

## Experimental study on magnetic induction property of solenoid coil used in cooling water treatment system

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### ABSTRACT

Magnetic induction intensity is a critical factor to determine electromagnetic descaling effects. The current in a solenoid coil is an important parameter affecting the intensity of electromagnetic induction. In order to explore how winding pipe diameter, number of turns and frequency affect the current in the solenoid coil wrapped around the carbon steel pipes, the variation of the current with those factors is investigated by an experiment in which the method of series resistance is used. The peak current is obtained by measuring the voltage crossing series resistance. In this paper, the effect of series resistance on measuring current is analyzed. In order to reduce the influence of series resistance to electric current and ensure measurement reliability, 1.18Ω of the resistance is used for experimental measurements. The magnetic induction decreases with the increase of frequency and pipe diameter, and increases when the number of turns increases. The peak current decreases with the increase of frequency, number of turns, and pipe diameter, respectively. The results of this study show that the variation of the current in the solenoid coil wrapped around the carbon steel pipes can be affected by various factors, and design guidance for the power of electronic anti-fouling equipment is provided.

**Key words** | carbon steel pipe, current, electronic anti-fouling, magnetic induction, solenoid coil

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### INTRODUCTION

Water is an important heat transfer medium which plays an important role in the process of industrial production. However, when hard water is used as circulating water, calcium ions and magnesium ions dissolved in water will attach on the surface of the heat exchanger in the form of scale. The formation of scale is inevitably associated with two direct disadvantages (Suitor *et al.* 1977; Cho *et al.* 1997; Fan & Cho 1997): one is the reducing of heat transfer performance, the other is the significant decreasing of the flow rate and increasing of the pressure drop, both of which are caused by the change of the pipe diameter as a result of scale blockage. Moreover, if there is a high heat flux, scale can even lead to local hot spots of heat exchanger and result in equipment damage or suspend production (Quan *et al.* 2009).

Some methods have been carried out in preventing or mitigating mineral fouling, which can be classified into chemical methods and physical methods. Including chelation, dispersion and inhibition, etc., the advantage of chemical methods is the high success rate in preventing or mitigating mineral fouling, but the secondary pollution to environment and the high cost are their insuperable disadvantages (Cho *et al.* 1998a; Kim *et al.* 2001). For these reasons, physical methods, such as electromagnetic field, catalytic material, ultrasound, and sudden pressure change, have been developed in recent years. Compared with chemical methods, the common superiority of physical methods is the avoidance of chemicals and the consequent pollution.

Electronic anti-fouling technology (EAFT) is a new kind of physical methods, which can be used in scale dissolution of recycle cooling water systems without polluting and low consumption. Generally, the system consists of a controlling unit and solenoid coil. When it works, pulsing electric field produced by the controlling unit of EAFT creates the time-varying magnetic field in the solenoid coil. Subsequently, the time-varying magnetic field produces an induced electric field in the circulating cooling water which provides the necessary molecular agitation to achieve a scale cleaning effect (Cho *et al.* 1998b).

Cho *et al.* (1997) provided a scientific explanation for the operating principle of the EAFT. Liu & Cho (1999) found that the fouling resistance in the tube with the EAFT treatment was 46% less than in the one without the EAFT treatment at the end of 4 days testing, and the brush punching of the tube for the case with treatment resulted in zero fouling resistance. Kim *et al.* (2001) conducted a fouling test in a rectangular heat-transfer channel at five cycles of concentration and found that the fouling resistance using EAFT treatment is about 70% less when compared with the result without using the EAFT. Cho *et al.* (1998b) studied the effect of the EAFT with a filter, and each individual test lasted for 40 hours. The results showed that the overall heat transfer coefficient decreased 6% and pressure drop increased 75% compared with the initial state by using the EAFT. Meanwhile, without any treatment, the heat transfer coefficient decreased 29% and the pressure drop increased 132% from the initial state. Cho & Choi (1999) conducted a fouling test in a once-through flow system with a single-tube heat exchanger and found that the EAFT reduced fouling resistance by 20–38% at a flow velocity between 0.52 and 0.78 m/s. At the same time, the SEM photographs obtained support the validity of the EAFT in mitigating precipitation fouling. The experimental study of Xing *et al.* (2006) showed that the EAFT could prolong the delay time of fouling effectively. On this foundation, an extensive study was carried out by Kim & Cho (2011) by using a solenoid-coil device with filtration, the experiment finally confirmed that the fouling resistances in the water treated by the EAFT are significantly less than those with no-treatment. The experimental study of Wang *et al.* (2015) showed that 90% of the scale inhibition rate can be obtained using the

EAFT when the frequency is 1 kHz. Zhang *et al.* (2016) studied the effect of the EAFT with a closed cooling tower and found that the fouling resistance in the case with and without EAFT increased by 7.51 and 25.14%, respectively, at the end of 214 h of tests. These tests demonstrate that the EAFT treatment can effectively reduce precipitation fouling in actual heat exchangers.

Jiang *et al.* (2008) and Jiang & Zhou (2008) experimented and discovered that the higher the induction magnetic field is, the more effective the treatment effect is. According to Ampere's loop theorem and Faraday's rule, the magnetic induction intensity is determined by the current in the solenoid coil. It means that the descaling effect is decided by the current size in the solenoid coil. Jiang *et al.* (2008) and Jiang & Zhou (2008) studied out the relationship between magnetic field and scale quantity by changing the magnetic field strength, and magnetic field strength change along with the current. Liu (1999) experimented and showed that higher current makes better cleaning effect. Han (2013) and Quan *et al.* (2008) drew the same conclusion in their experiments. These tests demonstrate that the current in the coil can be used to characterize the descaling effect of the EAFT.

To ensure the efficiency of descaling and antiscaling for different kinds of water, some electronic anti-fouling equipment (EAFT) works with the frequency of periodic variation (Jiang *et al.* 2008). As an indirect characterization of the descaling effect, however, the relationship between the change rule of the current in the solenoid coil with winding diameter, the number of turns, and frequency is not clear. Cho *et al.* (1998b) found that the impedance increases with the diameter of the solenoid coil increasing, and this phenomenon makes the magnitude of current significantly reduced in large diameter pipes. The study of how diameter affects the current did not continue, and Cho *et al.* (1998b) chose to study the cleaning effect by constant. Chai (2011) and Wu (2005) used the constant voltage to explore the effect of descaling without considering the influence of the current change. The EAFT achieves the scale cleaning effect by electromagnetic field, and the current is one significant parameter which affects the size of electromagnetic field directly. However, further investigation on the current change mechanism influenced by the number of turns, diameter and frequency at a given voltage has not been developed.

Accordingly, the objective of the present study is to explore how winding diameters, the numbers of turns and frequencies affect the current in the solenoid coil wrapped around the carbon steel pipe. Peak current is obtained by measuring the voltage using the method of series resistance. The changing trend of the magnetic induction is also described. The results of this study show that the variation of the current was affected by various factors and provided design guidance for the power supply.

## EXPERIMENT FACILITY AND METHOD

### Facility

The solenoid coil was wound outside the pipe and connected with the power supply. When the water flows through the coil, the scaling ions dissolved in the water can be treated to produce insoluble calcium carbonate crystals so as to achieve the purpose of scale inhibition. Figure 1 shows a schematic diagram of test facilities, which consists of an EAFT control unit, three carbon steel pipes with different diameters, some wires, series resistance and an oscilloscope.

The EAFT control unit produces square wave voltage, and the frequency ranged from 2 to 27 kHz. Carbon steel tubes with different diameters were used in the experiment. The wire was tightly wrapped around the carbon steel pipe to form a solenoid coil, assuming that the diameter of winding coil was the diameter of the carbon steel pipe. The solution in the pipe was 5 mmol/L of calcium bicarbonate solution which was composed of a mixture of calcium chloride and sodium bicarbonate. The solution was in a static

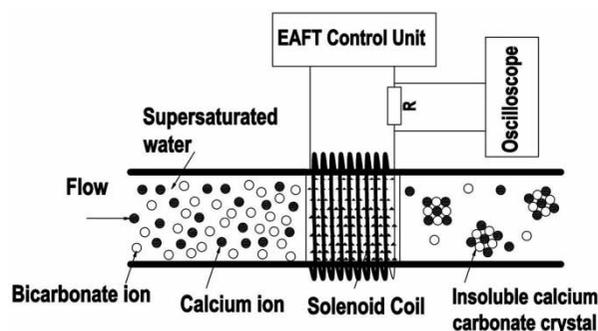


Figure 1 | Schematic drawing of the experimental device.

state. The type of wire was PVC insulated flexible cables with copper core meeting Chinese National Standards. The wire consisted of 19 copper wires 6 mm<sup>2</sup> in sectional area, 5.3 mm in diameter and 0.8 mm in insulation thickness, and the diameter of each copper wire was 0.64 mm. The wire was connected to the EAFT control unit, one end of the wire being indirectly connected to the EAFT control unit through a series resistance which was used to measure current value. A high precision oscilloscope was used to measure the voltage difference between the two ends of the resistance. The model of the oscilloscope was TBS1102 produced by Tektronix. The oscilloscope was 100 MHz in bandwidth,  $\pm 3\%$  in vertical precision.

A series of tests was carried out in the present study to obtain the magnetic induction property along with the change of factors. Different diameters of carbon steel tube were used in the experiment. Different turns of coils were wound around each carbon steel tube, respectively. The resistance R was connected in series between the solenoid coil and the EAFT control unit. When the equipment was in the working state, the voltage difference between the two ends of the series resistance was measured by the oscilloscope. Therefore, the current in the circuit with series resistance could be obtained. Based on the obtained current data, the change rule of the magnetic induction in the solenoid coil was obtained.

### Method

The operating frequency of the EAFT was almost less than 1 MHz, under these circumstances the solenoid coil can be seen as the combination of a resistance and an inductance (Chen *et al.* 2016). The diagram of experimental device equivalent circuit used in the study was established, as shown in Figure 2. The EAFT control unit included a control section of pulse waveform and another control section of voltage. The solenoid coil was equivalent to the resistance

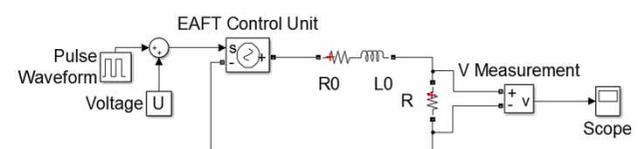


Figure 2 | Diagram of experimental device equivalent circuit.

R0 and inductance L0 being in series. Resistance R in series was used to measure the current in the circuit. V measurement and Scope together represent the oscilloscope for measuring voltage.

According to the voltage difference between the two ends of series resistance and the value of resistance, current in the circuit can be calculated by:

$$I = \frac{U}{R} \quad (1)$$

where  $U$  is the voltage difference between the two ends of series resistance, and  $R$  is the value of resistance.

In this paper, the property of magnetic induction will be analyzed. Therefore, the center point of the winding coil was selected for analysis.

The magnetic induction in the midpoint of the solenoid coil can be calculated by:

$$B = \frac{\mu_0 n I}{2} \frac{l_0}{(l_0^2/4 + r_0^2)^{1/2}} \quad (2)$$

where  $\mu_0$  is magnetic permeability,  $l_0$  is the length of solenoid coil,  $r_0$  is the radius of solenoid coil,  $n$  is the number of turns of solenoid coil. Thus, the change rule of the magnetic induction in the midpoint of the solenoid coil can also be obtained.

This experiment set the output voltage of the EAFT control unit on 9.6 V, and the frequency ranged from 2 to 27 kHz. The diameters of the three different carbon steel pipes were D160, D200 and D300 mm. The turns of the solenoid coil wrapped around each carbon steel pipe were 30, 50, 70 and 90 respectively. A high-precision oscilloscope

TBS1102 was used to measure the difference between the voltages across the series resistor. According to the voltage difference and the resistance value, the current value and magnetic induction can be indirectly obtained by calculation. Current and magnetic induction values in different parameters can be obtained by changing the frequency, the winding turns and the winding diameter.

The original series circuit with a resistor will certainly cause a certain impact on the current of the circuit. Also, when the value of series resistance increases, the current of the circuit measurement effect becomes larger. When the number of winding turns increases, the resistance of the coil increases, and the effect of the external series resistance on the current in the circuit becomes less.

The measurement of coil winding with 30 turns, the diameter of D160 and D300 mm were measured by using the resistance of  $R = 1.18$  and  $R = 2.43\Omega$ , respectively. Figure 3 shows that when the resistance is connected in series, the current variation trend of the circuit does not change, and the smaller the series resistance is, the smaller the impact on the circuit will be. When the diameter is 160 mm and the turn number is 30, it can be found that the relative error between the two currents is as high as 31.2% at a frequency of 2 kHz by comparing the influence on the current of different resistance values of 1.18 and 2.43 $\Omega$ . This error, caused by the series resistance, is decreased with the increase of frequency. It is 17.7 at a frequency of 27 kHz. Comparing (a) and (b) in Figure 3, the larger the diameter is, the smaller the effect of series resistance on measuring current will be. The relative error is 22.9% at a frequency of 2 kHz and 12.0% at a frequency of 27 kHz in the case of 300 mm diameter. So in the later

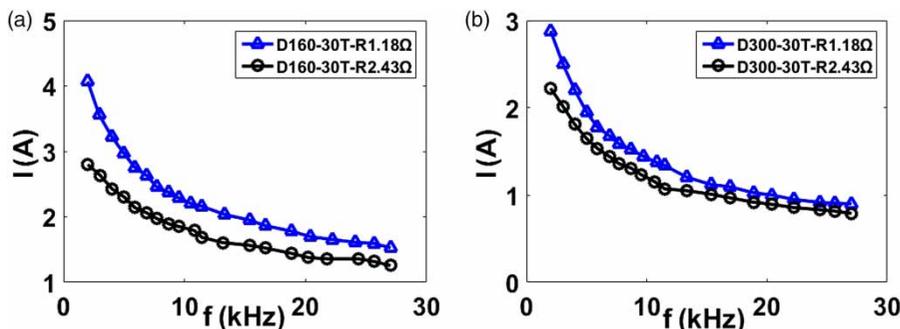


Figure 3 | The effect of series resistance on measuring current.

measurement experiment, the resistance  $R = 1.18\Omega$  was used in order to reduce the error. Meanwhile, the value of resistance is assumed to be a constant value because there is little variation with frequency. This paper has only discussed the influence of the factors on the current. The research on reducing the influence of series resistance on current will be described in future research.

## RESULTS AND DISCUSSION

Figures 4–9 respectively show variations of current and magnetic induction with respect to frequency, turns, and diameter.

### Effect of changes in current and magnetic induction with respect to frequency

The current of the circuit with the series resistance changes with frequency at different numbers of turns wrapped

around carbon steel pipes. The diameters of the carbon steel pipes are 160 and 300 mm, respectively, as shown in Figure 2. Both panels in Figure 4 show that the current gradually decreases as the frequency increases and the drop amplitude of current decreases with increasing frequency. For example, in the case of 30 turns coil winding around the diameter of D160 mm carbon steel pipe, the current decreases from 4 to 2 A as the frequency increases from 2 to 27 kHz. When the frequency increases from 2 to 5 kHz, the current decreases from 4 to 3 A. While the current decreases from 3 to 2 A, the frequency increases from 5 to 27 kHz. In different diameters and different numbers of turns, the current shows the same variation tendency. The main reason for the change may be that the total impedance is increased with increasing frequency, and as frequency is continually increased, the effect of frequency on total impedance becomes stable.

Figure 5 shows the effect of frequency on the magnetic induction. Both panels in Figure 5 show that the magnetic induction gradually decreases as the frequency increases,

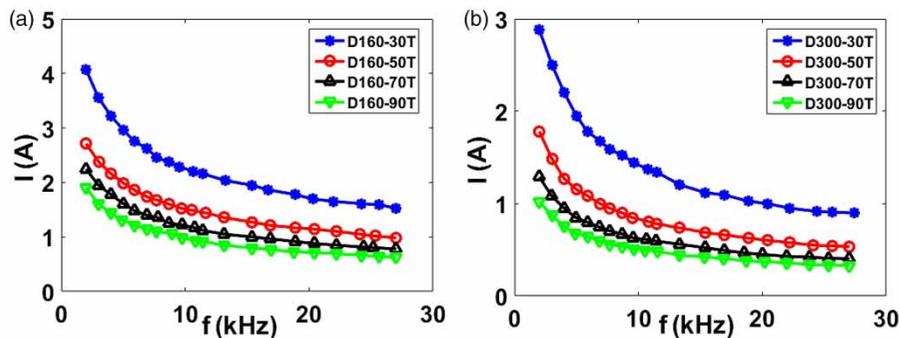


Figure 4 | Variation of current with frequency. (a) 160 diameter and (b) 300 diameter both under the turns of 30, 50, 70 and 90.

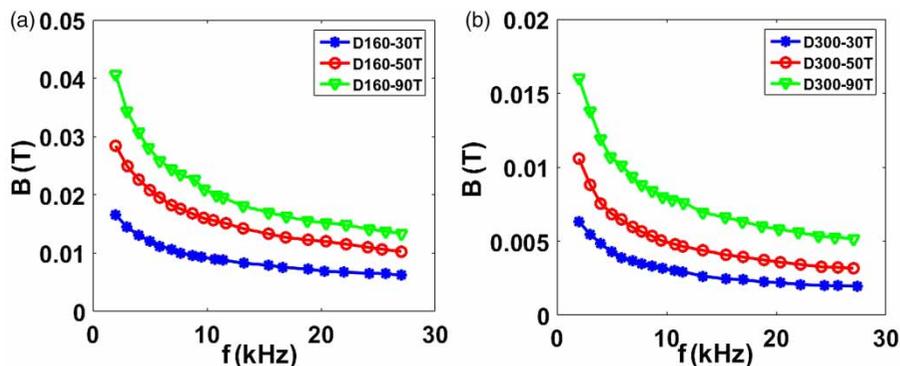


Figure 5 | Variation of magnetic induction with frequency. (a) 160 diameter and (b) 300 diameter both under the turns of 30, 50 and 90.

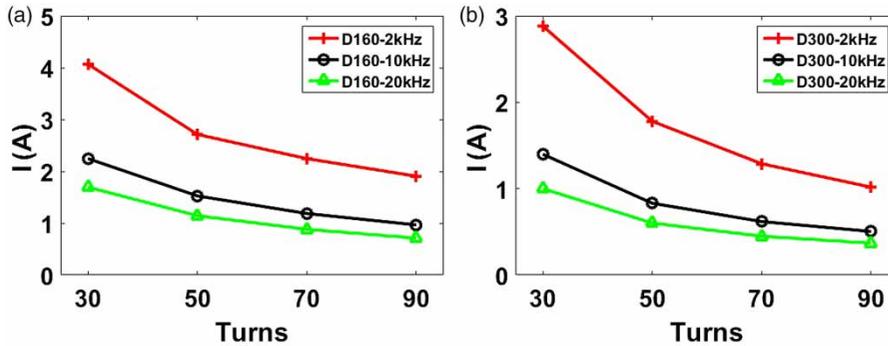


Figure 6 | Variation of current with the number of turns. (a) 160 diameter and (b) 300 diameter both under frequencies of 2, 10 and 20 kHz.

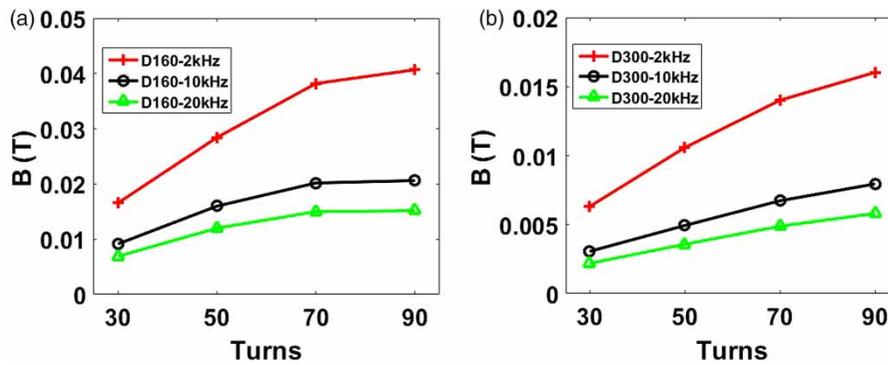


Figure 7 | Variation of magnetic induction with the number of turns. (a) 160 diameter and (b) 300 diameter both under frequencies of 2, 10 and 20 kHz.

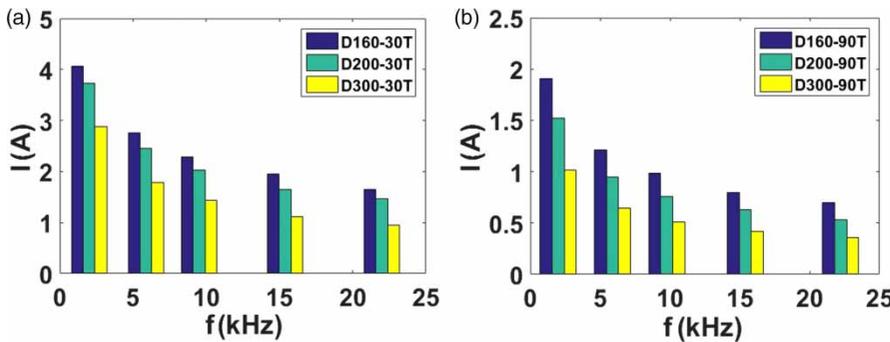
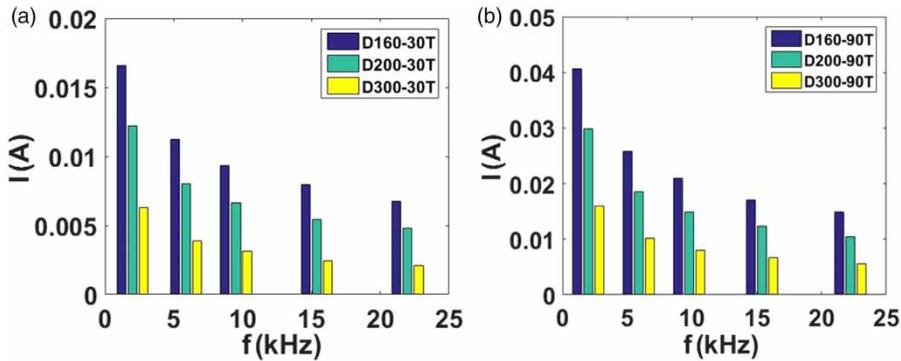


Figure 8 | Variation of current with frequency. (a) 30 turns and (b) 90 turns both under diameters of 160, 200 and 300 mm.

and the drop amplitude of magnetic induction decreases with increasing frequency. In the case of 90 turns coil and the diameter of D160 mm, the magnetic induction decreases from 0.042 to 0.017 T as the frequency increases from 2 to 27 kHz. When the frequency increases from 2 to 4 kHz, the current decreases from 0.042 to 0.031 T accordingly.

While the current decreases from 0.031 to 0.017 T, the frequency increases from 4 to 27 kHz accordingly. In different diameters and different numbers of turns, the magnetic induction shows the same variation tendency. This phenomenon can be explained by the change of current and Equation (2). The magnetic induction is influenced by



**Figure 9** | Variation of magnetic induction with frequency. (a) 30 turns and (b) 90 turns both under diameters of 160, 200 and 300 mm.

many factors, among which the current is the main factor, and the current is proportional to the magnetic induction.

#### Effect of changes in current and magnetic induction with respect to number of turns

Figure 6 shows the effect of numbers of turns on the current. As shown in Figure 6, the current in different frequencies of 2, 10 and 20 kHz decreases as the number of turns increases. As the number of turns increases, the decreased amplitude of current gradually becomes smaller. The current shows the same trend in different diameters of 160 and 300 mm. However, the actual decline of the current in the trend is approximately a linear decline, because the total impedance of the wire is increased linearly when the number of winding turns increases. The possible reason for the change of current is that the value of series resistance has an influence on the original circuit, so the total impedance with the increase in the number of turns of the coil does not increase linearly.

The effect of numbers of turns on the magnetic induction is shown in Figure 7. The magnetic induction in different frequencies of 2, 10 and 20 kHz increases as the number of turns increases. The magnetic induction shows the same trend in different diameters of 160 and 300 mm. Magnetic induction is influenced by many factors, and the relationship between the magnetic induction and turns is not just proportional. The effect of series resistance on current is also considered. Figure 7 shows the variation tendency of the magnetic induction with the turn number.

#### Effect of changes in current and magnetic induction with respect to different diameters

Figure 8 presents the current change with diameter in different frequencies. In Figure 8, it is obvious that the current value of diameter 160 mm is higher than the current value of the ones with 200 or 300 mm. The larger the diameter is, the smaller the current will be. The difference between the current caused by the change of diameter roughly remained constant when the frequency changed. This phenomenon is the same as the 30 turns and the 90 turns of the winding, as shown in Figure 8. The possible reason is that the increased impedance with the increasing diameter of the pipe is proportional to the diameter of the pipe.

Figure 9 shows the magnetic induction change with diameter in different frequencies. It is seen from Figure 9 that the magnetic induction decreases with the increasing of diameter. In other words, just as the number of turns has effects on the current, the diameter increase will cause the magnetic induction to decline. The magnetic induction is influenced by various factors, and the influence of the winding tube is not linear. The difference between the magnetic induction caused by the change of diameter is not kept constant when the frequency changes, which is different from current trends. This performance is the same as in different turns of the coil as shown in Figure 9.

Through the above research, the current is affected by factors such as frequency, turn number, diameter and so on. Magnetic induction is more complex than current. More factors need to be considered in order to determine the specific trends.

## CONCLUSIONS

The change of the current in the solenoid coil wrapped around carbon steel pipes and magnetic induction in the midpoint of the solenoid coil, with respect to each parameter, are observed in the experiment. The current is obtained by measuring the voltage across series resistance. So magnetic induction can be calculated. In order to reduce the influence of series resistance to electric current and ensure measurement reliability,  $1.18\Omega$  of the resistance is used for experimental measurements. Some of the key conclusions are summarized as follows:

1. The magnetic induction and current decrease with the increase of frequency, and the drop amplitude decreases with increasing frequency.
2. The trend of magnetic induction increases as the number of turns increases. The current in the solenoid coil decreases with the increasing number of turns, and the actual decline of the current in the trend is approximately a linear decline.
3. The trend of magnetic induction decreases as the diameter increases. The current in the solenoid coil decreases with the increasing diameter, and the difference between the current caused by the change of diameter roughly keeps constant.
4. The effect of electronic anti-fouling can be judged by the current indirectly. The power of EAFE can be guided by the current change trends.

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