

DESIGN AND TESTING OF MAGNETIC FIELD APPARATUS FOR IMPROVING FLOW PROPERTIES OF LONGAN HONEY (*Dimocarpus longan* Luor)

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Abstract

A novel magnetic field (MF) apparatus was designed and constructed for honey treatment to improve honey's rheological properties. Permanent magnets were mounted on the outside wall of stainless steel tubes to create MF strengths. The inverted arrangement of the magnets' poles gave an alternating MF strength pattern along a tube's length with the field strengths up to about 0.39 T. The MF lines of force were characterized using iron powders, and the MF distribution patterns were analyzed. The MF treatments were conducted on longan honey by holding the honey samples in the tubes for 2 h at 15°C and 28°C. The effects of the MF were evaluated by examining the pollen's characteristics and the honey's flow behavior. Similar to natural honey, large pollen agglomerates were found in the control samples and the magnetically treated samples with a low magnetic field strength at both temperatures. Nevertheless, at higher strengths, there were no agglomerates but individual pollen grains were observed in the samples. Rheological analysis showed that all honey samples exhibited Newtonian flow behavior. The flow consistency indexes of the samples carried out at 28°C were lower than those at 15°C and were further reduced with increasing MF strengths, as a result causing reduction in the viscosity of the samples. Therefore, this new MF treatment apparatus could successfully be used to improve the flow property of honey.

Keywords: Magnetic field, viscosity, Newtonian, shear stress, pollen

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Introduction

Magnetic field (MF) treatment is a non-thermal, physical method and has been used for microbial deactivation (Hofmann, 1985). Research on the use of magnetic fields in the food and related industries has long been reported (Bermúdez-Aguirre *et al.*, 2016). The magnetic fields can be classified according to the mode of operation, such as static magnetic field (SMF) and oscillating magnetic field (OMF), and according to the fields' strengths, such as low intensity (around 10 G) and high intensity (thousands of G) (Barbosa-Cánovas *et al.*, 2005). A SMF device can be more advantageous than an OMF one in terms of construction, operation, and maintenance since it does not require an additional instrument to generate pulses. The SMF is generated by permanent magnets with magnetic lines of force exiting from the north pole and entering into the south pole of the magnet to form a complete loop. The arrangement of the north and south poles of the magnets along the magnetic device determines the pattern of the magnetic field strength. If the north and south poles are arranged alternately in opposite directions, the alternating magnetic field is generated (Hirschbein *et al.*, 1982; Gabrielli *et al.*, 2001). This type of magnetic field generated by permanent magnets has been

successfully applied for wastewater treatments (Štefušová *et al.*, 2012; Zaidi *et al.*, 2013; Liu *et al.*, 2016) and improvement of water quality (Kochmarsky, 1996; Dobersek and Goricanec, 2014; Lipus *et al.*, 2015). In the food industry, the magnetic field is used for various purposes, such as a magnetic separator for metal decontamination of food materials (Agri-Industry Development Division, 2018), immobilization of enzymes on magnetic nanosupport material (Ilyina *et al.*, 2016), separation of food-borne pathogens using magnetic nanoparticles (Augustine *et al.*, 2016), microbial inactivation (Yadollahpour *et al.*, 2014; Bermúdez-Aguirre *et al.*, 2016), and honey treatment (Sakdatorn *et al.*, 2017, 2018). Amongst them, the uses of the permanent magnets for metal decontamination and quality control of foods have been widely practiced. A magnetic field was shown to have significant effects on the texture and rheological properties of honey. The consistency index and viscosity of honey were decreased with an increasing magnetic field strength (Sakdatorn *et al.*, 2017, 2018). It was also reported that human blood's viscosity could be reduced by a magnetic field (Tao and Huang, 2011).

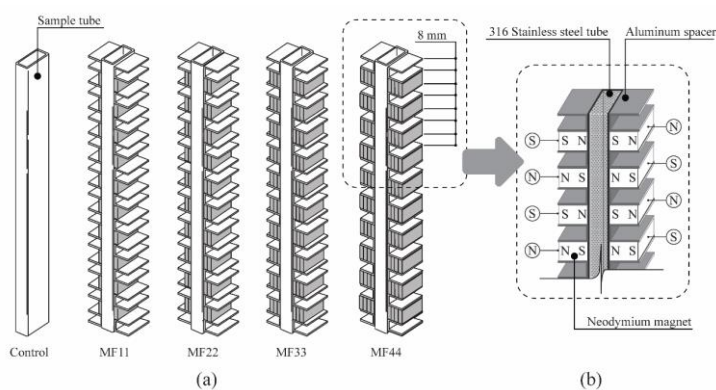


Figure 1. Design and construction of magnetic field treatment apparatus: (a) design and construction of sample tube and (b) north-south poles' inverted arrangement of magnets

Although it has been reported that the magnetic field could reduce the viscosity of fluids (Tao and Xu, 2006; Tao and Huang, 2011), prevent scale formation in water (Baker and Judd, 1996; Gholizadeh *et al.*, 2005; Lipus *et al.*, 2015), and improve the rheological and physicochemical properties of honey (Sakdatorn *et al.*, 2018, 2017), the underlining mechanism of the magnetic field was not clear. Moreover, despite the merits of the operating and maintenance costs (Gilart *et al.*, 2013), the applications of permanent magnets in food processing are still limited due to the lack of a fundamental understanding of the magnetic field mechanism and its potential effect on food materials during processing. Additionally, appropriate designs of magnetic field systems for food processing applications are not readily commercialized. Therefore, this research was aimed at developing a new magnetic field apparatus, characterizing the generated magnetic field, and testing its potential use for liquid food processing using honey as a food example.

Materials and Method

Honey Sample

A commercial longan honey sample was purchased from Patthanakit Bee Farm Ltd., Part. in Chiang Mai Province, Thailand. The honey was harvested during the normal flowering season of longan (February to May 2016).

Materials and Construction of Magnetic Field Apparatus

The experimental apparatus for the magnetic field (MF) treatment was composed of tubes with 10 sets of magnets (Figure 1(a)). The tubes were non-magnetized, commercial grade 316 stainless steel with dimensions of 10×20×200 mm. The thickness of the tubes was 1 mm. There were 4 MF treatments using different numbers of the neodymium permanent magnets of about equal magnetic fields mounted outside the tubes. Equal numbers of magnet sets were affixed to opposite sides of the tubes, i.e. 1:1, 2:2, 3:3,

and 4:4 representing 1, 2, 3, and 4 magnets on each side, respectively. Correspondingly, they were designated as MF11, MF22, MF33, and MF44. The north and south poles of each magnet set were inversely fixed on the opposite sides, and inversely arranged with those of the neighboring sets (Figure 1(b)). Each set of the magnets was aligned and equally placed at 8 mm apart by using non-magnetized aluminum spacers between the magnet sets. A tube without a magnet attachment was used as the control sample.

The MF11, MF22, MF33, and MF44 sample treatment tubes were affixed with the total numbers of 20, 40, 60, and 80 permanent magnets, respectively, in order to generate 4 different levels of the magnetic field strength. From a preliminary study, the minimum number of 20 magnets (MF11) was selected to cause noticeable changes in the honey's properties, whereas the maximum number of 80 magnets (MF44) was used since using 20 more magnets could generate only a small increase in the magnetic field strength inside the sample treatment tubes.

Characterization of Magnetic Field Distribution using Iron Powders

Iron powders (Intereducation Supplies Co., Ltd., Bangkok, Thailand) with a particle size range of 20-200 μm were used to characterize the magnetic field. A paper sheet (120 g/m² density) was placed on the magnetic apparatus. Then, the iron powders were gently sprinkled on the paper. The powders were drawn toward the magnetic poles according to the flux intensity of the magnetic field. The directions of the magnetic field lines of force were observed. A magnetograph was taken, and the magnetic field lines of force were drawn according to the flow directions of the iron powders under the influence of the magnetic field.

Measurement of Magnetic Field Strengths of the Experimental Setups

The magnetic field strengths of the experimental apparatus were measured using an AlphaLab High-Stability DC Gaussmeter (Model GM-2 with ST universal probe,

AlphaLab Inc., Salt Lake City, Utah, USA). The measurements were carried out in the cross-sectional areas of the tube at positions a to i along the tube's length, which was divided into layers 1 to 17 (Figure 2). The schematic diagram of the magnetic field strength distribution was constructed using the values measured at the center of the MF tube (position e).

Application Test of Magnetic Field on Improvement of Honey Properties

The longan honey samples were subjected to 4 different magnetic fields (MF11, MF22, MF33, and MF44) and carried out at 2 controlled temperatures ($15\pm 2^\circ\text{C}$ and $28\pm 2^\circ\text{C}$). The 2 temperatures were the average temperatures during the winter and summer seasons, respectively, in the northern part of Thailand (Thai Meteorological Department, 2015) where majority of the types of Thai honey are cultivated and processed. The $15\pm 2^\circ\text{C}$ condition was set in a refrigeration chamber, whereas the $28\pm 2^\circ\text{C}$ condition was obtained in an air-conditioned room. The magnetic exposure time of 2 hours was applied to all treatments. An adequate time for magnetic field exposure is required to cause a significant reduction in viscosity (Sakdatorn *et al.*, 2018). The samples without magnetic exposure and held at each temperature for

2 h were used as the control samples. Figure 3 shows the experimental setup for the control and magnetic field treatment of the longan honey. Immediately after the treatments, the samples were subjected to pollen analysis, flow properties analysis, and color measurement. Details of the measurements are as follows:

Pollen Analysis

Pollen analysis was done using the method of Belay *et al.* (2017) with adjustments in an addition of distilled water to the honey and the centrifugation time. Ten grams of honey sample were weighed into a centrifugal test tube (50 ml), and 20 ml of distilled water was added. The sample was gently mixed to completely dissolve the honey. The sample was then centrifuged at 4500 rpm for 20 min. The supernatant was drained, and 5 ml distilled water was added to the tube to disperse the sediment content. The dispersed liquid was dropped onto a glass slide with a glass cover and viewed under a light microscope (CHK-2-F-GS, Olympus Optical Co., Ltd., Tokyo, Japan) at 100x magnification. Images of the pollen were taken using a digital camera (Panasonic BSI CMOS sensor, 13 megapixels, 1/3.06-inch, pixel size of $1.12\ \mu\text{m}$, Panasonic Corp., Osaka, Japan) attached to the eye piece of the microscope.

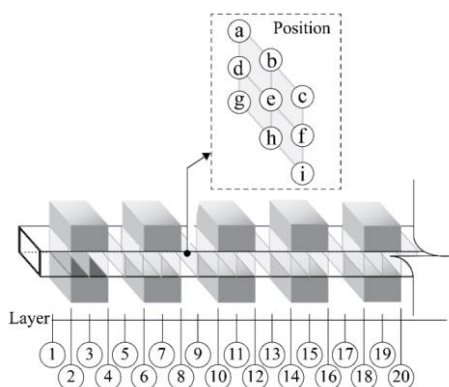


Figure 2. Magnetic field strength measurement positions a-i across the cross-section areas along the sample tube layers 1-20

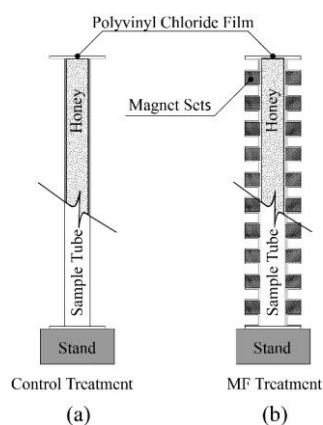


Figure 3. Experimental setup: (a) Control sample treatment and (b) magnetic field sample treatment

Flow Property and Viscosity Measurements

Shear stresses were measured at different shear rates using a viscometer (model DV-II+, AMETEK Brookfield, Middleboro, MA, USA) with the attachment of a small sample cell and spindle number 29 (S29). Plots of the shear stress vs shear rate were constructed to determine the type of flow behavior (Sahin and Sumnu, 2006; Bakier, 2017). The Herschel-Bulkley equation (Equation 1) was used to fit the shear stress and shear rate data to obtain the consistency index (K). The viscosities at the highest shear rates (at shear rates of 1.25 s^{-1} and 3.75 s^{-1} for the samples treated at $15 \pm 2^\circ\text{C}$ and $28 \pm 2^\circ\text{C}$, respectively) were also recorded. The data between the K value (obtained from the shear stress vs shear rate plots) and viscosity at the maximum torque were plotted.

$$\tau = K\dot{\gamma}^n + \tau_0 \quad (1)$$

where τ is the shear stress (Pa), $\dot{\gamma}$ is the shear rate (s^{-1}), n is the flow behavior index ($n = 1$ for Newtonian fluids, $n > 1$ for dilatant fluids, $n < 1$ for pseudoplastic fluids), K is the flow consistency index (Pa s^n), and τ_0 is the yield stress (Pa) which is the minimum stress to generate flow (Sahin and Sumnu, 2006).

Experimental Design and Data Analysis

The experiment on the MF treatment of the honey was conducted using a complete randomized design with 3 replicates. Mean values and standard deviations (SD) of the measured values were computed. Data related to the flow (shear stress vs shear rate) were presented as the mean values without SD bars due to their very small magnitudes as compared with the mean values.

Results and Discussion

The magnetic field apparatus was designed, constructed, and tested for its application for improvement of the flow properties of longan honey. The directions of the magnetic field lines of force, magnetic field strength, magnetic field distribution patterns, and effects of the magnetic field treatment on the pollen characteristics and flow properties of longan honey are reported in this article.

Characteristics of Magnetic Field Lines

Figure 3 shows the magnetic field lines of force generated by the MF apparatus, as observed from the top-view of the sample tube.

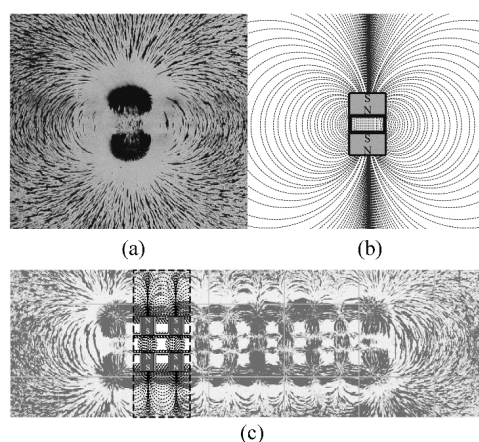


Figure 4. Magnetic field lines of force measured at 0.39 T: (a) observation from the top view of a sample tube, (b) schematic drawing where dotted lines help visualize the magnetic lines of force, and (c) observation from the side view of the sample tube with partial superimposed dotted lines to help visualize the magnetic lines of force

Figure 4(a) shows that iron powder particles aligned themselves according to the attraction force of the magnetic lines. The magnetic lines of force moved between the north and south poles of the magnet pieces. The magnetic lines of force exist in 3 dimensions but only 2 dimensions are observed in the magnetograph. Between the magnet facets directly mounted on the opposite sides of the sample tube, the straight-line alignment of the iron powders was observed. The field lines in the central area between the magnets were denser than those in the surrounding areas (Figure 4(b)). Moreover, the density of the magnetic field lines decreased with increasing the distance from the poles. Outside the sample tube, the curved magnetic field lines between the north and south poles with fewer densities were observed. Therefore, stronger magnetic fields were expected inside the sample tube.

Figure 4(c) shows the magnetograph of the magnetic apparatus examined from the side view of the sample tube. The magnetic lines of force and field strengths were observed from the alignment and density of the iron powders. The stronger attraction force was observed when more magnets were used (Figure 5). This was shown by the amount of iron powders being attracted to the magnet poles and the effective distance from the magnets. The

higher number of magnets showed larger effective areas outside the tubes. Additionally, when compared with the non-magnetic areas, more attraction of iron powders was present across the tube in the magnetic areas. The magnetic field lines moved from the north to south poles with high field line densities present at the origins of the magnetic fields and between the opposite facets of the magnets. Due to the inverted north to south poles arrangement of the magnets, there were magnetic field lines connected between the paired magnet sets. These distributions resembling magnetic fields on the magnet sets along the sample tube could be observed. Nevertheless, the areas between the magnet sets revealed very low magnetic fields.

Magnetic Field Distribution Patterns and Strength Distribution

Measurements of the magnetic field strengths across the cross-section areas (positions *a-i* in Figure 2) along the tube revealed that large magnetic field strengths were observed at the central facets of the magnets - positions *b* and *h* on the layers 3, 7, 11, and so on. On the same layers, the strengths decreased when measured toward both sides of the magnets - positions *a* and *c* and positions *g* and *i*. The strengths decreased further when

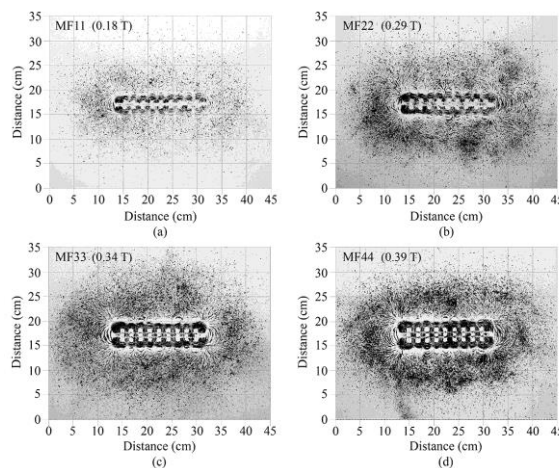


Figure 5. Effective area of magnetic fields at different magnetic field strengths on tubes: (a) MF11 0.18 T, (b) MF22 0.29 T, (c) MF33 0.34 T, and (d) MF44 0.39 T

measured at the center of the tube or the midpoint between the central facets of the magnets, position *e*, and decreased even more toward the sides at positions *d* and *f*. At the magnets' edges, as shown on the layers 2, 4, 6, 8, and so on, the magnetic field distributions across the cross-section areas were similar, but their field strengths were less than those measured at the central facets of the magnets. Farther away from the magnets, the distributions across the cross-section areas on layers 1, 5, 9, 13, and so on were still in a similar manner, but their field strengths were reduced much further.

The magnetic field strength distributions along the tubes of all the MF treatments were similar but different in magnitudes. The distributions from the center positions obtained from all sample tubes are displayed in Figure 6. As represented from other positions across the cross-section area, the distribution obtained from the center position of a tube exhibits an alternating MF strength pattern along the tube's length. The maximum magnetic field strengths in both positive and negative values depending on the field directions are located at the central positions of the magnets, i.e., layers 3, 7, 11, and so on. From these positions, the field strengths are approaching zero at the midpoints between the

magnet sets, i.e., layers 5, 9, 13, and so on. This observation was also confirmed by magnetic line densities, as shown in Figure 3. Because the north and south poles of the magnets were arranged alternately in opposite directions, an alternating magnetic field was created along the length of the MF tube (Hirschbein *et al.*, 1982). A similar magnetic field distribution pattern was reported by Gabrielli *et al.* (2001) for water treatment in a pipe equipped with magnets with an inverted pole arrangement in which the inverted arrangement generated a stronger magnetic field and had a stronger influence on the properties of the sample as compared with a non-inverted pole arrangement. Lipus *et al.* (2015) also reported a similar magnetic field distribution using 0.16 T magnetic devices for water-scale prevention.

Using the magnetic field strength measurements at all central facets of the magnets (positions *b* and *h* in Figure 2), the average magnetic field strengths in the tubes of MF11, MF22, MF33, and MF44 were 1789 ± 251 G (0.18 T), 2881 ± 251 G (0.29 T), 3444 ± 520 G (0.34 T), and 3941 ± 377 G (0.39 T), respectively. In this study, the field strengths generated by the magnetic apparatus were higher than those reported by Sakdatorn *et al.* (2017) for honey treatment, Gabrielli *et al.* (2001), Gilart *et al.* (2013), and Alkhazan

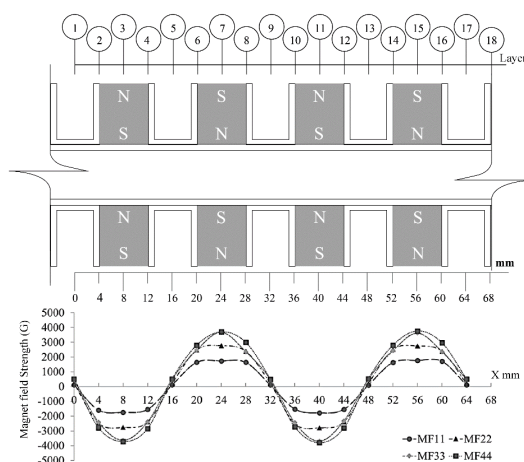


Figure 6. Magnetic field distribution patterns measured at the center position of the cross-sectional area along the sample tube: MF11, MF22, MF33, and MF44

and Saddiq (2010) for water treatments. The effectiveness of magnetic applications does not only depend on the MF strength but also on the magnetic gradient or the magnetic flux concentration, which changes frequently along the magnetic device (Oshitani *et al.*, 1999). The combination of a magnetic gradient and a magnetic field of alternating strength is more effective than a static magnetic field (Zaidi *et al.*, 2014). Hence, such magnetic fields can be applied in the food industry to improve physicochemical properties while preserving nutritional benefits and natural functions due to their non- thermal effects on the food materials (Sakdatorn *et al.*, 2018). However, a much stronger magnetic field could induce an effect in a short time. For example, a magnetic field of 1.3 T for 1 min was applied to reduce blood viscosity (Tao and Huang, 2011).

Effects of Magnetic Field on Pollen Particles

The characteristics of the pollen in the honey samples after the magnetic field treatments were compared with those in the control samples (Figure 7). It was found that large pollen agglomerates were found in the control samples, whereas smaller agglomerates were observed in the MF11 samples. The agglomerates were not found in the MF22, MF33, and MF44 samples;

however, individual pollen particles were observed. In the MF44 samples, some fragments of broken grains of pollen in addition to the individual pollen particles were found. These results were observed for the samples treated at 15°C (CL) and 28°C (RT). It might suggest that the magnetic gradient and strong alternating MF strengths could break down the pollen agglomerates. The mechanism of pollen deagglomeration could be due to the presence of the Lorentz force causing the opposite ionic charges to move in opposite directions (Gholizadeh *et al.*, 2005) and hence decrease the adhesion of the pollen particles. Moreover, a magnetic field could increase the surface energy of small particles and might prevent them from agglomeration (El Hafidi and El Hafidi, 2017). As a result, smaller particles could exhibit less flow resistance than the larger particles did and cause a reduction of the consistency index (K) (Rao and Tattiyakul, 1999). This result could also be supported by the mechanism of magnetic dissolution enhancement (Baker and Judd, 1996). Therefore, the influences of magnetic fields on flow-related properties, e.g., shear stress and viscosity of the samples, were expected.

Improvement of Honey’s Rheological Property

The plots between the shear stress and shear rate of all the samples show a linear

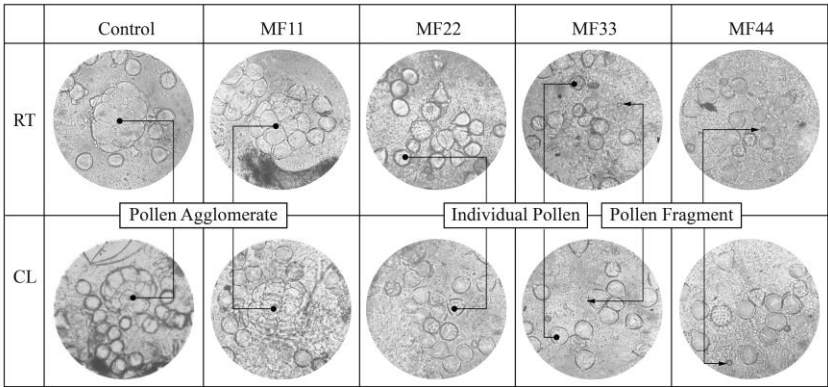


Figure 7. Pollen particles and distribution after magnetic treatments (MF11, MF22, MF33, and MF44) at 28°C (RT) and 15°C (CL) as compared with the control samples

relationship (Figure 8(a-b)). The Herschel-Bulkley model was fitted to the experimental data, and the flow consistency index (K) and flow behavior index (n) could be obtained for every sample. The flow behavior indexes for all samples were found to be 1 ($n = 1$) with the linear correlation coefficients (R^2) above 0.999 (data not shown), and τ_0 was 0 since the plot started at the origin for all the samples. These linear relationships indicated that the flow behavior of the honey belonged to the Newtonian type, in which the increase in shear stress is proportional to the increase in shear rate with the flow behavior index of 1 (Sahin and Sumnu, 2006). Other types of honey were also found to be Newtonian fluids (Cohen and Weihs, 2010; Trávníček *et al.*, 2012; Belay *et al.*, 2017). However, some honey types were reported as being non-Newtonian when measured at high shear rates up to 500 s^{-1} (Boussaid *et al.*, 2015).

It was shown that the MF treatments influenced the flow behaviors of the honey samples at both 28°C and 15°C , as shown in Figure 8(a-b), respectively. It was found that the flow consistency indexes (K) were decreased with an increasing magnetic field strength and temperature as a result of

reducing the slopes between the shear stress and shear rate. Reductions in the consistency indexes with increasing magnetic field strengths at the low temperature (15°C) were larger than those at the high temperature (28°C). Since the flow behaviors of the honey samples were Newtonian, the consistency index was equivalent to the apparent viscosity. An increasing consistency index is closely correlated to the increasing viscosity of the sample at the final shear rate. Figure 8(c, d) shows the relationship between the consistency index and final viscosity of the honey samples after MF treatments with different magnetic field strengths. Decreases in honey viscosity, as affected by magnetic fields, were also reported by Sakdatorn *et al.* (2017, 2018). A similar effect of the magnetic field on other liquids, such as human blood, was also shown by Tao and Huang (2011). Similar effects of the temperature on viscosity reduction were reported by Trávníček *et al.* (2012) and Saxena *et al.* (2014). At a constant temperature, the higher magnetic field strengths induced greater reductions in the consistency indexes, and hence viscosity reductions. The flow improvement of the honey samples could be closely related to the breaking down of the

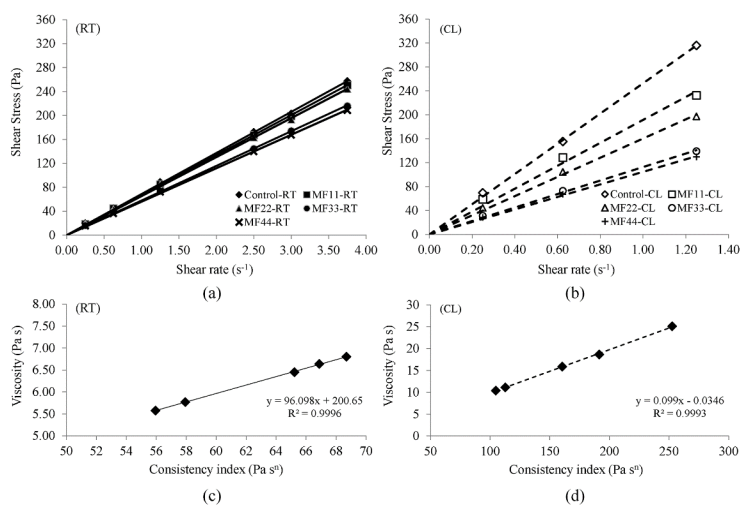


Figure 8. Flow behavior of honey samples after magnetic treatments at (a) 28°C (RT) and (b) 15°C (CL), and relationships between viscosity and consistency index (K) of honey samples after magnetic treatments at (c) 28°C (RT) and (d) 15°C (CL)

pollen agglomerates into smaller, individual particles, as shown in Figure 7. Pollen agglomerate was not found in the samples after being treated with higher magnetic field strengths. Since the smaller particles could easily align themselves with the direction of the shear, they exerted less resistance to flow as compared with the larger particles (Rao and Tattiyakul, 1999).

Moreover, reduction in the resistance to flow could be due to decreasing friction between water molecules (Al-Mahasneh *et al.*, 2014) in the honey. The stronger magnetic field strength could result in a greater reduction in water molecular friction (Sakdatorn *et al.*, 2018). This was caused by weakening of the thermal motion of water in the magnetic field that could lead to stronger hydrogen bonding of a water molecule (Wang *et al.*, 2018). Hence, the intermolecular friction of a water molecule could be reduced. The reduction in the flow consistency index and viscosity that could allow better flow dynamics, and the consequent ease of handling, pumping, and packaging, in addition to energy saving, could be achieved in honey processing.

From the results of the pollen analysis and rheological analysis, it can be suggested that the magnetic field strength of 0.39 T could be successfully applied for improvement of honey flow properties for pretreatment and packaging purposes since smaller pollen particles and low viscosity were observed. At this magnetic field strength, the honey's viscosity could be reduced by 50% and 20% at 15°C and 28°C, respectively. The lower final viscosity obtained from the magnetic field treatment allowed ease of flow and easy handling of honey through the processing and packaging steps. The use of higher magnetic field strengths would increase the cost of the equipment, while it did not show a significant reduction in viscosity.

Conclusions

A novel non-thermal magnetic field apparatus was constructed to provide MF strengths ranging from 0.18 T to 0.39 T. The inverted

arrangement of the magnets' north to south poles provided alternating MF strengths. In the magnetic areas of the apparatus, a high density of linear lines was observed. The strong magnetic field distribution along the sample tube with 10 magnet sets mounted at equal spacing could give a uniform effect on the sample during treatment. The MF apparatus was used to treat longan honey samples at low and ambient temperatures. The longan honey samples showed Newtonian behavior. Temperature and MF strength did not influence the Newtonian behavior. However, increasing the temperature to 28°C and the MF strength could reduce the consistency index (K) and viscosity of the samples. This might be related to the breakdown of the pollen agglomerates by the magnetic fields. Additionally, it was believed that reductions in the shear stress and viscosity were due to less water molecular friction after the weakening of the molecular motion under the influence of the magnetic fields. As a result, the honey had improved flowability and had advantages in terms of transportation and processing.

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References

- Agri-Industry Development Division. (2018). Magnetic separators in food processing. Winnipeg, MB, Canada. Available from: www.gov.mb.ca. Accessed date: April 12, 2018.
- Alkhazan, M.M.K. and Saddiq, A.A.N. (2010). The effect of magnetic field on the physical, chemical and microbiological properties of the lake water in Saudi Arabia. *J. Evol. Bio. Res.*, 2(1):7-14.
- Al-Mahasneh, M. A., Rababah, T. M., Amer, M., and Al-Omouh, M. (2014). Modeling physical and rheological behavior of minimally processed wild flowers honey. *J. Food Process. Pres.*, 38:21-30.

- Augustine, R., Abraham, A.R., Kalarikkal, N., and Thoma, S. (2016). Monitoring and separation of food-borne pathogens using magnetic nanoparticles. In: *Novel Approaches of Nanotechnology in Food*. Grumezescu, A. M., (ed). Elsevier, Amsterdam, Netherlands, p. 271-312.
- Baker, J.S. and Judd, S.J. (1996). Magnetic amelioration of scale formation. *Water Res.*, 30:247-260.
- Bakier, S. (2017). Rheological properties of honey in a liquid and crystallized state. In: *Honey Analysis*. Toledo, V.A.A. (ed). InTech, Rijeka, Croatia, p. 115-137.
- Barbosa-Cánovas, G. V., Swanson, B. G., San Martín, G.M.F., and Harte, F. (2005). Use of magnetic fields as a nonthermal technology. In: *Novel Food Processing Technologies*. Barbosa-Cánovas, G.V., Tapia, M.S., and Cano, P., (eds). CRC Press, Boca Raton, FL, USA, p. 443-451.
- Belay, A., Haki, G.D., Birringer, M., Borck, H., Addi, A., Baye, K., and Melaku, S. (2017). Rheology and botanical origin of Ethiopian monofloral honey. *LWT - Food Sci. Tech.*, 75:393-401.
- Bermúdez-Aguirre, D., Rodríguez-Justo, O., Haber-Perez, V., García-Perez, M., and Barbosa-Cánovas, G.V. (2016). Use of magnetic fields technology in food processing and preservation. In: *Handbook of Food Processing*. Varzakas, T. and Tzia, C., (eds). CRC Press, Boca Raton, FL, USA, p. 509-516.
- Boussaid, A., Chouaibi, M., Rezig, L., Missaoui, R., Donsí, F., Ferrari, G., and Hamdi, S. (2015). Physicochemical, rheological, and thermal properties of six types of honey from various floral origins in Tunisia. *Int. J. Food Prop.*, 18(12):2624-2637.
- Cohen, I. and Weihs, D. (2010). Rheology and microrheology of natural and reduced- calorie Israeli honeys as a model for high- viscosity Newtonian liquids. *J. Food Eng.*, 100:366-371.
- Dobersek, D. and Goricanec, D. (2014). An experimentally evaluated magnetic device's efficiency for water scale reduction on electric heaters. *Energy*, 77:271-278.
- El Hafidi, M.Y. and El Hafidi, M. (2017). Existing scale deposits removal by magnetic water treatment: Theoretical study and experiment. *International Journal of Water and Wastewater Treatment*, 3(3):1-3.
- Gabrielli, C., Jaourari, R., Maurin, G., and Keddad, M. (2001). Magnetic water treatment for scale prevention. *Water Res.*, 35(13):3249-3259.
- Gholizadeh, M., Arabshahi, H., and Benam, M.R. (2005). The effect of magnetic field on scale prevention in the industrial boilers. *Int. J. Appl. Chem.*, 1(1):84-89.
- Gilart, F., Deas, D., Ferrer, D., López, P., Ribeaux, G., and Castill, J. (2013). High flow capacity devices for anti-scale magnetic treatment of water. *Chem. Eng. Process.*, 70:211-216.
- Hirschbein, B.L., Brown, D.W., and Whitesides, G.M. (1982). Magnetic separation in chemistry and biotechnology. *Chem. Technol.*, 12(3):172-179.
- Hofmann, G.A., inventor; Maxwell Laboratories, Inc., assignee. June 18, 1985. Deactivation of Microorganisms by an Oscillating Magnetic Field. U.S. patent no. 4,524,079.
- Ilyina, A., Ramos- González, R., Vargas- Segura, A., Sánchez- Ramírez, J., Palacios- Ponce, S. A., Martínez-Hernández, J.L., Segura-Ceniceros, E.P., Contreras- Esquivel, J.C., and Aguilar- González, C.N. (2016). Magnetic separation of nanobiostructured systems for innovation of biocatalytic processes in food industry. In: *Novel Approaches of Nanotechnology in Food*. Grumezescu, A.M., (ed). Elsevier, Amsterdam, Netherlands, p. 67-96.
- Kochmarsky, V. (1996). Magnetic treatment of water: Possible mechanisms and conditions for applications. *Magnetic and Electrical Separation*, 7(2):77-107.
- Lipus, L.C., Hamier, A., Ban, I., and Acko, B. (2015). Permanent magnets for water- scale prevention. *Adv. Prod. Eng. Manag.*, 10(4):209-216.
- Liu, Y.-Q., Suhartini, S., Guo, L., and Xiong, Y. (2016). Improved biological wastewater treatment and sludge characteristics by applying magnetic field to aerobic granules. *AIMS Bioengineering*, 3(4):412-424.
- Oshitani, J., Yamada, D., Miyahara, M., and Higashitani, K. (1999). Magnetic effects on ion exchange kinetics. *J. Colloid Interf. Sci.*, 210:1-7.
- Rao, M.A. and Tattiyakul, J. (1999). Granule size and rheological behavior of heated tapioca starch dispersions. *Carbohydr. Polym.*, 38:123-132.
- Sahin, S. and Sumnu, S.G. (2006). *Physical Properties of Foods*. Springer, New York, NY, USA, 267p.
- Sakdatorn, V., Thavarungkul, N., and Srisukhumbowornchai, N. (2017). The effects of magnetic fields on viscosity, colour and pH of longan honey. *Naresuan University Engineering Journal*, 12(2):15-20.
- Sakdatorn, V., Thavarungkul, N., Srisukhumbowornchai, N., and Intipunya, P. (2018). Improvement of rheological and physicochemical properties of longan honey by non-thermal magnetic technique. *Int. J. Food Sci. Tech.*, 53(7):1717-1725.
- Saxena, S., Panicker, L., and Gautam, S. (2014). Rheology of Indian honey: Effect of temperature and gamma radiation. *Int. J. Food Sci.*, 935129:1-6.
- Štefušová, K., Václavíková, M., Lovás, M., and Hrdzák, S. (2012). Use of magnetic filtration in waste water treatment. *Acta Montan. Slovaca*, 17(1):81-84.
- Tao, R. and Huang, K. (2011). Reducing blood viscosity with magnetic fields. *Phys. Rev. E*, 00(001900): 1-5.
- Tao, R. and Xu, X. (2006). Reducing the viscosity of crude oil by pulsed electric or magnetic field. *Energy Fuels*, 20:2046-2051.
- Thai Meteorological Department. (2015). The climate of Thailand. Bangkok, Thailand: TMD. Available from: www.tmd.go.th/en/archive/thailand_climate.pdf. Accessed date: April 14, 2017.
- Trávníček, P., Vítěz, T., and Pridal, A. (2012). Rheological properties of honey. *Scientia Agriculturae Bohemica*, 43(4):160-165.
- Wang, Y., Wei, H., and Li, Z. (2018). Effect of magnetic field on the physical properties of water. *Results Phys.*, 8:262-267.

- Yadollahpour, A., Jalilifar, M., and Rashidi, S. (2014). Antimicrobial effects of electromagnetic fields: A review of current techniques and mechanisms of action. *J. Pure Appl. Microbio.*, 8(5):4031-4043.
- Zaidi, N. S., Sohaili, J., Muda, K., and Sillanpää, M. (2013). Magnetic field application and its potential in water and wastewater treatment systems. *Sep. Purif. Rev.*, 43(3):206-240.