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A Newly-Designed Nano–Fluid BATIO$_3$ Ethanol System for Modern Electromagnetic Absorption Applications

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Abstract

Electrical shielding effectiveness (ESE) has become a popular research topic after EM waves have begun to be used in our everyday lives. Although the absorption and reflection of electromagnetic energy are those two basic methods used, the efficient techniques used in shielding are based on suppressing the reflection of EM waves and increasing the absorption of energy. This study has focused on BaTiO$_3$-ethanol nano–fluid as an absorber. Absorbing fluid/material was prepared by means of magnetic stirring, heating and ultrasonic bathing methods then the tubings that are going to behave as shielding screen (SS) were filled with this nano–fluid material. Transmission Line Method (TLM) was preferred to obtain reflection, transmission, and absorption coefficients of ESE by means of S_{11} and S_{21}. Fluid speed and its temperature have a potential to change the performance of ESE that it has been observed that increasing flow rate from 0 ml/min to 500 ml/min results in 12% increase in shielding effectiveness at low fluid temperature (30^{o}C). In the second case which measurements repeated at high fluid temperature (60^{o}C) it is seen that 1.05% increase in shielding effectiveness while flow rate increased from 0 ml/min to 500 ml/min.

1. INTRODUCTION

The increase in the use of electronic devices that emit electromagnetic radiation has resulted in increased effort on electromagnetic emission/ shielding. A major problem originated from the electromagnetic emissions is related to electronic devices mainly known as electromagnetic interference (EMI), and it is a part of electromagnetic compatibility (EMC) problem. Electronics may be interfered from electronics (emitting electrometric fields) such that interference may cause malfunctions in the system, and equivalently electromagnetic emissions from any electronics may interfere other electronics. In order to prevent electronics and electronics' sensitivity, one needs to control electromagnetic emissions in both ways (Cakir et al., 2017). Three interactive elements are required for electromagnetic interference (EMI) to take place. The first one is the source that emits electromagnetic energy, the second one is the victim, and the third one is the appropriate propagation path between them. To prevent EMI problems, shielding is most commonly used method. EM shielding is used to block the EM energy completely or partially from entering a defined zone or to control the EM energywithin the boundaries of a defined zone. While making calculation of shielding, one needs to take into account reflection, absorption and transmission parts of electromagnetic energy. However, contrary to the traditional and widespread understanding, the elimination of electromagnetic waves by means of absorption has become more preferred. Traditional wave absorbers can be divided into three types as electric loss, magnetic loss and dielectric loss materials with respect to wave absorbing mechanisms. Conductive polymers are electric attenuation absorbent materials having higher electric loss tangent (tan δ_e), and the electromagnetic energy is mostly attenuated as heating in a resistor. Ferrites and fine chips are magnetic loss absorbents having higher magnetic loss tangent (tan δm), and polarization process (hysteresis loss and magnetic domain resonance) are dominant factors to attenuate and absorb electromagnetic energy (Balanis, 2012). Nano fluids behave like dielectric loss absorbents that they attenuate electromagnetic energy by ionic polarization.

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Seeking solutions to longstanding problems with developing technology is quite common today. Nowadays, from the most critical devices (such as health and military applications) to the simplest in-home electronic devices, EMI has become a major problem that needs to be dealt with. As an example, Çakır et al. (2017) focused on the progress and prospective future of cementitious building materials by using waste metallic chips (WMC) as a constituent for the purpose of EM shielding, wave absorbing activities and electrical properties of materials. From this point of view, one of the methods used to protect against unwanted EM waves is to absorb the EM waves by means of materials with high dielectric properties (Choudhary and Patri, 2009; Sadiku, 2011; Balanis, 2012). Dielectric materials lack the ability to transmit electricity, but they are effective in electrostatic fields (Choudhary and Patri, 2009). Sardarian et al. (2017) conducted to evaluate the synergistic effect of newly-designed magnetic/dielectric [Fe_3O_4/ $BaTiO_3$@MWCNT] nano-composite system on the mechanism of enhanced microwave absorption properties.

Nanotechnology is another technology getting popular in the last few decades and the materials that are produced by this technology have unexplored features. It is known that the characteristics of the materials vary in nano-scales. Nano–fluid is a mixture of nanometer sized solid particles like nanoparticles, nanotubes or nanowires suspended in the fluid. It is quite a new field for researchers. Nano–fluids attract researchers for their enhanced heat transfer properties. Nano–fluids have better heat transfer performance than the base fluid (Kumar et al., 2016). In addition to heat transfer properties, electrical and EM features of nano–fluids are also investigated in the literature. Primo et al. (2016) presented a literature survey on the development of new nano-dielectric fluids suitable for electro-technical applications. Afsar et al. (2009) held broad-band measurements on the real and imaginary parts of permeability and permittivity of micron and nano sized commercial nickel ferrites. They found out that both permittivity and permeability depends on the density, size, and volume fraction matter of magnetic particles. Rafiq et al. (2015) prepared transformer oil-based silica nano–fluids with different concentrations. The AC breakdown strength of nano–fluids was measured. Nano–fluids showed improved breakdown strength at high concentration and there was only a negligible effect on breakdown strength at low concentration. Lv et al. (2013) investigated the different types of nanoparticles with various electrical conductivities which were used to modify the mineral oil. Karakas (2017) and Sens et al. (2014) described a methodology developed by Eletrobras Cepel Laboratories for electromagnetic characterization of Magnetic Nano–fluid (MNF). Based on the experimental results, the application of MNF in electrical transformers proved to be promising. Karthik et al. (2014) carried out a study to analyze the performance of ferro-fluids along with mineral oil for various concentrations. Cimbala et al. (2016) investigated magnetic fluids based on transformer oil (ITO100) and the behavior of these fluids under influence of permanent magnetic field. Mergos et al. (2012) studied nano–fluids, by investigating polarization phenomena induced by nanoparticle inclusions in paraffin oil which is an insulating organic liquid.

Vas et al. (2015) reported that traditionally used metallic shields lack flexibility and hence may not be the right choice for certain applications. In such situations, filled polymer composites provide a good alternative for EM shielding applications. Micheli et al. (2009) worked on designing EM absorbers for radar absorbing material (RAM) and microwave shielding systems. They figured out that the use of nano-filler like carbon nano-fibers pushes absorption performances over the more conventional graphite absorber, which generally requires higher thickness to obtain similar absorption properties. Eswaraiah et al. (2010) developed a graphene film using vacuum infiltration technique and evaluated its EM interference shielding effectiveness. They used Multi walled carbon nanotubes (MWCNT). 99.99% of the radiation has been attenuated due to 150 μm thickness film and reflection was the dominant shielding mechanism in their work. Micheli et al. (2015) investigated the shielding effectiveness of carbon nanotube reinforced concrete composite using a reverberation chamber. EM field attenuation has been found to be strictly dependent on the commercial carbon nanotube filling weight percentage. Yasir et al. (2014) searched the electrical characteristics of nano–composites obtained by dispersing MWCNT in epoxy resins. Results show that MWCNT based nano–composites are good candidates for being flexible shielding materials operating at microwave frequencies. Chrobak et al. (2012) investigated magnetic field shielding effectiveness SE_H of the selected iron-based amorphous alloys and some magnetic composites. $BaTiO_3$ has a considerable potential candidate for shielding applications as a dielectric absorber, because of its high permittivity and a large propagation constant, which leads to a high attenuation constant (Zhu et al. 2015).

In this manuscript, performance of $BaTiO_3$-ethanol nano–fluid itself and fluid speed effect on ESE at two different temperatures have been investigated. The manuscript is organized as follows: first, the theoretical background is presented with materials and methods. Subsequently, measurement campaign is described. Afterwards, the performance of proposed nano–fluid is discussed. Finally, the paper is concluded with a brief summary and future works with an appendix.

2. MATERIALS AND METHODS

2.1. Synthesis of $BaTiO_3$

There are different methods for preparing nano–fluids in the literature. Two-step method was used to prepare the fluid in this study. In two-step method, nanoparticles previously synthesized by different techniques are dispersed into the base fluid. The biggest problem in this method is forming of lumps. This can be attributed to the high surface energy of the nanoparticles. The tendency of the particles to lump is to reduce surface energy. The clumping of nanoparticles causes the properties of the nano–fluid to deteriorate. In order to avoid this, loading methods are used in order to push the particles together by surface inhibitors or electrostatic dispersion. In addition, dispersants, ultrasonic baths/probes or solution pH modifiers at high speed are frequently used (Chopkar et al., 2006; Ebrahimi et al., 2010; Rafiq et al., 2015). The ability to prepare stable and durable solutions is crucial for the reliability of the results.

In the study; Sigma Aldrich ≥99.8% pure ethanol, Sigma Aldrich ≥ 99% pure and <100nm particle size Barium Titanate ($BaTiO_3$) were used. The nano–fluid was prepared by mixing 0.5 grams of $BaTiO_3$ with 300 grams of ethanol heated at temperatures ranging from 90^0 to 100^0 C for 30 minutes, mixing the compound with a magnetic stirrer at 1000-800 rpm, and then putting it in an ultrasonic bath for 15 minutes. Prepared nano–fluid was left to rest for 1 day and was used for measurements after resting process. The purpose of leaving the prepared fluid to rest for 1 day is to control the collapsing conditions that may occur and to wait for the temperature to return to normal level. The reason why the fluid is not heated further is to prevent the evaporation of the ethanol. The room temperature was constantly recorded at 18^0-20^0 C during the measurements. In Fig.1 flow chart of the process to obtain the nano–fluid is shown. The preparation of the nano–fluid is shown in Fig.2.

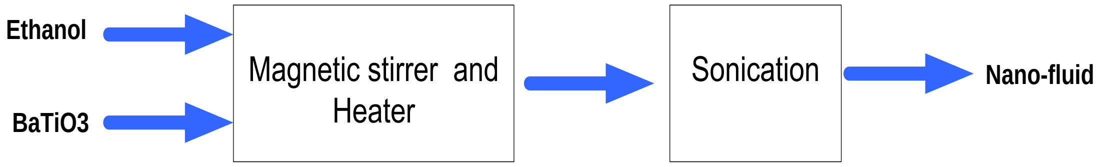


Figure 1.*Flowchart of preparation procedures for Nano–fluid.*

Figure 2.*Nano–fluid (BaTiO$_3$–Ethanol).*

2.1.1. Movement of nano particle in fluid

As the thermal conductivity of a solid metal is higher than the base fluid, it increases the thermal conductivity of the fluid when suspended in the base fluid. The nanoparticles incorporated into the fluid are less than 0.1 μm in diameter, resulting in irregular movements. However, nanoparticles move randomly when they collide with molecules in the fluid. The algebraic sum of the pathways is also zero. Such a movement is defined as the Brownian movement. As the particle size decreases, the Brownian movement and motion activity increases. The force created by this motion is almost equal to the magnitude of the total net force acting on the fluid (gravity and lift forces of the fluid). For this reason, nanoparticles float in the liquid depending on the ambient temperature. The role of the Brownian motion is great in improving the heat transfer of fluid when the volumetric proportions of nanoparticles in the liquid are small (Koo and Kleinstreuer, 2004). The Brownian movement, which allows nanoparticles to be used effectively in thermal conduction, has inspired us to come up with the idea to use it in a different situation. The nanoparticle which is exposed to the EM field in the measurement field will have a different splitting transfer by floating with the Brownian motion. Instead of this particle, the new nanoparticle, which EM wave can influence, will come. This will be sustained cyclically in a closed loop system. Thus, EM power will be continuously transformed into another energy form and can be moved away from the surface.

2.2. Electromagnetic shielding effectiveness (ESE)

It is well known that dominant component is reflection rather than absorption in calculation of electrical shielding, and it is directly related to materials' properties. ESE is a measure of difference between the incident and transmitted waves, and absorption and reflections are two main segments of it (Roger et al. 2000). Electrical shielding effectiveness (ESE) and magnetic field shielding effectiveness (MSE) are two major well known shielding effectiveness measure, but MSE is not our concern in this study. Shielding effectiveness including reflection, absorption and multi reflections is commonly expressed in terms of dB, and electrical shielding effectiveness (SE_E) is given by Eq.1

$$SE_E = 20\log\left[\frac{\vec{E}^{inc}}{\vec{E}^{tran}}\right], (dB) \tag{1}$$

where, $\vec{E}^{inc}$ and $\vec{E}^{tran}$ are incident and transmitted electric field intensities (V/m), respectively. In shielding, the attenuation of electromagnetic waves from the air/conductive surface and with regard to the interaction enters the nano fluid takes place in three stages. These are Reflection Losses (R_{dB}), Absorption Losses (A_{dB}) and Multiple Reflections (M_{dB}), and finally SE can be denoted as the summation of those three components as in Eq.2 and Eq.3.

$$SE_{dB} = R_{dB} + A_{dB} + M_{dB} \tag{2}$$

$$SE_{dB} \approx \underbrace{20\log_{10}\left|\frac{\eta_0}{4\eta}\right|}_{R_{dB}} + \underbrace{20\log_{10} e^{t/\delta}}_{A_{dB}} + \underbrace{20\log_{10}\left|1 - e^{-2t/\delta} e^{-j2t/\delta}\right|}_{M_{dB}} \tag{3}$$

Where $\delta = \sqrt{\dfrac{1}{\pi\mu\sigma f}}$ is the skin depth.

2.3. Measurement Set–up

Measurements were made via vector network analyzer (VNA) operating at [9kHz-9 GHz]. During the study, different type of sample holders are designed and integrated into the system for the appropriate frequency band. The first holder is in the range of 3.30 - 4.90 GHz (compatible with WR 229 type waveguides) and the second holder is in the range of 4.90 - 7.05 GHz (compatible with WR 159 type waveguides). Calibration procedures are similar to those made by Çakır et al. (2017), Kocakuşak et al. (2017) and Helhel and Kurnaz (2016). The actual setup for the measurements and the schema to explain the elements are shown in Fig.3. Note that errors in reflection measurements are critical for such environments (Çolak and Helhel, 2018). The nano–fluid used during the measurements was pumped to the measurement surface from the main tank through the Longer Precision Peristaltic Pump (BT-100L). This device can pump 0.002 to 500 mL/min of fluid to the desired surface. The fluid surface pumped for the measurement area is shown in Fig.4.

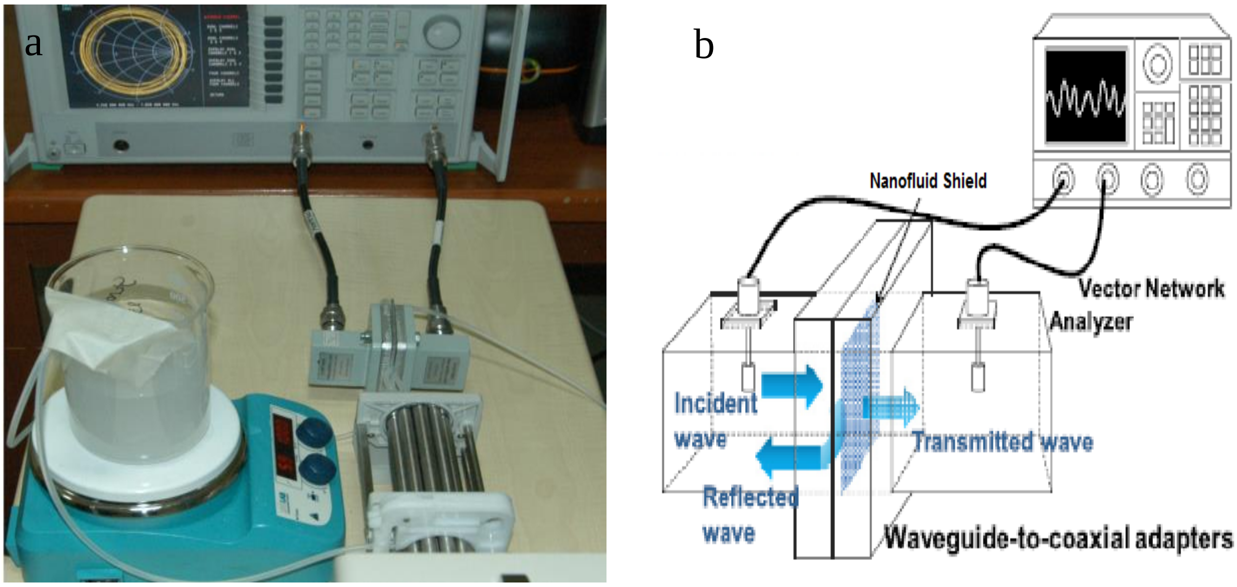


Figure 3.*Experimental set–up. (a) General view. (b) Schematic view.*

The speed of this pump can be adjusted between 1.0 to 100.0 rpm (reversible) with a precision of 0.1 rpm. The reason for the choice of a pump with such a precision is due to the importance of observing small changes in flow velocity in the study. The fluid in the measuring tank was continuously mixed at 1000 rpm via magnetic stirrer and pumped to the measuring surface while the temperature is kept constant at the desired measurement temperature. All the details about this procedure can be seen in Fig.5.

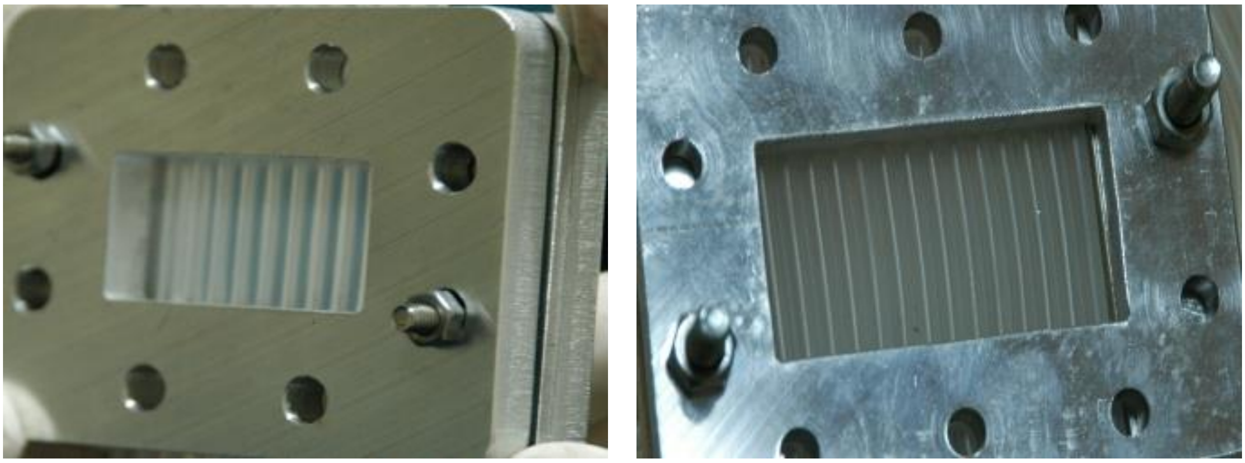


Figure 4.*Nano–fluid shield in flange.*

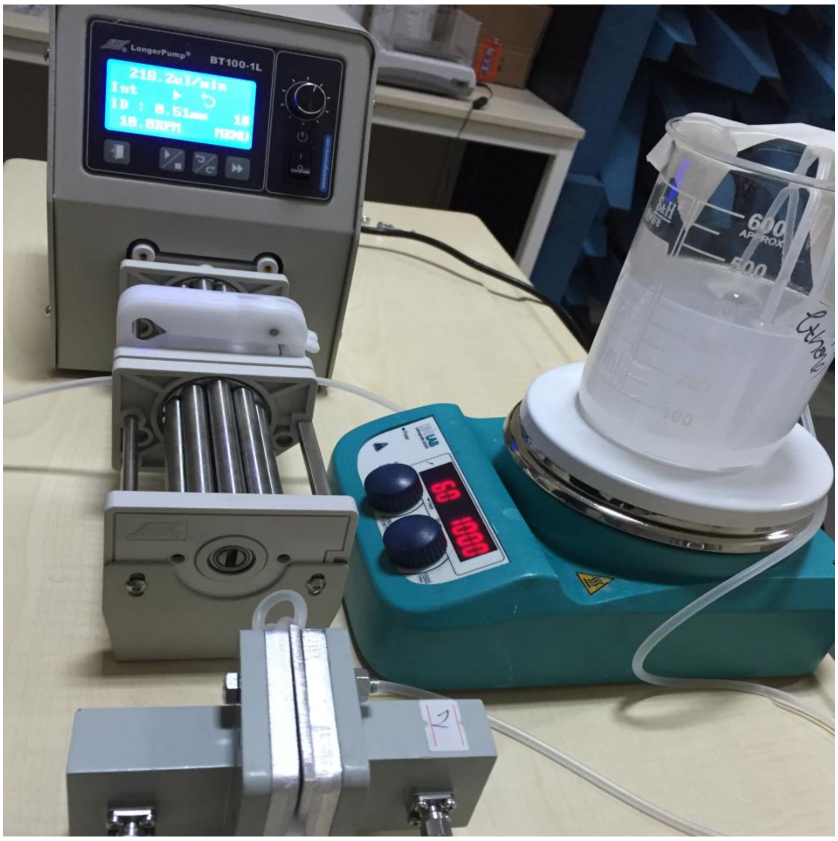


Figure 5.*Nano–fluid pumping mechanism*

2.3.1. Removing systematic error

There are two basic approaches to get rid of systematic errors. These are the de-embedding method and the line reflection method (LRM) (Helhel and Kurnaz, 2016; Kocakuşak et al., 2017). De-embedding method is used in the cases when the calibration is not done or could not be done because of some complexities in the system. Text fixtures, which are completed when the calibration was done are used in mathematical formulations to transform the faulty measurements without calibration to correct measurements.In technical terms, de-embedding method uses a model of the test fixture and mathematically subtracts the properties of the fixture from the overall measurement. De-embedding procedure with test fixture for non-coaxial instrument testing can produce very accurate results without complicated non-coaxial and calibration standards. De-embedding can be performed using the scattering transfer parameter matrix in the sample under test. In this case, the de-embedding metrics can be processed after measurements are made on the test fixture and the sample under test (Kocakuşak et al. (2017).

LRM calibration method can be summarized as calibrating the line used (waveguide, coaxial, etc.) by introducing it to the device. In technical terms, the method was developed to reduce the size of the calibration set without compromising the accuracy of measurement and then it started to be used in coplanar waveguides. The method uses a compact set of reflector line calibrations that includes a short line, a medium line and a symmetrical reflector to determine the transmission line characteristic impedance and propagation constant and also to measure the embedded resistor. This measurement information corrects the natural reference impedance error of the calibration of the LRM method on the basis of short line, symmetrical reflector and embedded resistor, and accurately translates the reference plane (Kocakuşak et al., 2017). The LRM method was selected and applied because it is more suitable than de-embedding method in this study.

3. RESULTS AND DISCUSSION

The plots in this section show how much of the EM energy is reflected (R), absorbed (A) and transferred (T). The vertical axes represent the sum of the reflected, absorbed and transferred energy ratios, sum of them is equal to 1, and the horizontal axes show the frequency.

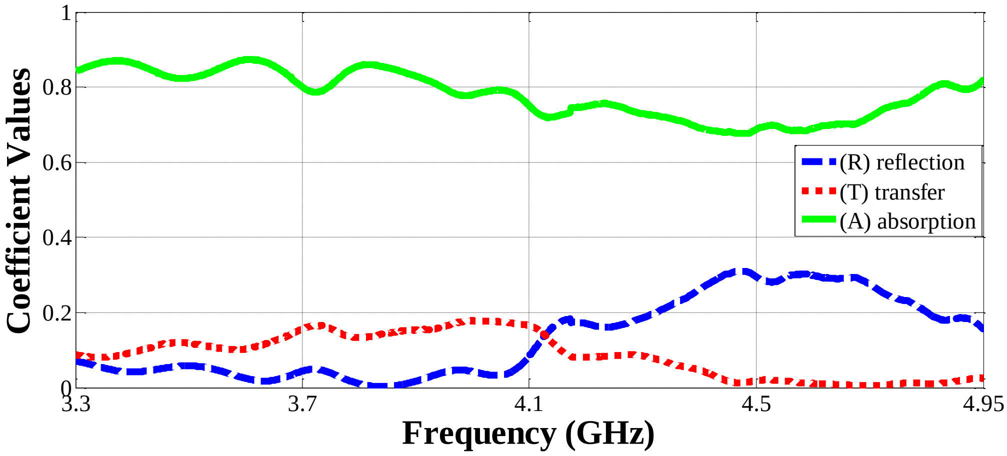
3.1. Flow rate affect at 30^0 C

In Fig.6, changing the fluid velocity in the 3.3-4.95 GHz frequency band did not have a major effect on the EM components of transfer however; it had a significant effect on the absorption and reflection. Here, the total observed EM change is about %12. In addition in Fig.7, by changing the fluid velocity in the 4.95-7.05 GHz frequency band, EM component has some insignificant effect on the transfer however the effect on the absorption and reflection is significant. The effect on these two components, namely absorption and reflection, lasts throughout the band. The total observed EM change in this case is about %3.

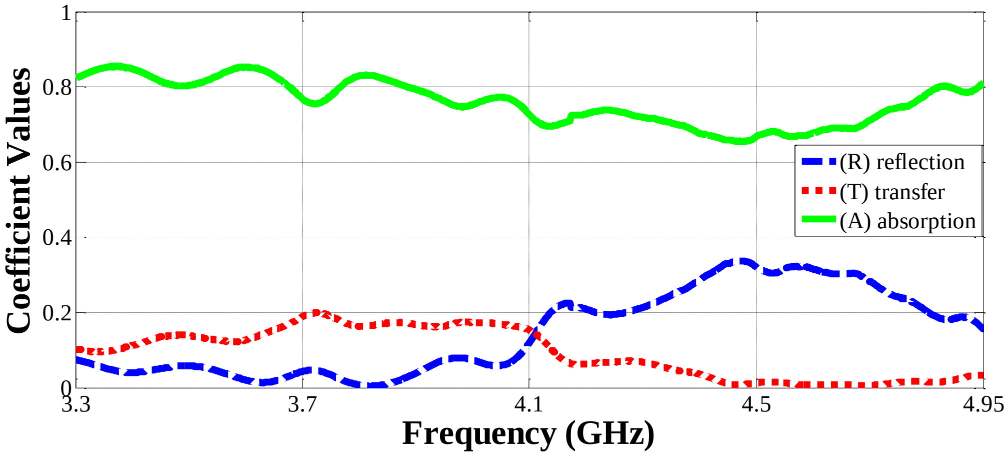
It is quite remarkable that, when all the conditions are the same, these two EM components, which the most challenging aspect of EM are shielding, exhibit almost mutually opposite behavior with the change of flow rate. These results suggest that fluid velocity can be used effectively to control the proportions of the EM components.

In Fig.6 (A), the absorption coefficient starts as greater than 0.8 at 3.3 GHz, it decreases by 0.2 around 4.5 GHz and from 4.5 GHz to 4.95 GHz, it shows an increasing behavior to complete the band above 0.8 level. In Fig.6 (A), the reflection coefficient is slightly less than 0.1 at 3.3 GHz, it approaches to 0 at 4.1 GHz and from 4.0 GHz to 4.5 GHz it increases by approximately 0.3. At the end of the band, with a decrease of 0.12 between 4.5 GHz and 4.95 GHz, the reflection coefficient eventually reaches to 0.18 levels. In Fig.6 (A), the transfer coefficient is slightly greater than 0.1 at 3.3 GHz and with a constant increase of approximately 0.1, it reaches to 0.19 at 4.1 GHz. It is approaching to 0 with a decreasing trend with the magnitude of 0.2, between 4.1 and 4.95 GHz and it continues this behavior up to 4.8 GHz and it completes the band with an increase of 0.02 from 4.8 to 4.95 GHz. The absorption, reflection and transfer coefficients in Fig.6 (B) exhibit similar behavior to the described behavior of the absorption, reflection and transfer coefficients in Fig.6 (A).In Fig.6 (C), the absorption coefficient is about 0 at 3.3 GHz, it continues with ripples of magnitude 0.001 until 3.8 GHz, and it increases by 0.05 between 3.8 GHz and 4.2 GHz. After 4.2 GHz, it decreases with a fixed rate to reach to 0 levels at the end of the band. In Fig.6 (C), the reflection coefficient is around 0 at 3.3 GHz, it continues with ripples of magnitude 0.001 until

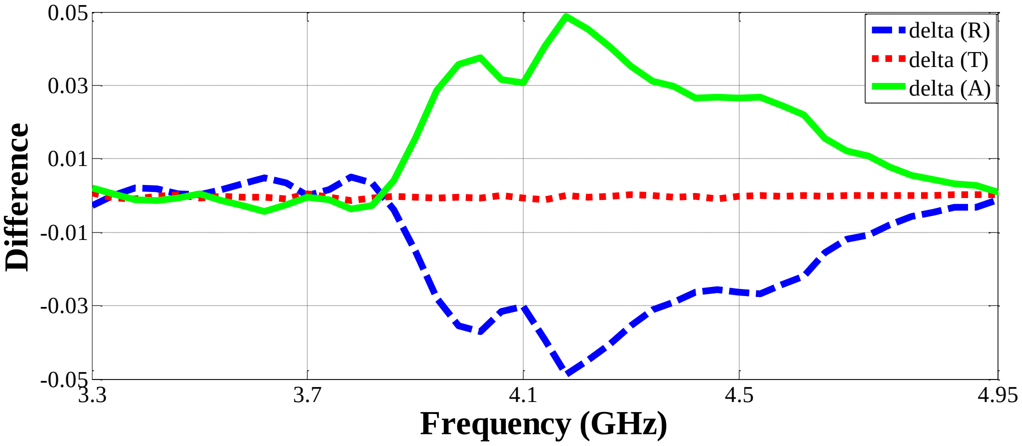
3.8 GHz and it decreases by 0.05 between 3.8 GHz and 4.2 GHz. After 4.2 GHz, it increases with a fixed rate to reach to 0 levels at the end of the band. In Fig.6 (C), the transfer coefficient ripples with a very small error rate and maintains the 0 level from the beginning to the end of the band. One may observe similarities and variation between plots in Fig.6 and Fig.7.



(A) Flow rate 0 ml/min

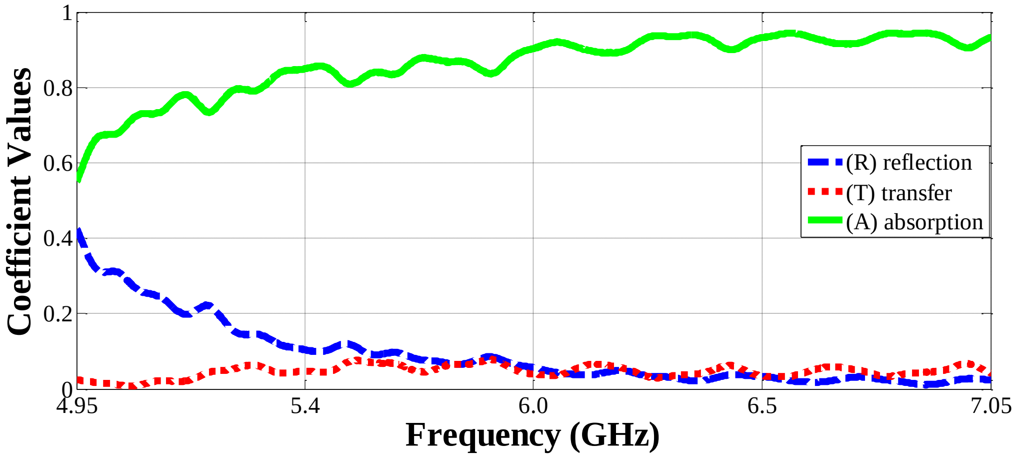


(B) Flow rate 500 ml/min

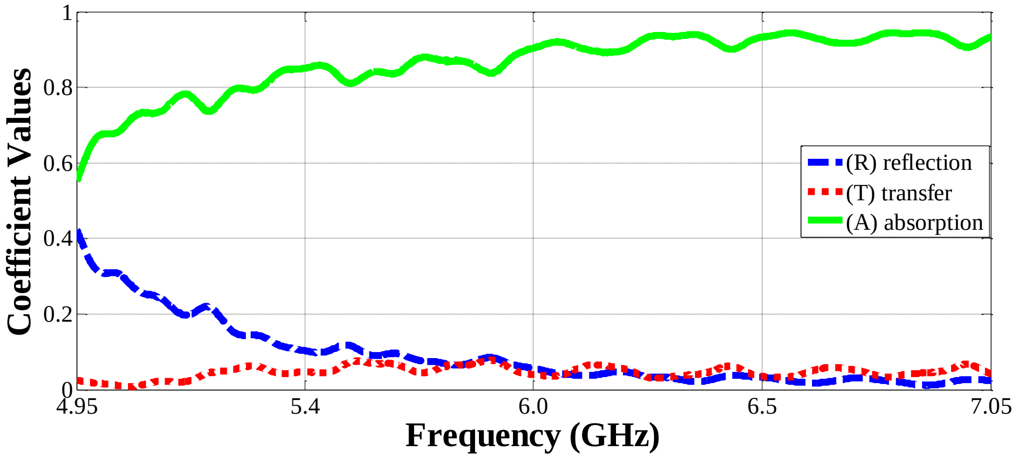


(C)

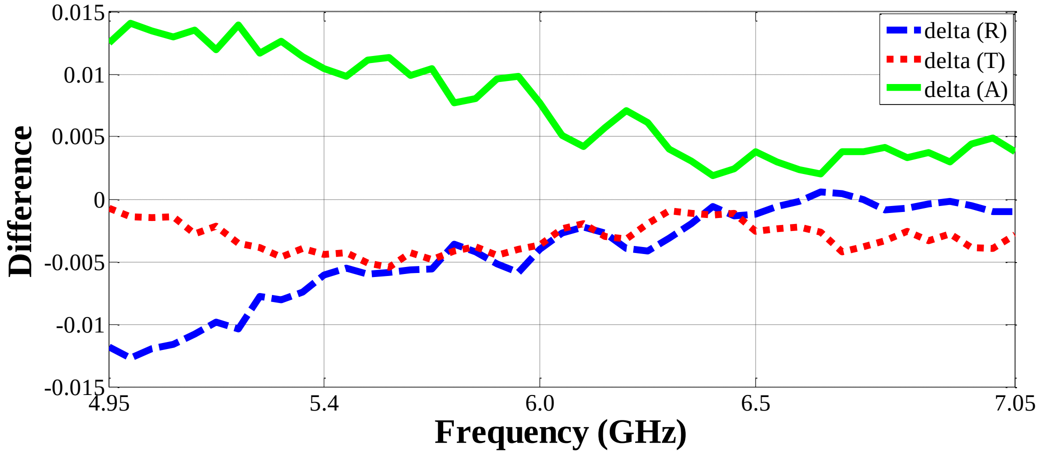
Figure 6. *3.3 GHz–4.95 GHz band measurement at 30°C*



(A) Flow rate 0 ml/min



(B) Flow rate 500 ml/min



(C)

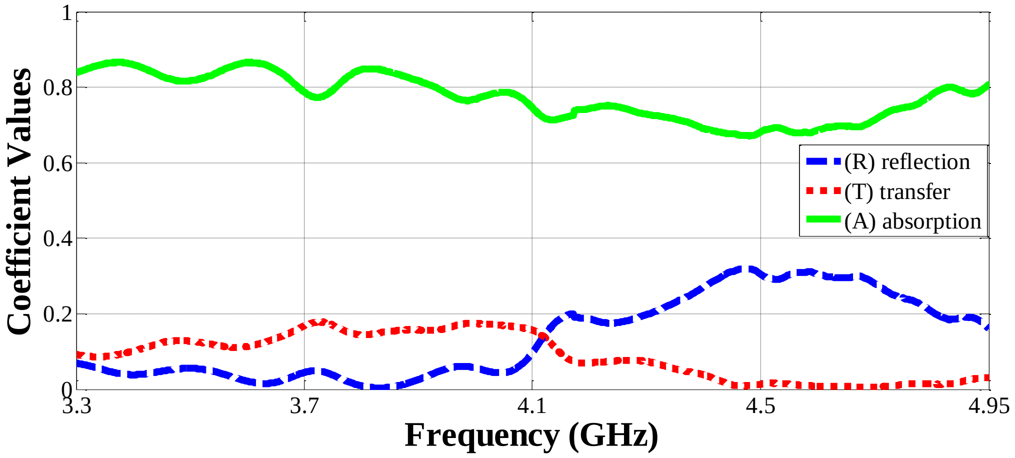
Figure 7. *4.95 GHz–7.05 GHz band measurement at 30°C*

3.2. Flow rate affect at 60^0 C

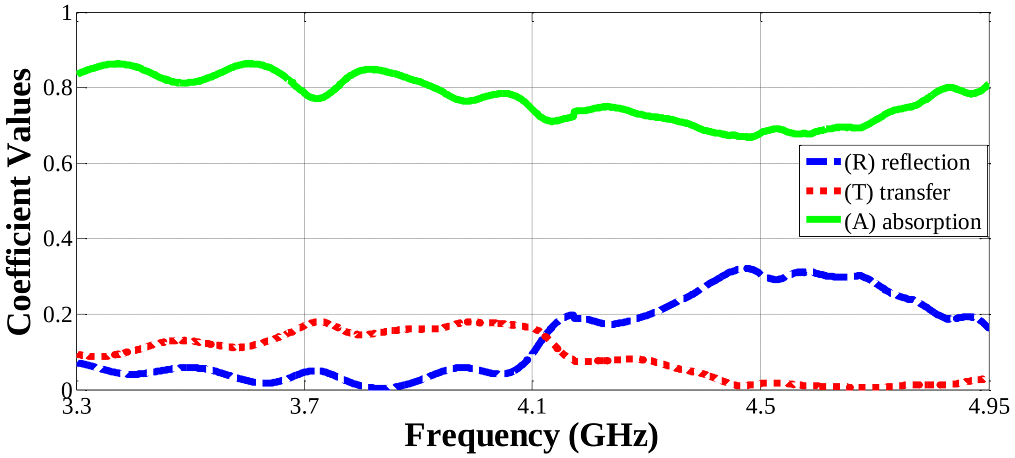
In Fig.8, changing the fluid temperature in the measurements gave quite different results compared to the previous section. The large variation in the transfer EM component in the 3.3-4.95 GHz band can be given as an example. In the previous case, the transfer coefficient was almost constant. In addition, transfer coefficient showed some changes in its behavior with increasing temperature, and it behaved opposite to the reflection component along the band. The total observed EM change in this case is about %1.05. In Fig.9, at the 4.95-7.05 GHz band, the transfer component continued to exhibit reciprocal behavior with the reflection component. In this case, the total observed EM change is about %0.9.

From this point, it can be observed that the effect of fluid velocity on the EM components can be changed in repeated measurements by increasing the fluid temperature while keeping all the other conditions the same. Another result is that the rate of EM component variations obtained by changing the fluid temperature is lower than the previous case.

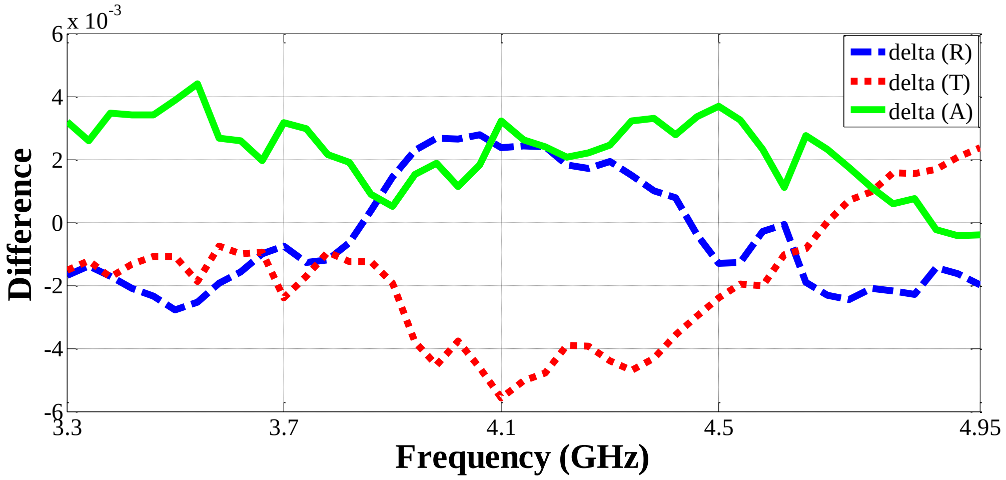
In Fig.8 (A), the absorption coefficient is slightly greater than 0.8 at 3.3 GHz, it decreases by 0.2 around 4.5 GHz and it completes the band above 0.8 level with an increase between 4.5 GHz and 4.95 GHz. In Fig.8 (A), the reflection coefficient is slightly less than 0.1 at 3.3 GHz, it approaches to 0 at 4.1 GHz and it increases by 0.3 between 4.0 GHz and 4.5 GHz. At the end of band, with a decrease by 0.12 between 4.5 GHz and 4.95 GHz, it eventually reaches to 0.18 levels. In Fig.8 (A), the transfer coefficient is slightly greater than 0.1 at 3.3 GHz and with a constant increase of 0.1, it reaches to 0.19 at 4.1 GHz. It approaches to 0 between 4.1 and 4.95 GHz and it continues this behavior until 4.8 GHz. It completes the band with an increase of 0.02 between 4.8 and 4.95 GHz. The absorption, reflection and transfer coefficients in Fig.8 (B) exhibit similar behavior to the described behavior of the absorption, reflection and transfer coefficients in Fig.8 (A). In Fig.8 (C) the absorption coefficient is about 0.003 at 3.3 GHz, and it approaches to almost 0 with ripples at 3.9 GHz. Afterwards, it increases to 0.004 level between 3.9 GHz and 4.5 GHz. After 4.5 GHz, it completes the band at a level of -0.0001 with a certain fixed rate decrease. In Fig.8 (C) the reflection coefficient is around -0.0019 at 3.3 GHz, it continues to behave consistently until 4.0 GHz and it reaches to 0.002 levels. Then, it decreases to -0.001 between 4.0 GHz to 4.5 GHz with ripples. It shows an oscillating behavior between 4.5 GHz and 4.95 GHz and it finishes the band at -0.002. In Fig.8 (C), the transfer coefficient starts at a value slightly less than -0.002, it ripples until 4.1 GHz and it drops back to -0.006 levels. This is followed by a steady increase until the end of the band and it finishes above 0.002 level. One may observe similarities and variation between plots in Fig.8 and Fig.9.



(A) Flow rate 0 ml/min

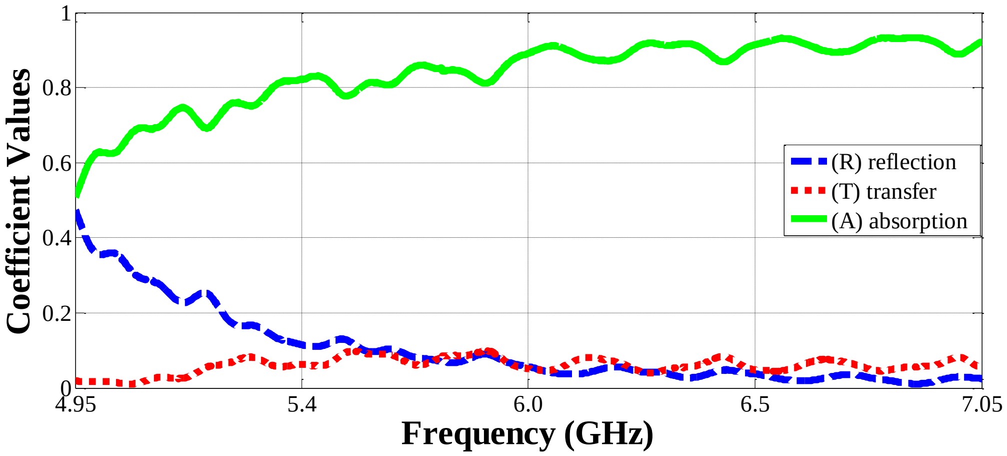


(B) Flow rate 500 ml/min

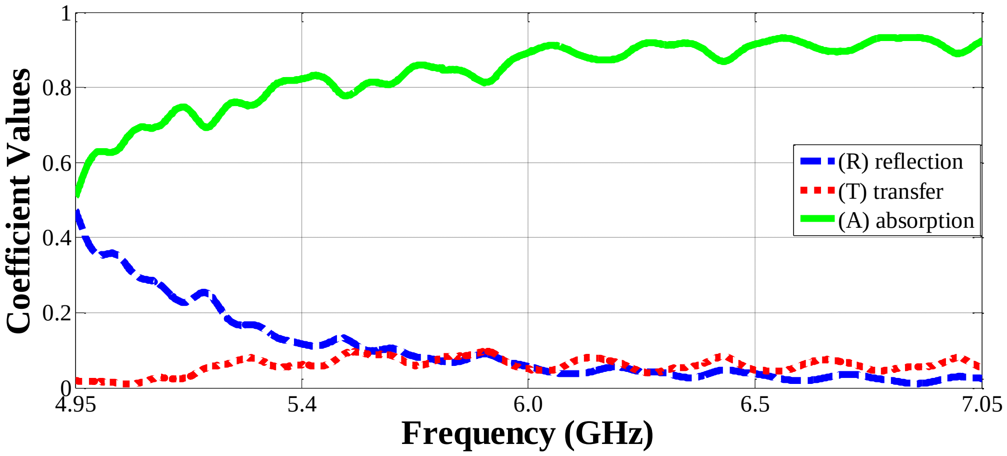


(C)

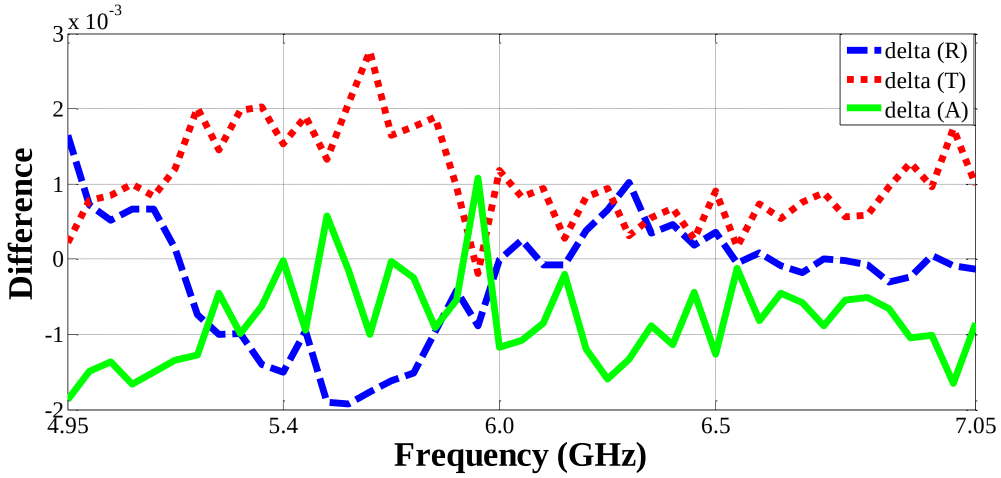
Figure 8. *3.3 GHz–4.95 GHz band measurement at 60^{o}C*



(A) Flow rate 0 ml/min



(B) Flow rate 500 ml/min



(C)

Figure 9. *4.95 GHz–7.05 GHz band measurement at 60°C*

4. CONCLUSIONS

The effort to find an innovative approach to the problem of EM shielding has gained a new level of attention with today's quickly increasing technological developments. It is of great importance to find a solution by removing the EM shielding limitations. In order to meet all these requirements, nano–fluid $BaTiO_3$ ethanol system for modern electromagnetic absorption applications has been studied. Remarkable concussions are given as below.

- Flow rate change of nano-fluid in the system between 0 ml/min to 500 ml/min has resulted in 12% better shielding effectiveness performance. This improvement has occurred with the increase in absorption despite the fall in the reflection of the electromagnetic wave, and this is a desirable condition.

- Switching the temperature of nano-fluid from $30^{o}C$ to $60^{o}C$ and applying the same flow rate change has resulted in 1.05% improvement, which is not valuable result.

- Temperature increase of nano-fluid has resulted in higher transmission coefficient and lower reflection coefficient. This may be due to the effect of positive increase in fluid temperature on the vector forces of the nanoparticles.

- Fluid speed can be used as a control parameter for nano–fluid $BaTiO_3$ ethanol system.

- Experiments with different solvents and higher fluid velocities in subsequent studies are in future work plan.

- Nano-fluids can be classified as flexible, controllable, surface-independent and cost-effective methods/systems/materials for modern electromagnetic absorption/shielding applications.

- Flexible absorbers and reflectors (which are typically controllable medium) are receiving considerable attention due to their controllable dielectric properties and robust structures. In particular, the military stealth applications have been proved feasible and have lots of advantages, including unchanging the shape of aircraft, a reasonable absorption efficiency, being easy to use and protect, etc. Thus, for coming years, there will be numerous investigations to be proposed that they influence of controllable dielectric properties materials.

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DISCLOSURE STATEMENT

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Notes on Contributors

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