doi.org/10.5109/4102458>]
- [55] I. Jahan, M.A. Islam, M.L. Palash, K.A. Rocky, T.H. Rupam, and B.B. Saha, "Experimental study on the influence of metal doping

- on thermophysical properties of porous aluminum fumarate", *Heat Transf. Eng.*, vol. 42, no. 13-14, pp. 1132-1141, 2021.
[<http://dx.doi.org/10.1080/01457632.2020.1777005>]
- [56] J. Møgaard, and W.W. Smeltzer, "Thermal conductivity of Magnetite and Hematite", *J. Appl. Phys.*, vol. 42, pp. 3644-3647, 1971.
[<http://dx.doi.org/10.1063/1.1660785>]
- [57] M.F. Elmahaishi, R.S. Azis, I. Ismail, M.S. Mustafa, Z. Abbas, K.A. Matori, F.D. Muhammad, N.K. Saat, R. Nazlan, I.R. Ibrahim, N.H. Abdullah, and N. Mokhtar, "Structural, electromagnetic and microwave properties of magnetite extracted from mill scale waste via conventional ball milling and mechanical alloying techniques", *Materials*, vol. 14, no. 22, p. 7075, 2021.
[<http://dx.doi.org/10.3390/ma14227075>] [PMID: 34832475]
- [58] P. Yan, Y. Shen, X. Du, and J. Chong, "Microwave absorption properties of magnetite particles extracted from nickel slag", *Materials*, vol. 13, no. 9, p. 2162, 2020.
[<http://dx.doi.org/10.3390/ma13092162>] [PMID: 32392790]
- [59] J. Sun, W. Wang, and Q. Yue, "Review on microwave-matter interaction fundamentals and efficient microwave-associated heating strategies", *Materials*, vol. 9, no. 4, p. 231, 2016.
[<http://dx.doi.org/10.3390/ma9040231>] [PMID: 28773355]
- [60] A.S. Vanetsev, and Y.D. Tretyakov, "Microwave-assisted synthesis of individual and multicomponent oxides", *Russ. Chem. Rev.*, vol. 76, no. 5, pp. 397-413, 2007.
[<http://dx.doi.org/10.1070/RC2007v076n05ABEH003650>]
- [61] C. Wang, L. Hua, H. Yan, B. Li, Y. Tu, and R. Wang, "A thermal management strategy for electronic devices based on moisture sorption-desorption processes", *Joule*, vol. 4, no. 2, pp. 435-447, 2020.
[<http://dx.doi.org/10.1016/j.joule.2019.12.005>]
- [62] R. Warmbier, A. Quandt, G. Seifert, and G. Seifert, "Dielectric properties of selected metal-organic frameworks", *J. Phys. Chem. C*, vol. 118, no. 22, pp. 11799-11805, 2014.
[<http://dx.doi.org/10.1021/jp5029646>]
- [63] S.V. Stolyar, O.A. Li, E.D. Nikolaeva, N.M. Boev, A.M. Vorotynov, D.A. Velikanov, R.S. Iskhakov, V.F. P'yankov, Yu.V. Knyazev, O.A. Bayukov, A.O. Shokhrina, M.S. Molokeev, and A.D. Vasiliev, "Heating of magnetic powders in the ferromagnetic resonance mode at a frequency of 8.9 GHz", *Phys. Solid State*, vol. 65, no. 6, pp. 963-970, 2023.
[<http://dx.doi.org/10.21883/PSS.2023.06.56109.21H>]
- [64] L. Melag, M.M. Sadiq, S.J.D. Smith, K. Konstas, K. Suzuki, and M.R. Hill, "Efficient delivery of oxygen via magnetic framework composites", *J. Mater. Chem. A Mater. Energy Sustain.*, vol. 7, no. 8, pp. 3790-3796, 2019.
[<http://dx.doi.org/10.1039/C8TA07739H>]