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Analysis of Factors Affecting the Rotation Speed of Axial-Flux Free-Rotor Electromagnetic Stirrer

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Abstract— **In this study, a new PIC (programmable – integrated - circuit) microcontroller controlled electromagnetic stirrer is designed. The electromagnetic stirrer system consists of axial-flux permanent-magnet synchronous motor-based rotating magnetic field source (stator), heater, a cup for the liquid to be stirred and a magnetic stir bar (magnetic fish-rotor) which is immersed into the liquid to stir it by rotating with the rotary magnetic field. The rotary magnetic field source is constituted of 3 identical winding groups which are connected in star. For ensuring the rotary magnetic field, square wave-shaped voltage signals are applied to the 3 winding groups with 120° phase differences between each couple of signals. The frequency of the square waves which directly affects the stirring speed is controlled by a PIC microprocessor-based supplier circuit. Magnetic stir bar iron core is produced from a magnetically oriented sample. In this study, the parameters which especially affect the rotation speed of the electromagnetic stirrer, the effects of the magnetic stir bar size on the stirring process, the principles of the supplier circuit, the effects of the liquid parameters like volume, viscosity, etc., are studied and discussed. Our previous studies on electromagnetic stirrers were carried out for small-volume liquids and 3% Si-Fe sheet metals were used for the magnetic stir bar core. In this study, easily magnetisable and bigger size cores are used for stirring bigger-volume liquids.**

Index Terms— **Synchronous motor, Electromagnetic stirrer, Microprocessor, Viscosity.**

I. INTRODUCTION

In industrial applications, generally a couple of magnets fixed on to the rotor of a conventional electric motor are used for mixing two liquids with different densities. These types of magnetic stirrers are referred to as motorized stirrers, and stirring is realized by a magnetic stir bar which follows the rotating electromagnetic field created by the pair of magnets fixed on the motor's rotor [1]-[3]. But especially for low rotation speeds, the magnetic stir bar may leave the rotation centre and cling to one of the fixed magnets. This situation affects the stirring process negatively, in terms of extending the stirring time for a homogeneous mixture or even making it impossible. On the other hand, it's obvious that the friction between rotor and stator decreases the efficiency of the electromagnetic stirrer.

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Recently, linear or rotary magnetic stirrers have become popular for stirring process [4]-[6]. The difference between these types of stirrer and others is that in the rotary magnetic stirrer there is no physical contact between magnetic fish (rotor) and rotary magnetic field source (stator). By the rotation of the magnetic field, the magnetic fish follows the magnetic field and consequently it rotates as well. But as long as the magnetic fish is at the center of the rotary magnetic field, liquid is stirred most effectively at the center, while the effectiveness decreases moving away from the center [6].

For a homogenous mixture of liquid, magnetic fish should also follow a circular trajectory with r radius and the same center as the magnetic field, while rotating around itself as well. This movement of the magnetic fish is quite like the movement of the rotating earth as it revolves around the sun. Here, r, the radius of the circular trajectory, is chosen according to the size of the base of the cup.

In our previous study, this type of electromagnetic stirrer was designed with a PIC microcontroller controlled supplier unit [6, 7]. In that study the main disadvantage is that the stirrer cannot reach high stirring speeds. That's because the core is just simple iron, and based on this reason, the electromagnetic field is not high enough. Also, the core size and so the electromagnetic field's magnitude become more important for high-volume liquids.

However, all the parameters affecting the stirring process must be analysed one-by-one and deeply. The most important parameters to be analysed are the distance between magnetic fish and core, the number of phases, the number of turns in winding, the core's magnetic permeability, the inner resistance and self-inductance coefficient of windings, the size and top-view sectional shape of the magnetic fish, the distance between the center of magnetic field and poles of the magnetic fish, the fish's magnetic flux density, the frequency of the supplier voltage, the height of the liquid in the cup and liquid's density. It is also important to analyse the synchronization time between the phase change and the magnetic fish's adaptation time to the new magnetic field line (fish's movement on the circular trajectory while rotating around itself). If synchronization does not occur, the magnetic fish does not move off as expected. For synchronization, the magnetic fish's linear velocity becomes very important. So, the volume of the liquid and the friction force between the magnetic fish and the cup are the additional parameters which should be investigated [7].

The main purpose of the study is designing new PIC-controlled, economic and easy-to-use electromagnetic stirrers with different characteristics which allow the analysis of the parameters which affect the stirring process one-by-one, and undertaking the necessary analysis to define the optimum design parameters of the electromagnetic stirrer.

II. MATERıAL AND METHOD

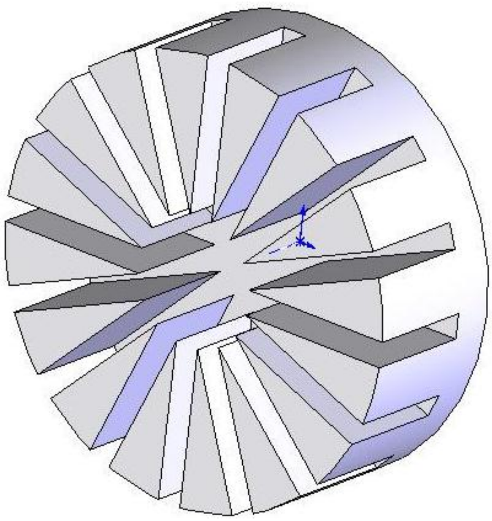
In the study, first of all, the cores of the electromagnetic stirrer are defined and bought, and their lathe processes are carried out. The cores of 2 electromagnetic stirrers are chosen as steel coded AISI1030 and AISI1050 by the American Iron and Steel Institute (AISI). 2 electromagnetic stirrers with different stator cores having different magnetic permeability are produced to enable us to see the effects of core characteristics. The chemical content of these manufactured steels is given in Table 2.1.

Steel Code	C	Si	Mn	P	S	Cr	Mo	Ni	Al	Sn	Cu
AISI 1030	0.308	0.222	0.747	0.013	0.017	0.250	0.050	0.288	0.014	0.008	0.252
AISI 1050	0.492	0.221	0.718	0.011	0.010	0.149	0.054	0.125	0.021	0.012	0.261

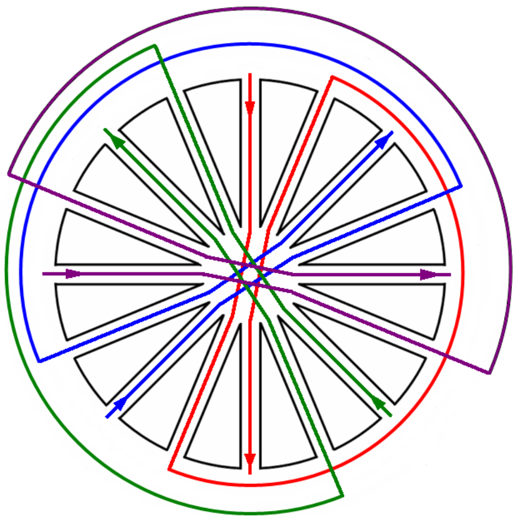
Table 2.1: Percentages of Chemical Contents in Manufactured Steels Used for Cores

Steel samples are cut and lathed for electromagnetic stirrer cores with 12 cm radius (r), and 3.5 cm height. After that, 12 separate channels with 0.5 cm width and 2.5 cm depth are opened on the cores for windings (Fig. 2.1a). After lathe treatment, just before the winding process, cores are exposed to the magnetic field for a while in order to remove the stress which may have occurred in the lathe process.

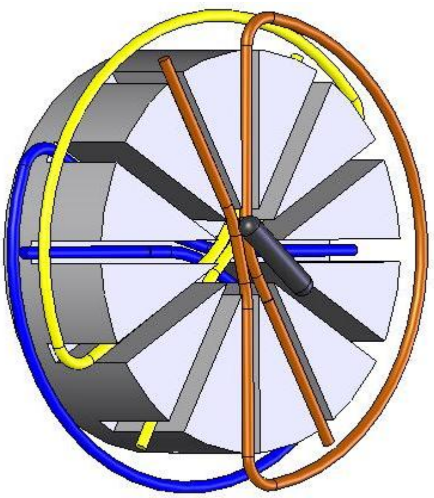
Next step, 3-phase winding groups are winded around the channels as seen in Fig. 2.1b. The number of turns of each winding group is 150, and 0.5 cm diameter copper wire is used for the windings. To each winding group, 120° phase delayed (regarding the previous winding group) sinus voltage signals are applied. Winding groups with the core and the stator of the developed electromagnetic stirrer can be seen in Fig.2.1c and Fig.2.1d, respectively.



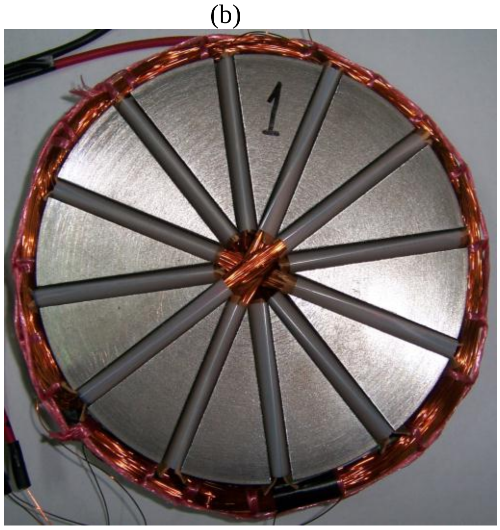
(a)



(b)



(c)

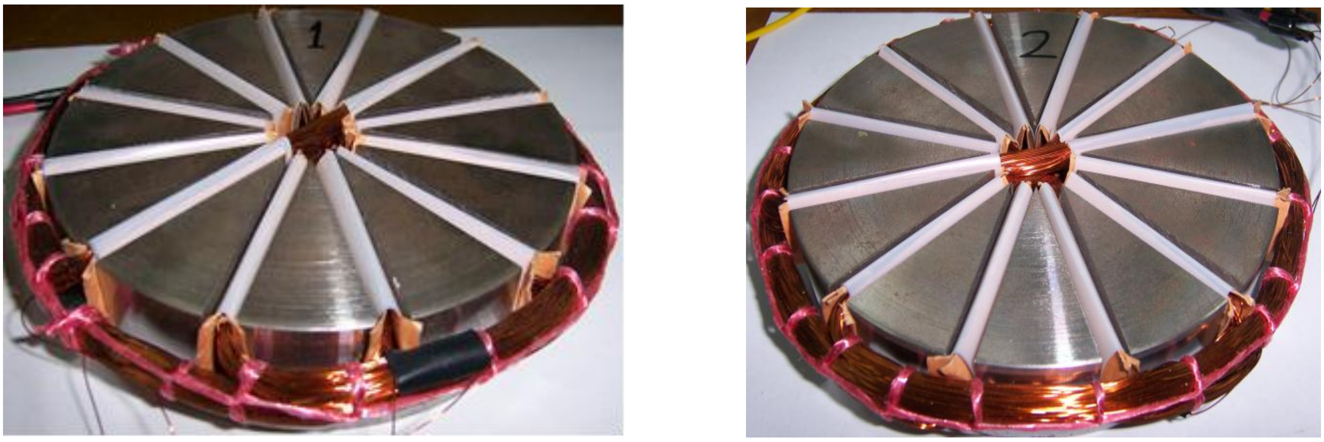


(d)

Fig. 2.1.: (a) Treated core, (b) Winding geometry, (c) Settlement of windings in the core, (d) Stator of the developed electromagnetic stirrer.

Designed and produced stators of electromagnetic stirrers with different core characteristics can be seen in Fig.2.2. The core geometries of these 2 stators is completely identical, while magnetic permeability coefficients are different. Magnetic permeability coefficient of the first electromagnetic stirrer's stator core is 1560 (Fig.2.2a), while second electromagnetic stirrer's is 1420 (Fig.2.2b).

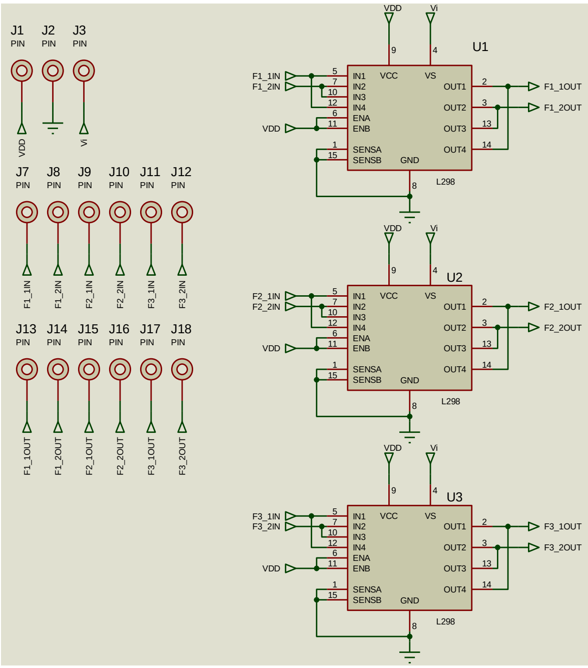
After developing stators of the electromagnetic stirrers, the design of the electronic driver circuits has been started. In the circuit, PIC16F876 is selected as the microprocessor, while L298N is selected as the driver IC (integrated circuit). For every phase, 3 ICs of L298N are responsible for driving each winding group. Thus, a current up to 3A is ensured of flowing through each winding group without any problems. An opto-isolator is used between microcontroller and L298N drivers to protect the system against short circuit and current leakage situations. For supplying the power to the electromagnetic stirrer, 9V and 24V DC power suppliers are developed to ensure a stable voltage level which is rectified and adapted from mains voltage. The last design step of the driver circuit is to design and produce the front panel with 2-line LCD screen and keypad allowing the entering of the rpm (rotation per minute) value and the starting and stopping of the stirring process. In Fig.2.3a and Fig.2.3b, ISIS Schematic view of the driver components and ISIS Schematic view of the microprocessor related components can be seen respectively. Also, the pictures from different angles of the all components placed in a packaging box can be seen in Fig.2.4a-b.



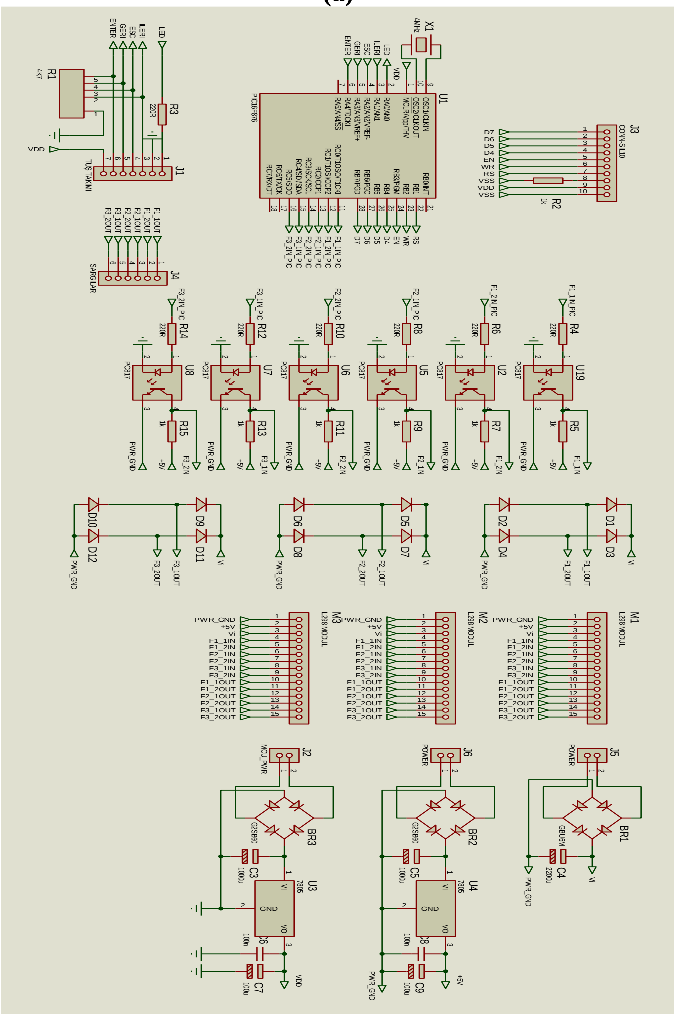
(a) (b)

Fig.2.2: (a) First electromagnetic stirrer's stator core (μ=1560), (b) Second electromagnetic stirrer's stator core (μ=1420).

The driver unit increases the rpm value of the magnetic fish step by step within a short time until it reaches the rpm value which is defined by the user. This is because the magnetic fish may not follow the rotating stator if the stator starts to rotate immediately at the defined rpm value, and may not be able to catch the stator's movements again. In the course of this rpm increasing period, the LED in the front panel is blinking, while it remains steadily ON after the required rpm is reached. The PIC16F876 microcontroller program for the driver is developed by using PIC BASIC Pro compiler software. The developed program can be seen in Appendix-1. This program contains mainly the current switching algorithms for every winding group, and also the codes for controlling and acquiring the information in the front panel. The experimental setup of the developed electromagnetic stirrers can be seen in Fig.2.5 a-b.

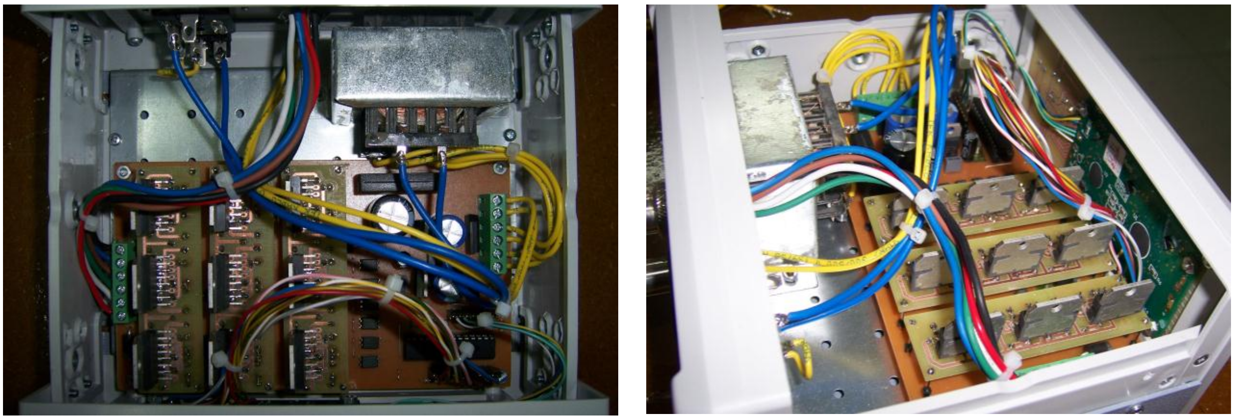


(a)



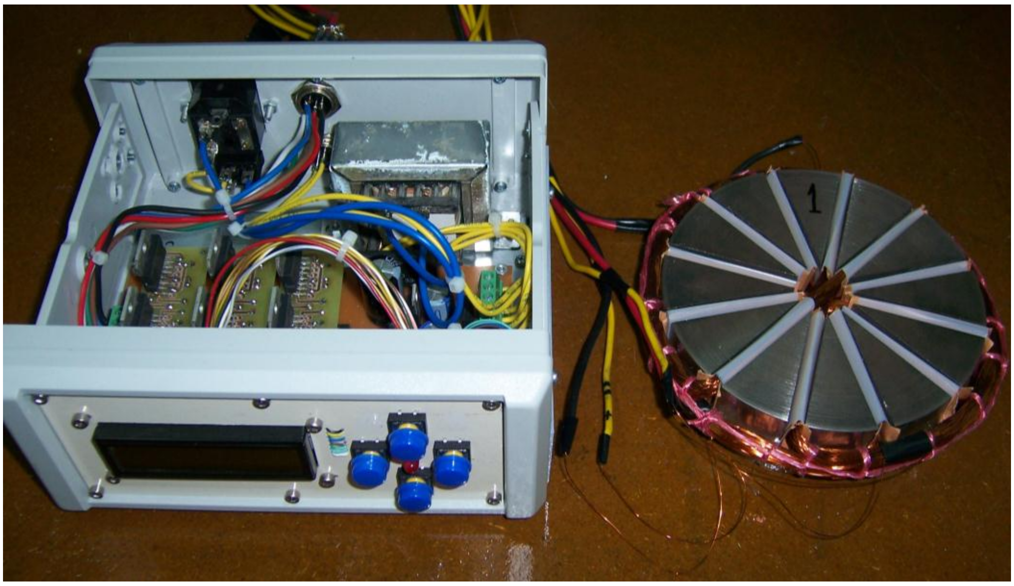
(b)

Fig. 2.3: ISIS Schematic view of the components in electronic design software- Proteus (a) driver components, (b) microprocessor related components.

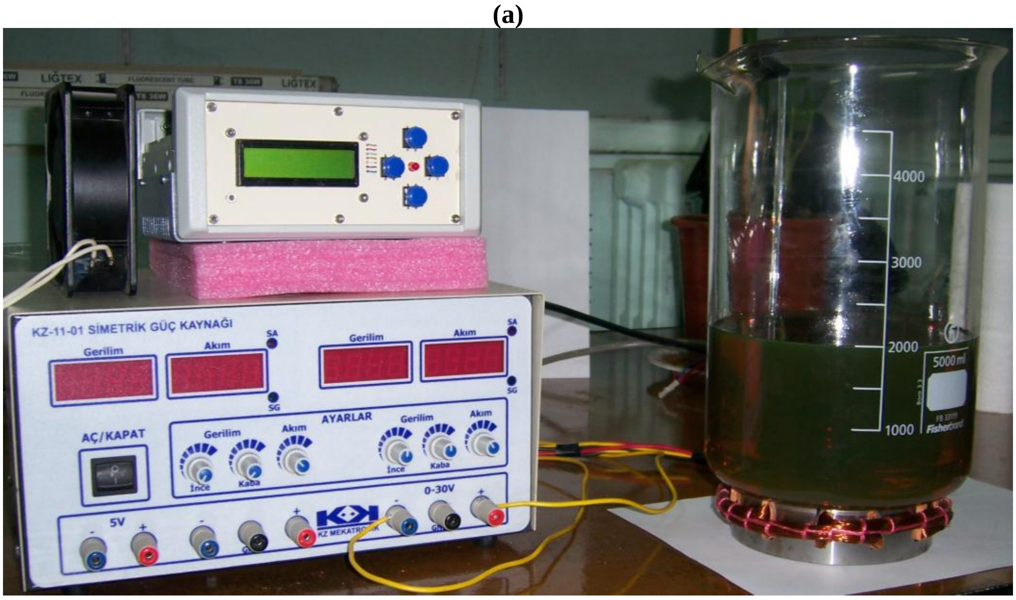


(a) (b)

Fig. 2.4: Pictures from different angles of the electronic driver unit developed for driving the electromagnetic stirrer's stator (a) from the top, (b) sideward



(a)



(b)

Fig. 2.5: The experimental setup of the developed electromagnetic stirrers (a) top view, (b) front view

In the study, essentially 3 different liquids with different density and viscosity are used with both of the electromagnetic stirrers (with different stator cores) for testing the stirring performances. For every test, rpm value is started from 100 rpm and increased until the magnetic fish is skidded on the inner wall of the cup because of the high rotation speed. Also the effect of the liquid volume on the stirring performance is analysed by increasing the liquid volume from 250 ml to 4000 ml by 250 ml steps for every test process. The numbers of turns in the winding groups, the wire diameter and the winding channel dimensions remain constant in all tests.

The magnetic fish that we have used as a rotor in our study is 1.4 cm in length, 2.04 g in mass and its magnetic flux density is B=0.981.10-3T . The movement of the magnetic fish on the core and all the parameters to be used in calculations can be seen in Fig. 2.6.

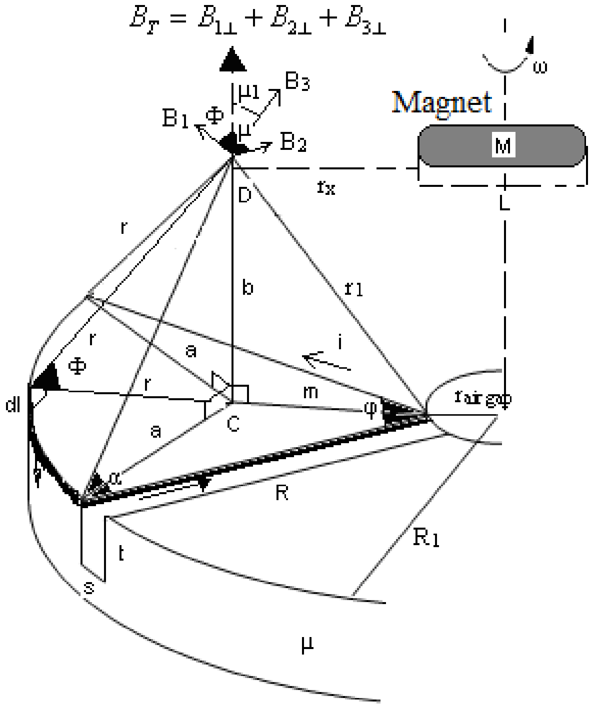


Fig. 2.6: The parameters in electromagnetic stirring process.

The parameter values of developed electromagnetic stirrers are t=2.5 cm, s=0.6 cm, R=5.2 cm, $r_{air\ gap}$=1.2 cm, r_x=3.2 cm and φ=32^0'dir. If the friction force between the magnetic fish and liquid cup is ignored (or in other terms all the magnetic energy is transferred to kinetic energy), then the angular velocity of the magnetic fish can be calculated as follows [6];

$$\omega = \sqrt{\frac{24 \times B \times B_T \times r_x^2 \times \cos\varphi}{M \times L}} \quad (1)$$

But if the friction is so high that it cannot be ignored, the energy loss due to friction can be calculated with (2).

$$W_s = \left[\mu_k (Mg + (\frac{\rho_s V_s g}{A_k} \times A) - \rho_s g V_c) \right] \times (\pi \times L) \quad (2)$$

As can be seen in Fig. 2.6, the parameters r_x (the distance between the magnetic fish and the center of the magnetic field) B (flux density of the magnetic fish), M (mass of the magnetic fish), L (length of the magnetic fish), η (viscosity of the liquid), A_k (sectional area of the magnetic fish), A (base area of the cup) and V_c (volume of the magnetic fish) don't change through the stirring process, so the total magnetic field (B_T), liquid volume (V_s) and the density of the liquid (ρ_s) are the parameters that affect the angular speed of the magnetic fish (ω).

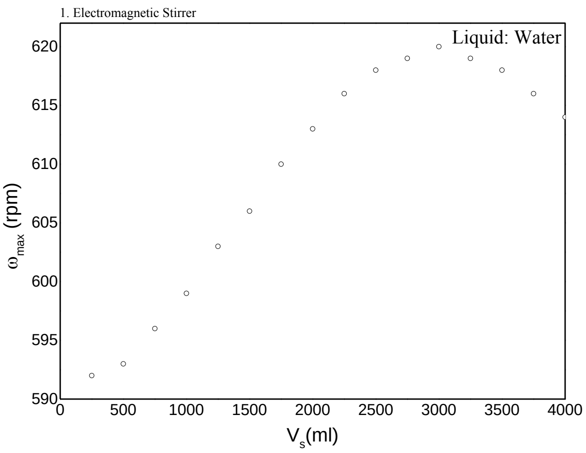
The total magnetic field (B_T) generated by the stator of the electromagnetic stirrer is calculated by (3).

$$B_T = \frac{10 \times s \times t}{n^2} \times (B_{1\perp} + B_{2\perp} + B_{3\perp}) \quad (3)$$

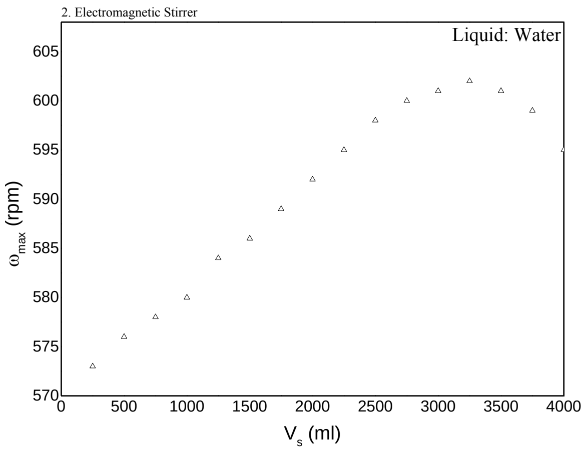
Here, s is the channel width, t is the channel depth and n is the turn number of the winding, and all these parameters are constant and never changed in the tests. $B_{1\perp}, B_{2\perp}, B_{3\perp}$ are the parameters related with the core's magnetic permeability. In our studies, two different magnetic stirrers are produced and used having cores with different magnetic permeability's. Thus, the total magnetic field (B_T) is a variable parameter in our analyses. Total magnetic fields effectuated by 1. and 2. Electromagnetic stirrers are 0.149 T and 0.138 T respectively.

III. Experimental Findings

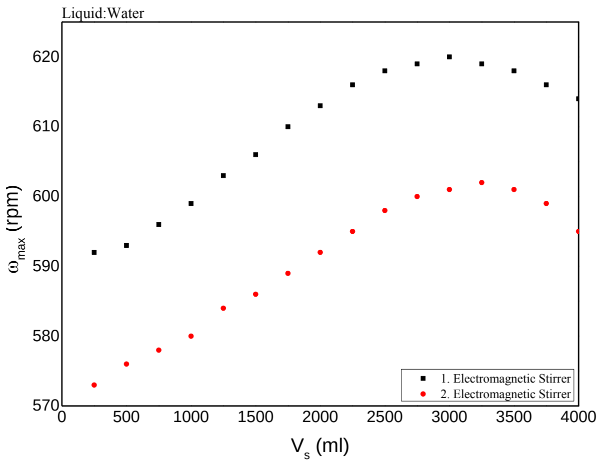
In the experimental phase of the study, first, the relationship between the liquid volume and maximum angular velocity has been investigated. For this purpose, all the parameters, except liquid volume, were kept constant. For three different liquid types, measurements were started with 250 ml and have been repeated until 4000 ml with 250 ml increments. Results are shown in graphics below (Fig.3.1a-i).


1. Electromagnetic Stirrer
Liquid: Water
ω_{max} (rpm)
V_s(ml)

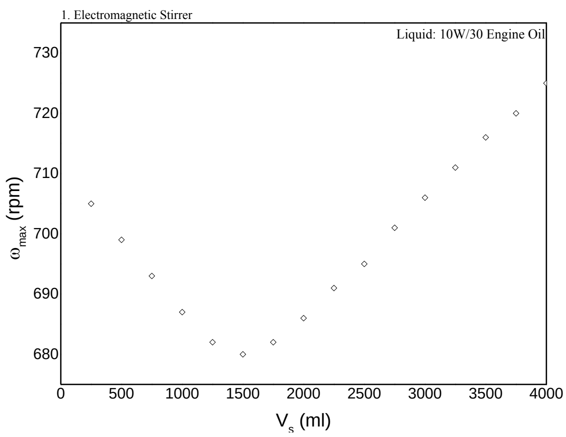
(a)


2. Electromagnetic Stirrer
Liquid: Water
ω_{max} (rpm)
V_s (ml)

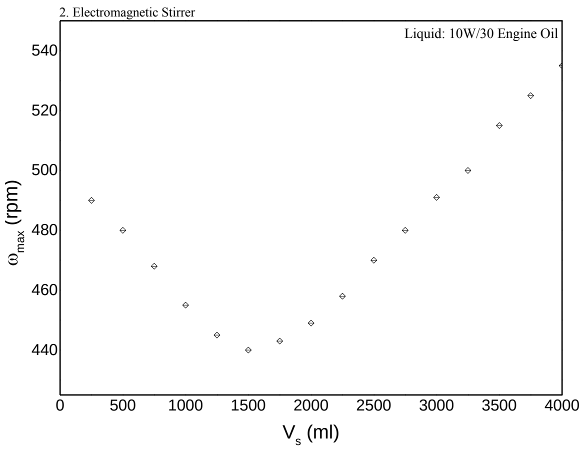
(b)


Liquid:Water
ω_{max} (rpm)
V_s (ml)
1. Electromagnetic Stirrer
2. Electromagnetic Stirrer

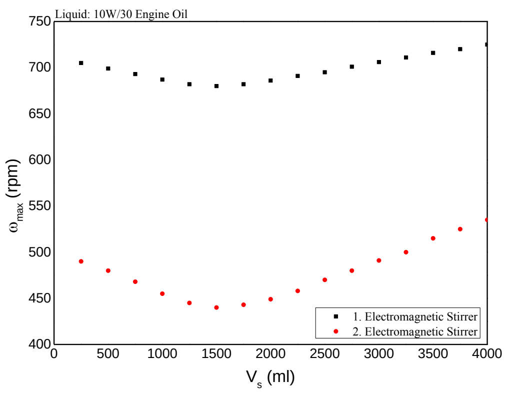
(c)


1. Electromagnetic Stirrer
Liquid: 10W/30 Engine Oil
ω_{max} (rpm)
V_s (ml)

(d)


2. Electromagnetic Stirrer
Liquid: 10W/30 Engine Oil
ω_{max} (rpm)
V_s (ml)

(e)


Liquid: 10W/30 Engine Oil
ω_{max} (rpm)
V_s (ml)
1. Electromagnetic Stirrer
2. Electromagnetic Stirrer

(f)

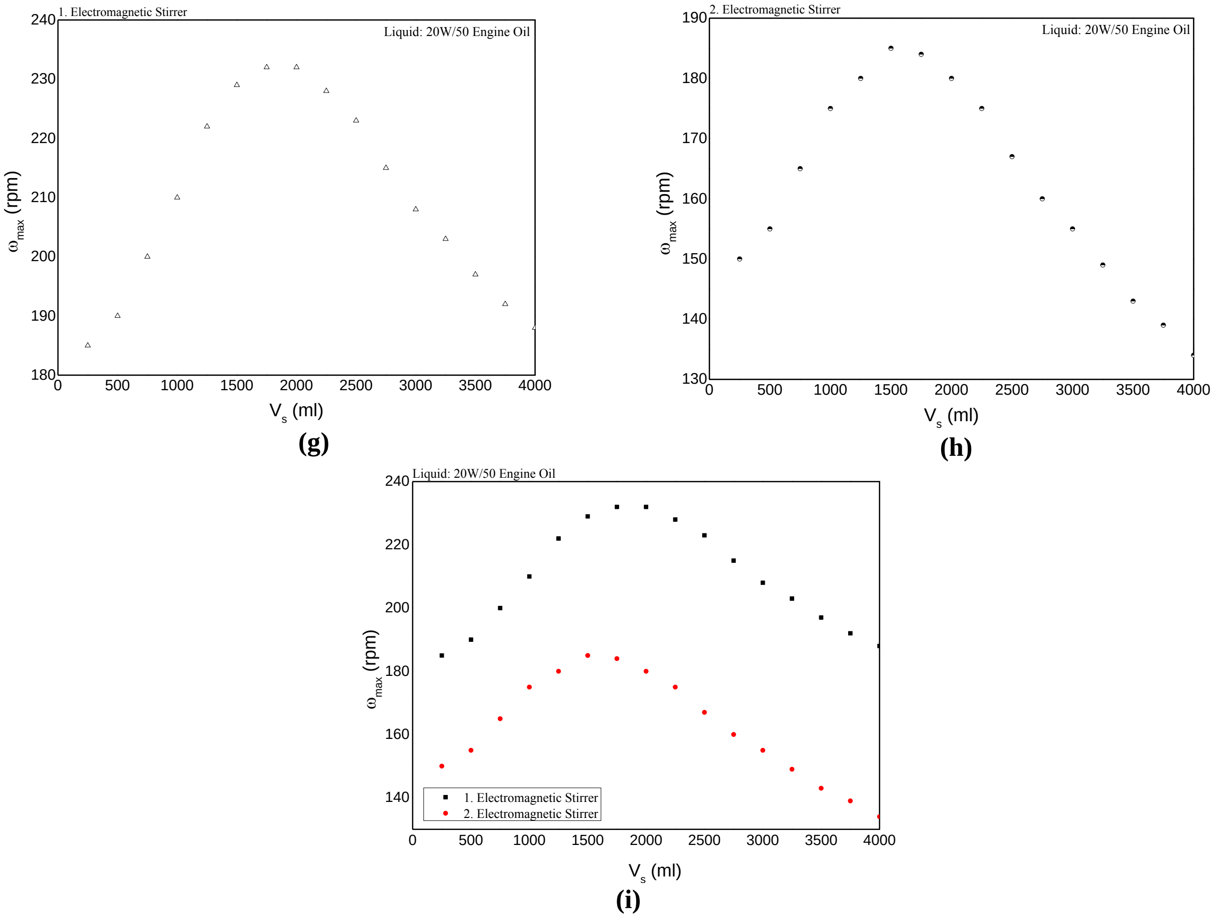


Fig. 3.1: The relationship between liquid volume and maximum angular speed (a) for water in 1st Stirrer, (b) for water in 2st Stirrer, (c) for water in both of Stirrers, (d) for 10W/30 engine oil in 1st Stirrer, (e) for 10W/30 engine oil in 2st Stirrer, (f) for 10W/30 engine oil in both of Stirrers, (g) for 20W/50 engine oil in 1st Stirrer, (h) for 20W/50 engine oil in 2st Stirrer, (i) for 20W/50 engine oil in both of Stirrers.

In the next step of our study, the relationship between density and angular velocity is investigated using liquids with different densities: water (1 g/ml), SAE 10W/30 (0.878 g/ml) and SAE 20W/50 (0.887 g/ml) types of engine oil. The relationship is defined with constant 2000 ml liquid volume and the results are shown in the graphics below (Fig. 3.2a-b).

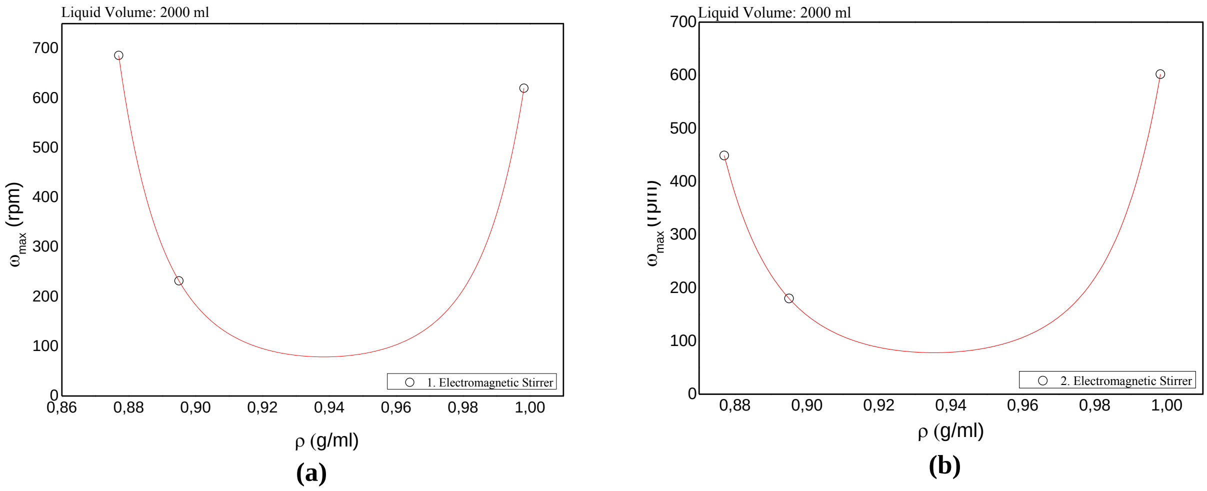


Fig. 3.2: The relationship between density and angular velocity for constant liquid volume (a) 1st electromagnetic stirrer, (b) 2st electromagnetic stirrer.

IV. Discussion

Fig. 3.1 demonstrates that increasing liquid volume causes an incremental increase in the maximum angular velocity until a certain value, after which the increasing liquid volume causes the maximum angular velocity to decrease. This phenomenon shows that the energy lost by friction (W_s) is decreased at first but starts increasing after a specified point. On the other hand, looking at (2) one can think that the increment on V_s should also make F_s and W_s increase. But with increased V_s, the magnetic fish makes contact with the cup surface and starts being exposed to a different friction coefficient. Consequently, the magnetic fish is exposed to a different friction after about 3000 ml. As a result, we can say that the friction coefficient between magnetic fish and water is smaller than the friction coefficient between magnetic fish and cup.

On the other hand, looking at the graphics related with water in Fig. 3.1a-c, it can be seen that there is a similar variation for 2 electromagnetic stirrers with different stator cores having different magnetic permeability's. This also shows that magnetic permeability has no effect on variation characteristics of the graphic. Also, looking at 20W-50 engine oil graphics on Fig. 3.1g-i, it is seen that those variation graphics are similar to the water variation graphics. Thus, we can say that the friction coefficient between engine oil and magnetic fish is smaller than the friction coefficient between magnetic fish and cup.

On the contrary, the graphics related with 10W/30 engine oil in Fig. 3.1d-f show that increased liquid volume causes a decrement on the maximum angular velocity boundary until a specified value, after which it increases the maximum angular velocity. This means the energy lost by friction (W_s) is increased at first but starts decreasing after a specified point. The reason for this variation could be explained by water pressure, depending on the water volume, forcing the magnetic fish to move to the bottom of the cup and thus change the friction coefficient. However, it is possible to say that, unlike water and 20W/50 engine oil, the friction coefficient between 10W/30 engine oil and magnetic fish is bigger than the friction coefficient between magnetic fish and the cup.

Looking at the maximum angular velocity variation against liquid density in Fig. 3.2a-b, it is demonstrated that around 0.94 g/ml density, maximum angular velocity reaches its lowest value. This condition has similar characteristics for both of the mixers and independent of the magnetic permeability of the core. In (2), it seems when the liquid density increases, it would cause W_s and consequently ω_{max} to decrease. But it should not be forgotten that when density increases, it also changes the kinetic friction coefficient, μ_k. An increase of ω_{max} above 0.94 g/ml density implies the decrease of W_s and the kinetic friction coefficient, μ_k. At that point, the relation between density and viscosity should be taken into consideration.

V. Conclusion

As result of the experiments undertaken in the scope of this study, it is proven that μ_k kinetic friction coefficient takes an active role in the variation of density and liquid volume with maximum angular velocity, depending on the position of the magnetic fish and surface roughness. For example, it is stated that on the variation of maximum angular velocity and density, it is affected by not only density but by a combined effect of μ_k and density. Also, it is stated that the most suitable liquid for developed electromagnetic mixers, among the tested samples, is 10W/30 engine oil. In addition, it is possible to say that maximum angular velocity during the mixing process depends on the geometry of the magnetic fish and on viscosity.

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Appendix I

(PIC Basic Code)

```
'@DEVICE XT_OSC,WDT_OFF,PWRT_ON
include "modedefs.bas"
DEFINE OSC 4
DATA @ $00, 3, 232
'DEFINE LOADER_USED 1
DEFINE LCD_DREG PORTB
DEFINE LCD_DBIT 4
DEFINE LCD_WRREG PORTB
DEFINE LCD_WRBIT 2
DEFINE LCD_RSREG PORTB
DEFINE LCD_RSBIT 1
DEFINE LCD_EREG PORTB
DEFINE LCD_EBIT 3
DEFINE LCD_BITS 4
DEFINE LCD_LINES 2
DEFINE LCD_COMMANDUS 2000
DEFINE LCD_DATAUS 50
LED     VAR PORTA.0
ILERI   VAR PORTA.1
ESC     VAR PORTA.2
GERI    VAR PORTA.3
ENTER   VAR PORTA.4
FAZ1_1 VAR PORTC.0
FAZ1_2 VAR PORTC.1
```

```
FAZ2_1 VAR PORTC.2
FAZ2_2 VAR PORTC.3
FAZ3_1 VAR PORTC.4
FAZ3_2 VAR PORTC.5
DEVIR   VAR WORD
DEVIRH VAR DEVIR.BYTE1
DEVIRL VAR DEVIR.BYTE0
SAYAC   VAR BYTE
BAYRAK VAR BIT
I       VAR BYTE
SAYICI VAR BYTE
KARARLI VAR BIT
INT     VAR BYTE
FARK    VAR BYTE
BEKLE   VAR WORD
A       VAR WORD
B       VAR WORD
C       VAR WORD
D       VAR WORD
G       VAR WORD
H       VAR WORD
J       VAR WORD
K       VAR WORD
L       VAR WORD
E       VAR WORD
F       VAR WORD
GECIK   VAR WORD
X       VAR WORD
CALL    INITIAL
LCDOUT $FE, $80,"ELEKTROMANYETiK"
LCDOUT $FE, $C0," KARISTIRICI   "
READ 0, DEVIRH
READ 1, DEVIRL
FOR I=0 TO 15
LED=1
PAUSE   50
LED=0
PAUSE   50
NEXT I
EN_BAS:
LED=1
SAYAC=0
BAYRAK=0
LCDOUT $FE,1
LCDOUT $FE,$80,"<Devir Say", $AA, "s",       $AA,"> "
LCDOUT $FE, $C0,"<",#DEVIR," rpm>"
BASLA_LCD:
IF ILERI=1 THEN
ILERI_CEK:
IF BAYRAK=0 THEN
PAUSE   50
IF ILERI=1 THEN
SAYAC=SAYAC+1
IF SAYAC=75 THEN BAYRAK=1
GOTO ILERI_CEK
ENDIF
ENDIF
PAUSE 50
DEVIR=DEVIR+1
IF DEVIR>3000 THEN DEVIR=3000
LCDOUT $FE, $C0,"<", #DEVIR," rpm>"
GOTO BASLA_LCD
ENDIF
IF GERI=1 THEN
GERI_CEK:
IF BAYRAK=0 THEN
PAUSE   50
IF GERI=1 THEN
SAYAC=SAYAC+1
IF SAYAC=75 THEN BAYRAK=1
GOTO GERI_CEK
ENDIF
ENDIF
PAUSE   50
DEVIR=DEVIR-1
IF DEVIR<100 THEN DEVIR=100
LCDOUT $FE, $C0,"<",#DEVIR," rpm>"
GOTO BASLA_LCD
ENDIF
IF ENTER=1 THEN
PAUSE   25
ENTER_CEK:
IF ENTER=1 THEN ENTER_CEK
GOTO KARISTIR
ENDIF
BAYRAK=0
SAYAC=0
GOTO BASLA_LCD
KARISTIR:
LCDOUT $FE,1
LCDOUT $FE,$80,"Haz",$AA,"rlan",$AA, "yor..."
WRITE 0, DEVIRH
WRITE 1, DEVIRL
PAUSE   1000
LCDOUT $FE, 1
LCDOUT $FE, $80, #DEVIR," rpm ile"
LCDOUT $FE, $C0,"kar",$aa,"st",$aa,"r", $aa, "l",$aa,"yor..."
GOTO HESAPLA
DURDUR_BAS:
IF ESC=1 THEN DURDUR
GOTO DURDUR_BAS
DURDUR_LCD:
LCDOUT $FE, 1
LCDOUT $FE, $80,"KARISTIRMA"
LCDOUT $FE, $C0,"DURDURULUYOR"
PAUSE   1000
GOTO DURDUR
'*******************************
HESAPLA:
FARK=150
A=50000/DEVIR
B=DEVIR*A
C=50000-B
D=C*10
E=D/DEVIR
G=E*DEVIR
H=D-G
J=H*10
K=I/DEVIR
F=A*100
F=F+E*10
F=F+K
GECIK=F
X=50000
IF DEVIR>300 THEN X=25000
FARK=150
SAYICI=0
KARARLI=0
FAZ1_1=1
FAZ2_2=1
FAZ3_1=1
PAUSE   1000
BASLA:
IF ESC=1 THEN DURDUR_LCD
FAZ3_1=0
FAZ3_2=1
PAUSEUS   X
PAUSEUS   X
FAZ2_2=0
FAZ2_1=1
PAUSEUS   X
PAUSEUS   X
FAZ1_1=0
FAZ1_2=1
PAUSEUS   X
PAUSEUS   X
FAZ3_2=0
FAZ3_1=1
PAUSEUS   X
PAUSEUS   X
FAZ2_1=0
FAZ2_2=1
PAUSEUS   X
PAUSEUS   X
FAZ1_2=0
FAZ1_1=1
```

```
PAUSEUS   X
PAUSEUS   X
IF X<GECIK THEN
LED=1
GOTO BASLA
ENDIF
IF INTCON.2=1 THEN
INTCON.2=0
TOGGLE LED
x=x-1
IF X>1000 THEN X=X-1
IF X>1660 THEN X=X-1
IF X>3500 THEN X=X-1
IF X>4000 THEN X=X-2
IF X>4500 THEN X=X-3
IF X>5000 THEN X=X-4
IF X>7500 THEN X=X-5
IF X>10000 THEN X=X-6
IF X>12500 THEN X=X-7
IF X>15000 THEN X=X-8
IF X>20000 THEN X=X-9
IF X>30000 THEN X=X-10
ENDIF
GOTO BASLA
DURDUR:
LED=1
FAZ1_1=0
FAZ1_2=0
FAZ2_1=0
FAZ2_2=0
FAZ3_1=0
FAZ3_2=0
GOTO EN_BAS
INITIAL:
TRISC=0
TRISB=0
PORTB=0
PAUSE   20
LCDOUT $FE, 1
TRISA=%11111110
OPTION_REG=%10000000
ADCON1=6
SAYICI=0
KARARLI=0
FARK=150
RETURN
```

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