Design and development of a new pump based on linear induction motor

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In this study a new pump based on the performance of linear induction motor was designed and developed to pump chemical liquids and agrochemicals. In this pump the secondary part of linear induction motor was substituted with liquids. The results of the experiment showed that pumping efficiency of the designed and developed pump depends on the electric conductivity of the liquid which is used in the secondary part of the pump.

Key words: linear induction motor, magnetic pump, agrochemicals, electric conductivity

Introduction

Electric motors are devices that convert electric power into mechanical power. Electric motors classified as induction or synchronous motors. Synchronous motors turn at a speed that is governed by the frequency of the electrical voltage and the number of poles but is independent of motor load. Conversely, loading of induction motors causes slippage which in turn causes the rotor to turn slower than the synchronous speed. Electric motor components included two important parts as stator and rotor. The stator includes electrical windings on a laminated magnetic core. The windings are arranged to provide at least two electrical poles, that is, a north and a south pole. Electric current flowing through the windings produces a magnetic field across a rotor, which rotates with the motor shaft (Chapman, 1991; Fitzgerald *et al*., 1998).

Since invention of induction motors, their role in the present civil life is increasing, especially in the process of automation in industrial and modern agricultural activities (Stout, 1989). Linear induction motor (**LIM**) is a kind of

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electric motor that directly converts electric power into linear movement. In a **LIM** the stator and rotor of the electric motor are transformed to flat components thereafter are referred to as primary and secondary parts of the **LIM**, respectively (Bradley, 1994). **LIM** is very applicable in the separator devices, vibrators, laboratories, robots, electrical saws, electrical hammers etc (Laith, 1987; Yamada, 1986). In **LIM,** electric power was converted into the linear movement of a solid secondary part. Now, the question is whether it is possible to convert the electric power into the fluid power by submitting the liquid secondary part instead of solid secondary part. In this case, new applications of this new design would be found. Some of these new applications are pumping of chemical liquids such as acids and bases; agrochemicals such as fertilizers, pesticides and other growth regulators; edible liquids in agricultural processing industries such as lemon juice, vinegar etc.

Genin and Krasnoshchekova (1990) studied the hydrodynamic and heat exchange of a conducting fluid in a tube within a longitudinal magnetic field. Stanislaw (1998) studied the mathematical analysis of induced magneto hydrodynamic pressure to fluids. Thompson (1998) studied the effect of magnetically induced heating in ferromagnetic fluids. Roach (2000) invented an especial kind of magnetic pump that circulated the liquid in closed circuit in order to create especial pulses. Lee (2000) invented a magneto hydrodynamic micro pump which used for pumping liquids in micro fluid systems. There has not been much study, however, on the investigation of the behavior of the fluids in the magnetic fields.

The main objective in this research was to answer the two following questions: (1) Is it possible to convert electric power into fluid power by using the **LIM** as a pump? And (2) If the answer of the first question is positive, whether the theoretical background of **LIM** with a solid secondary part can be used for **LIM** with a liquid secondary part as a pump or total changes is required?

Materials and methods

A **LIM** with liquid secondary part was as a pump designed and developed in order to investigate the possibility of converting the electric power into fluid power using the new pump. Some kinds of chemical liquids and agrochemicals were studied. The values of applied force to the liquids were calculated theoretically and experimentally. Based on the results of experimental and theoretical methods, similarities between theoretical equations of **LIM** with solid secondary part and **LIM** with liquid secondary part were determined.

Theoretical background of LIM

A schematic diagram of a dipole and six-slot **LIM** is shown in Fig. 1. There are air gaps between primary and secondary parts of the **LIM**. The primary part is surrounded by a magnetic field with two poles (one the north pole and the other the south pole). The secondary part in this case is made from solid metal.

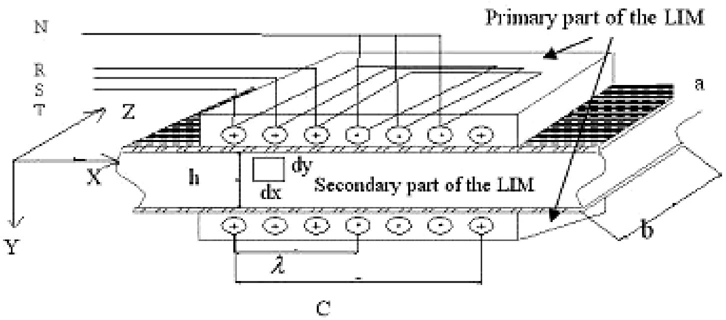

Fig. 1. Illustration of a LIM.

Assuming a three-phase voltage has been applied to the primary part of the **LIM**, a three-phase primary part current is flowing. This current produces a magnetic field which is moving in the speed of the magnetic field's movement is given by (Leander and Morgan, 1987):

$$U_S = \lambda f \tag{1}$$

Where U_S is the speed of magnetic field in meters per second, f is the system frequency in hertz and λ is the wavelength (distance between two poles) in meter.

This magnetic field passes over the secondary part and induces a voltage in it. Consequently the secondary part moves between plates of the primary part. The voltage induced in the secondary part of the **LIM** depends on the speed of the secondary part relative to the magnetic fields. Since the behavior of a **LIM** depends on the secondary part's voltage and current, it is often more logical to talk about this relative speed. The term that used to describe this relative motion is slip, which is relative speed, expressed on a per-unit or percentage basis. That is, slip is defined as (Leander and Morgan, 1987):

$$S = (U_S - U)/U_S \tag{2}$$

Where U is the speed of the secondary part in meters per second.
The speed of the secondary part can be expressed in terms of speed of the primary part and slip as follows:

$$U = U_S(1-S) \tag{3}$$

Assuming the imaginary element is moving in direction X axis with constant speed, as shown in Fig.1, the induced voltage in the element is given by (Leander and Morgan, 1987):

$$e_{ind} = BSU_S b \tag{4}$$

Where e_{ind} is the voltage of secondary part in volt, B is the magnetic flux in webers per square meter, known as teslas and b is the width of the primary part, measured in meter.

The magnitude of the current density in the element due to the induced voltage is calculated using following equation (Gieros, 1994):

$$j_e = \frac{\sigma e_{ind}}{b} \tag{5}$$

Where j_e is the current density in the element and σ is the electric conductivity of the secondary part.

At the startup of the **LIM**, the slip $S = 1$ and speed of the secondary part $U = 1$, thus current density has its maximum value. If the speed of the secondary part increased up to the speed of the magnetic field U_S, the slip, current density and induced voltage would be zero. Thus secondary part of the **LIM** could be moved with the speed which is lower than the speed of the magnetic field. Assuming the secondary part having speed U and current density j, the applied force on the element can be calculated by using the following equation (Gierops and Piech, 2000):

$$df = B^2 \sigma S U_S b\, dA \tag{6}$$

Where dA is the differential area of the element

The induced force on the secondary part of the **LIM** is obtained as:

$$F = \int_{y=-\frac{h}{2}}^{\frac{h}{2}} \int_{x=0}^{\lambda} B^2\, \sigma S U_S\, b\, dx\, dy \tag{7}$$

Waveform of induced current goes through its sinusoidal variation, consequently the magnetic flux goes through a full sine wave, and described as (Gierops and Piech, 2000):

$$B = B_m \sin(\omega t + \varphi) \tag{8}$$

Based on equation (7) and considering the average value of amplitude of magnetic flux wave as $\frac{B_m}{\sqrt{2}}$, the average induced force on the secondary part of the **LIM** can be found as (Gierops and Piech, 2000):

$$F_{ave} = \frac{B^2{}_m}{2} \sigma U_S S b \lambda h \qquad (9)$$

Where h is the height of the primary part in meter.

By dividing each terms of equation (9) into cross-sectional area of the secondary part on the parallel side to Y-Z plane, the induced pressure on the secondary part of the **LIM** is calculated as (Gieros, 1994):

$$P = \frac{B_m^2}{2} \sigma U_S S \lambda \qquad (10)$$

By multiplying induced force on the secondary part by the speed of the secondary part, the output power of the **LIM** can be calculated using the following equation (Gieros, 1994):

$$P_o = \frac{B^2{}_m}{2} \sigma U^2{}_S S (1 - S) b \lambda h \qquad (11)$$

The above equations indicate the theoretical background of **LIM** with solid secondary part.

New pump construction

With design specification and cost limitations in mind; a pump based on the **LIM** was designed and developed (Fig. 2). Pump components and specifications included primary and secondary parts.

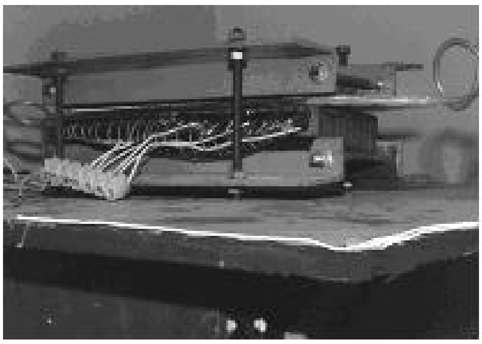

Fig. 2. Designed and developed pump.

The winding of the secondary part of the designed and developed pump is illustrated schematically in Fig. 3.

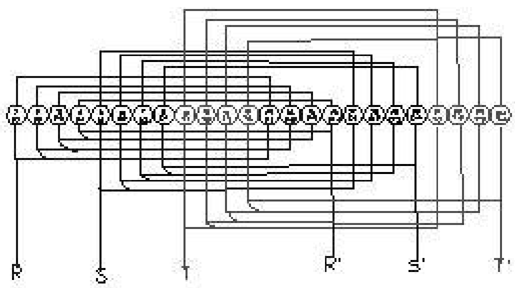

Fig. 3. Illustration of the winding of the primary part.

The liquid secondary part is shown in Fig. 4. It uses a flat glassy channel for passing liquids between the plates of the primary part.

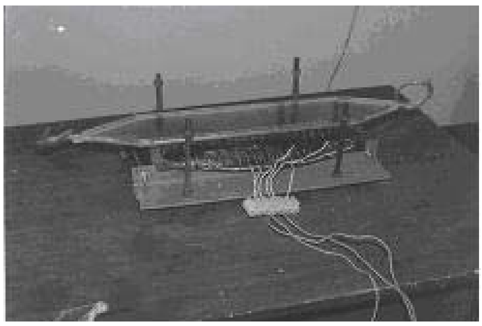

Fig. 4. Glassy channel in the secondary part of the pump.

Two graduated vertical tubes are connected vertically at the beginning and end points of the glassy channel as shown in Fig. 5.

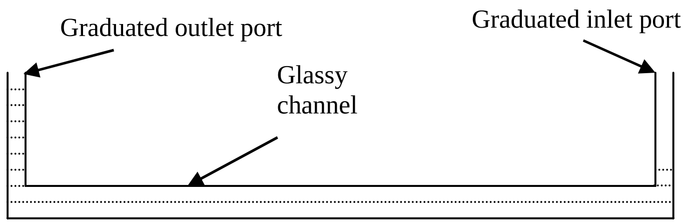

Fig. 5. Measurement of the induced pressure on the liquid secondary part.

The difference in pressure which exists at the beginning and end points of the glassy channel due to liquid flow from one end of the glassy channel to the other end can be observed by the level of liquid rise in the inlet and outlet ports. Table 1 shows the specifications of the designed and developed pump.

Table 1. Specifications of the designed and developed pump.

No	Parameters	Quantity	No	Parameters	Quantity
1	Number of slots	24	11	Pole pitch (cm)	36
2	Frequency (Hz)	50	12	Air gap (mm)	2
3	Input voltage (v)	220, 380	13	Length of primary part (*a*) (cm)	39
4	Number of Poles	2	14	Width of primary part (*b*) (cm)	12
5	Number of turns in each slot	65	15	Height of primary part (*h*) (cm)	5
6	Number of coils in each pole	4	16	Weight of primary part (kg)	20
7	Number of turns in each pole	260	17	Magnetic saturation point (teslas)	1.6
8	Wire diameter (mm)	0.95	18	Flux density in each pole (teslas)	0.8
9	Distance between two slots (cm)	1	19	Current (Amp)	15
10	Coil pitch (cm)	18	20	Power (Hp)	6

Experimentation

Performance of the designed and developed pump with liquid secondary part was evaluated during experiment for its pumping capability. In this study, some kinds of chemical liquids such as acids and bases; and agrochemicals such as fertilizers, pesticides and other growth regulators were selected. The performance of the designed and developed pump evaluated for all selected liquids. Based on the difference in level of liquid rise in the inlet and outlet ports, the induced pressure on the secondary part of the pump was calculated.

Results and discussion

The results of the experiment showed that it is possible to convert electric power into fluid power by using the pump based on **LIM** with liquid secondary part. The values of measured induced pressure on the liquid secondary part of the pump derived by experimental method and those calculated based on theoretical method are shown in Table 2.

Table 2. Calculated and measured induced pressure on the secondary part of the pump.

Liquid	Coefficient of electric conductivity $(\Omega m)^{-1}$	Calculated induced pressure (pa)	Measured induced pressure (pa)
Industrial hydrogen chloride (HCL)	70.92	588	520
Sulfuric acid	39.06	323.9	290
Sodium hydroxide	25.6	212.3	180
Potassium hydroxide	54.05	448.3	410
Mercury	106	8.2×106	Very high
Nitrate fertilizer	5.2	43	29
Phosphate fertilizer	4.1×10-3	0.03	Very low
Phosphate fertilizer + 1.0% HCL	8.1	67	40
Potash fertilizer	2.2×10-3	0.018	Very low
Potash fertilizer + 1.0% HCL	4.3	35	20
Malathion pesticide	3.5×10-4	2.9×10-3	Very low
Malathion pesticide + 1.0% HCL	1.5	12.5	9.8
Phosalone pesticide	2.1×10-5	1.74×10-4	Very low
Phosalone pesticide + 1.0% HCL	1	8.3	9.8
Azinphos pesticide	2.1×10-5	1.74×10-4	Very low
Azinphos pesticide + 1.0% HCL	1	8.3	9.8
Dizinon pesticide	8.1×10-5	6.7×10-4	Very low
Dizinon pesticide + 1.0% HCL	1	8.3	9.8

The calculated induced pressure (P_{cal}) on the secondary part has the following relationship with the measured (P_{mea}) induced pressure on the secondary part:

$$P_{cal} = 2.05880 + 1.11689\,P_{mea} \tag{12}$$

With R^2 = 0.998.

High coefficient of determination indicates that the calculated values of induced pressure on the liquid secondary part of the pump are in good agreement with the values measured in the experiment. Therefore the theoretical background of the **LIM** with solid secondary part is valid for modeling the behavior of the **LIM** with liquid secondary part.

The results indicate that the induced pressure on the liquid secondary part of the pump is directly proportional to the coefficient of electric conductivity of the liquids. The induced pressure on the liquids with high coefficient of electric conductivity is higher than those with lower coefficient of electric conductivity. Therefore, coefficient of electric conductivity is the most important property of hydraulic fluid in the new pump based on **LIM**.

Consequently the efficiency of the pump with liquid secondary part increases with coefficient of electric conductivity of the liquids.

Conclusions

1. It is possible to convert electric power into fluid power by using the **LIM** with liquid secondary part as a pump.
2. The theoretical background of the **LIM** with solid secondary part is valid for modeling the behavior of the new pump based on the **LIM**.
3. The induced pressure on the liquid secondary part of the pump is directly proportional to the coefficient of electric conductivity of the liquids.
4. A hydraulic fluid using the new pump based on the **LIM** is more efficient for liquids with high coefficient of electric conductivity.

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