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Control, Intrumentation, and Measurements

Communication System and Techniques

Development of the Miniaturised Electromagnetically Driven Pump for *flow injection analysis (FIA)*

Hiskia*, Nana Subarna†

* Puslitbang Telkoma, LIPI, Jl. Cisitu No. 21/154D Bandung 40135
Phone (022) 250 4661, Fax. (022) 250 4659, e-mail : hiskia_sirait@yahoo.com
† Institut Teknologi Nasional (ITENAS), Jl. KHP. Hasan Mustafa No. 23 Bandung 40124
Phone (022) 727 2215, Fax. (022) 720 2892, e-mail : nana@elka.ee.itb.ac.id

Abstract – **In this paper, specially designed constant and rippleless flow miniature planar pumps with electromagnetic driven actuators were developed. A novel approach in this project was the incorporation of electronic control of the pumps to achieve an accurate four phase pumping process. Four pumps were interconnected as a single pumping module according to the principles of rippleless pump. The miniaturised 4-phase pump has been evaluated and has the following specifications: suitable for liquid, self-priming under the applied conditions, low power consumption (about 10 watt), DC power supply (7.5V to 11 volts) square wave signal, flow rate 1.5 to 3.5 ml min^{-1}, chemical inertness, low maintenance, and low cost. The miniaturised electromagnetic pumps described in this research were purpose-designed for the flow injection analysis measurement. However, it is possible they could also be employed in other microanalytical applications such as μTAS.**

Keywords– Miniaturised pump, micropump, Electro-magnetic actuation, sensor, FIA, μTAS

I. INTRODUCTION

Micro Total Analysis System (μTAS) are miniaturized chemical analyzer in which all necessary components are integrated [1]. In developing a μTAS, design and fabrication of suitable microfluid components (micropumps, microchannels, microvalves, reaction chambers, filters and mixers) is an essential step toward the integrated system. For a fully functional system careful selection of suitable pumping components is essential.

Typical flow injection analysis (FIA) systems employ peristaltic pumps, which give a continuous delivery rate for all reagents, with sample and reagent delivery ratios controlled by varying the pump tubing size. These pumps are large, and pump tubing may require daily change for some reagents. Many applications, including in situ wastewater analysis, would benefit from a reduction in pump size, weight, maintenance, and power requirements. Constant and rippleless flow is required in chemical analysis systems, because the ripple causes a noise at the detector [2].

The specific goals of this project were to design and fabricate an electronically controlled miniaturised pump to deliver a constant flow rate through the flow cell developed. The pumps system is part of a modular miniaturised chemical analysis system (*μTAS*) for the detection of multiple species in liquid media developed by the authors.

Four pumps were interconnected as a single pumping module according to the principles of rippleless pump [3]. The pump consisted of a rare earth magnet type NF0635 (diameter 3 mm, 9 mm length) and solenoid driver as the actuator, a stack of five layers as the pump body, and stainless steel tubing (ID 1 mm). The pump body consisted of polycarbonate for the first layer, a thin silicone rubber diaphragm membrane for the second layer, polycarbonate as pump main volume for the third layer, polymer (silicone) valves for the fourth layer, and polycarbonate body and tubing connection as the fifth layer.

II. SPECIFICATION AND DESIGN OF THE MINIATURISED ELECTROMAGNETIC PUMP

The pump for this research was required to meet the following specifications:

a) Robust
b) DC voltage operated
c) constant and rippleless flow at outlet

d) fluid volume : 100 µl
e) flow rate : 2 to 4 $ml.min^{-1}$
f) Type of solution : aqueous-based
g) Operating temperature : up to 40 ^0C

Several different types of micropump were considered for use in this present research. However, silicon based pumps such as piezoelectric, thermopneumatic, electrostatic, and bimetallic only develop small flow-rates in the range of 8 µl to 350 $\mu l.min^{-1}$ [3]. They are also fragile and so are not suitable for the flow cell developed.

In addition, electrostatic actuation was rejected for it may have problems firstly with charge accumulation in the dielectric where the two charged surfaces make contact, and secondly the electrostatic drive will not work in a conductive fluid such as water. Magnetic actuation may be an attractive alternative (see for example [4], but an external electromagnetic drive approach was chosen because of its ease of use and practicality in controlling the valve actuator. Compared to electrostatic actuators, electromagnetic actuators typically can be operated at substantially smaller voltages but with larger driving currents and have the potential to generate larger forces.

In the design of the miniaturised pump, there were three essential components which required special consideration, namely, the actuator, the diaphragm, and the check valves. Diaphragm mechanisms provide reliable pumping performance though they often suffer fluctuations in flow rates. The mechanism is, however, adequate for generating a stable flow at low flow rates.

In this present research, the pump was of the reciprocating type and consisted of three main building blocks: an electromagnetically driven actuator, a pump chamber with a flexible pump membrane which acted as a capacitor (C), and passive circular silicon based check valves.

The pump functioned by means of a rare earth magnet driven piston pressing or releasing a diaphragm, which was integrated with dual check valves. Due to the deflection of the pump membrane, the volume of the pump chamber changed. By means of the two valves, the liquid was periodically sucked in (through one valve) and forced out (through the other valve), thus creating unidirectional flow.

2.1 Pump actuator Principles

Magnetic actuators [5, 6] are characterised by large deflections, high efficiency, large driving forces, simple fabrication, and low cost. The actuator selected by the author relied on the interaction between a permanent rare earth magnet (NF0635, Neodymium Iron Boron grade N35) and a magnetic field generated by an electric current circulating in a microcoil.

The physical action involved in the operation of any electromagnetic device is the conversion of electric energy into work by motion of a rotor, armature, or plunger in such a way as to change its flux linkage, and thereby induce a voltage in a current-carrying coil. This energy will include, besides that converted directly from the electrical to the mechanical form by the motion, that made available by any change in stored energy of the magnet by the motion.

2.2 Diaphragm design parameters

An analysis of the diaphragm deflection characteristic is essential to understanding the operation of the micropump.

- Diaphragm material and thickness

The pump membrane acts as a capacitor (Figure 1) which stores a volume, related to a pressure drop. The membrane capacitance, however, shows a strong non linear behaviour for large centre displacements [7].

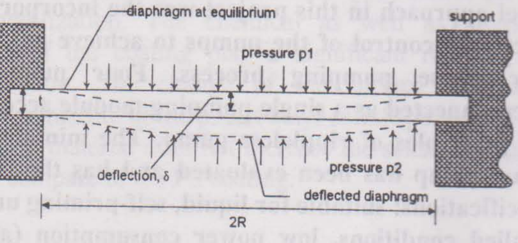


Figure 1. A diaphragm. Its deflection under a pressure difference is used for sensing or as an actuator [8]

The diaphragm membrane can be considered as a thin disk deflecting when there is pressure difference Δp applied across its two surfaces. Figure 1. shows a diaphragm of radius R and thickness t. A pressure difference $p = p_1 - p_2$ acts across it. The deflection δ, a function of applied pressure, can be calculated using the load deflection relationship of a disk diaphragm (Equation 1). The deflection characteristics are decided by various parameters such as material constants (in particular, Young's modulus), the thickness of the diaphragm, built-in stress and external pressure [8].

$$\delta = \frac{c_1}{c_2^{1/2}}\left[\frac{R_1}{\Delta p^{1/2}}\right]\left[\frac{\sigma f^{3/2}(1-\upsilon)^2}{E}\right] \quad (1)$$

The deflection, δ, of a diaphragm, for clamped edges (c_1 = 3/16, and c_2 = 1/2), is

$$\delta = \frac{3}{16}(1-\upsilon^2)\frac{\Delta p R^4}{Et^3} \quad (2)$$

The maximum stress, σ_{max}, in the diaphragm is

$$\sigma_{max} = \frac{3}{8}(1-\upsilon^2)\frac{\Delta p R^4}{t^2} \quad (3)$$

where, $\Delta p = p1 - p2$: pressure difference

R : diaphragm radius
t : thickness of diaphragm
E : Young's modulus
υ : Poisson's ratio

The properties of the diaphragm material are separated to the last bracket in Equation 1 because other parameters are constant. Since the quantity $(1-\upsilon)^2$ is approximately 1 for all solids, the best choice of material for the diaphragm would be the one having the largest value of $M_{diaphragm}$, where

$$M_{diaphragm} = \frac{\sigma f^{3/2}}{E} \quad (4)$$

A typical value of $M_{diaphragm}$ for nylons, polypropylene, HDPE and PTFE is 0.3 $(MPa)^{1/2}$, and for elastomers (rubbers) the range is 0.5 - 10 $(MPa)^{1/2}$. Elastomers, or rubbers, are polymeric materials, the dimensions of which can be greatly changed when stressed and which return to their original dimensions (or almost) when the deforming stress is removed. There are many types of elastomeric materials, such as natural rubber, synthetic polyisoprene, styrene-butadiene rubber, nitrile rubbers, polychloroprene, and silicone. In this present work, the author used silicone rubber as a diaphragm because it is one of the best materials capable of withstanding large deflections.

2.3 Valve structure

Since valve structure is strongly related to pump characteristics such as response time, frequency response and output pressure, careful consideration of valve material and structure is essential. Wear and fatigue of check valves are a risk, high-pressure loss may be a problem and there is also a considerable danger of valve clogging. The maximum output pressure of a micropump depends directly on the available force an actuator can deliver. The check valve and actuator therefore play very important roles in setting the maximum flow rate and output pressure of the pump. Silicone rubber was chosen as the material for the check valves because its major advantage is that it can be used over a wide temperature range [9].

2.4 Fabrication of pumping system

Micropumps consist of many components such as pump body, actuators, fluid interface, electric interface, and package. The pump body usually involves more than two layers. Five were used in the pump described below. The fabricated pump bodies have to be connected to the external actuator and fluid interface. External actuators require a driving signal for operation.

Figure 2. shows the cross section view of a single miniaturised pump designed and constructed by the author, while Figure 3. shows a photograph of the pump. The pump consisted of a rare earth magnet type NF0635 (diameter 3 mm, 9 mm length) and solenoid driver as the actuator, a stack of five layers as the pump body, and stainless steel tubing (ID 1 mm).

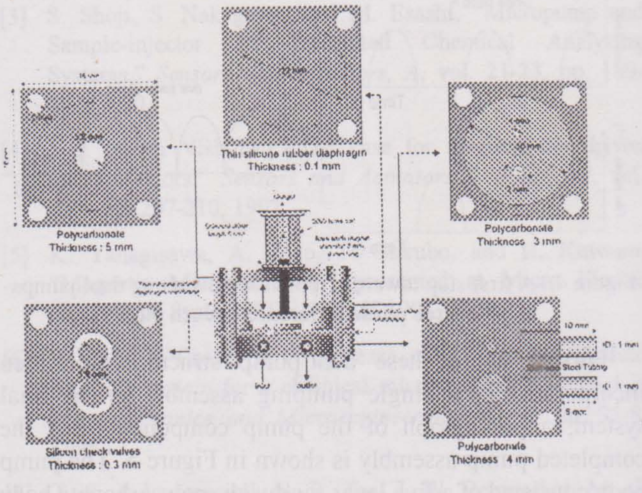
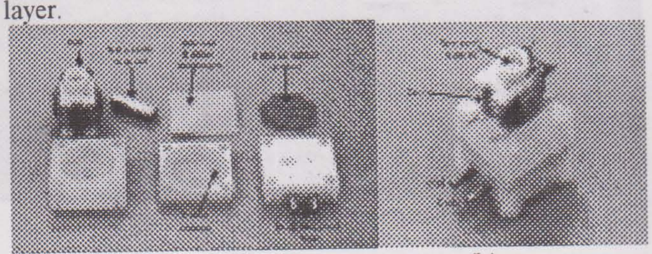


Figure 2. Cross section of a planar miniaturised pump

The pump body consisted of polycarbonate for the first layer, a thin silicone rubber diaphragm membrane for the second layer, polycarbonate as pump main volume for the third layer, polymer (silicone) valves for the fourth layer, and polycarbonate body and tubing connection as the fifth layer.



(a) (b)

Figure 3. Photograph of a planar miniaturised pump (a) showing pump components (b) assembled system (dimensions 18 mm long, 18 mm wide, 25 mm high)

Commercially available polycarbonate was used for the pump body because of its very high resistance to impact damage. Polycarbonate is resistant to aqueous solutions of acids, aliphatic hydrocarbons, paraffin, alcohol (except methanol), animal and vegetable fats and oils, but is attacked by alkalis, ammonia, and aromatic and chlorinated hydrocarbons [10]. Standard tubes (Tygon®, Cole-Palmer Instrument Co.) were used for the fluid interface while Loc-tite 406 epoxy glue was used to attach the tubing and the diaphragm membrane.

In order to achieve reliable flow in a FIA system, which may contain numerous reagent streams, a pulse free or rippleless, constant flow characteristic must be maintained. To meet these requirements the author firstly incorporated two single pumps into a dual pump unit. The outcome of using dual pump is illustrated in Figure 4.

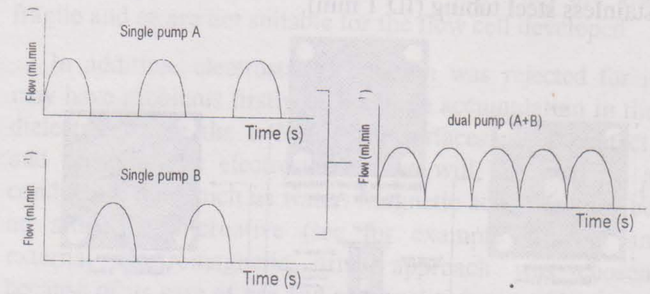


Figure 4. A first step towards rippleless flow using dual pumps at 90-degree phase difference to each other

Further, two of these 'dual pump' structures were then incorporated in a single pumping assembly as the final system, a photograph of the pump components and the completed pump assembly is shown in Figure 5. The pump body consisted of a five layer sandwich: polycarbonate body for the first layer (29.5x 29.5x 5 mm), thin silicone rubber diaphragm membrane for the second layer (29.5x 29.5x 0.1 mm), polycarbonate as pump main volume for the third layer (29.5x 29.5x 3 mm), polymer (silicone) valves for the fourth layer (29.5x 29.5x 0.3 mm), and polycarbonate as tubing connection for the fifth layer (29.5x 29.5x 4 mm).

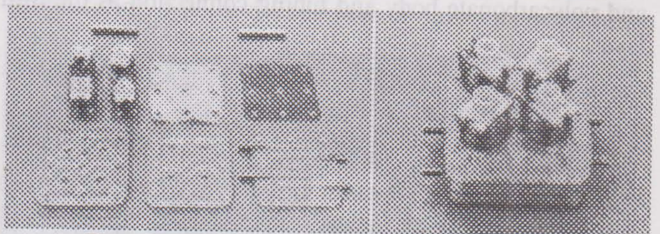


Figure 5. Photograph of the final pump assembly

2.5 Electronic controller

The design and objectives of the electronic controller were to maintain a constant and rippleless flow, control or set the pump speed (flow rate). The electronic controller consisted of a 4-phase clock generator for the pumps. The circuit consists of an astable multivibrator, synchronously clocking the pair of D flip-flops. The timing diagram of pump operation is shown in Figure 6.

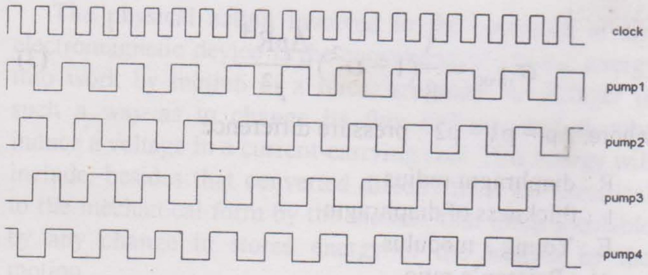


Figure 6. Timing diagram of 4-phase pump operation

III. EXPERIMENTAL RESULTS

The miniaturised 4-phase pump has been evaluated and has the following specifications:

- electronically controlled flow rate to maintain constant, rippleless flow
- the developed pump was self-priming under the applied conditions.
- low power consumption (about 10 watt)
- DC power supply (7.5 to 11 volts, square wave signal compared to piezoelectrically driven pumps which need about 100 V).
- flow rate 1.5 to 3.5 ml min^{-1} which is higher than silicon type micropumps
- simple to operate
- chemical inertness : polycarbonate body and silicon based valve membrane
- pumps analyte in the liquid state
- dimensions : 29.5 mm long x 29.5 mm wide x 25 mm high
- low maintenance, and
- low cost

Figure 7 shows the flow rate as a function of the different actuation frequencies at ± 7.5 volts (squarewave) for single unit, dual unit, and four unit pumps. The flow rate increased with the frequency of the applied voltage. The flow rate of the dual unit pump was approximately twice that of the single unit. Flow rate of the four unit and dual unit pumps reached a maximum around 11 Hz and that of the single unit pump, around 10 Hz.

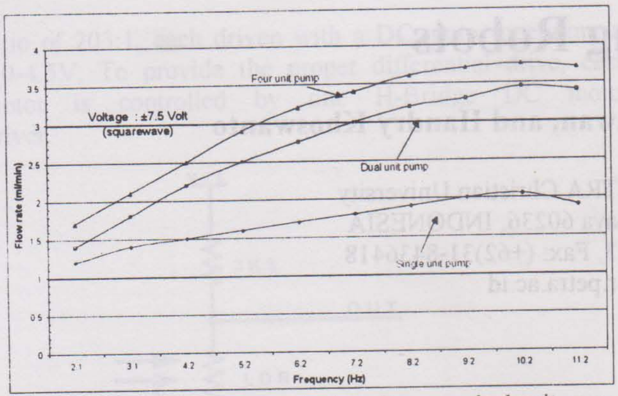


Figure 7. Pumping rates of a single unit pump, dual unit pump, and four unit pump

For correct operation of a pump, air bubbles should be removed from the pump system. The existence of air bubbles inside the pump degrades pumping performance since most of the energy coming from the diaphragm deflection can be lost in the compression of the air bubbles. The single unit and dual unit pumps developed did not show self-priming under the test conditions (10 cm pump head), however, the four unit pump was self-priming.

During a test period in which the voltage and frequency were held constant, the rate of flow of liquid through the pump was measured. As expected, constant flow was produced in the dual unit and four unit pumps (4-phase) during application of squarewave voltages in the intended range (7.5 to 11 volts peak).

IV. CONCLUSIONS

Design aspects of the planar miniaturised pump developed specially for the author's flow cell are discussed, together with the structure, materials, and fabrication process. The miniaturised electromagnetic pumps described in this research were purpose-designed for the flow injection analysis measurement. However, it is possible they could also be employed in other microanalytical applications.

Acknowledgments

The authors wish to acknowledge the contribution of Mr. Paul White and Mr. J. Bannigan of the Microelectronics Centre for their assistance in laboratory work. Acknowledgment is also due DEETYA for providing Targeted Institutional Links Scholarship funds to support the research work between MEC (University of South Australia) and Institut Teknologi Bandung, Indonesia.

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By Nana Subarna

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I. INTRODUCTION

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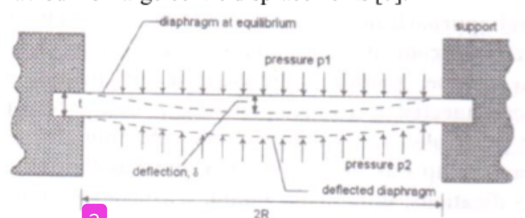

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R : diaphragm radius
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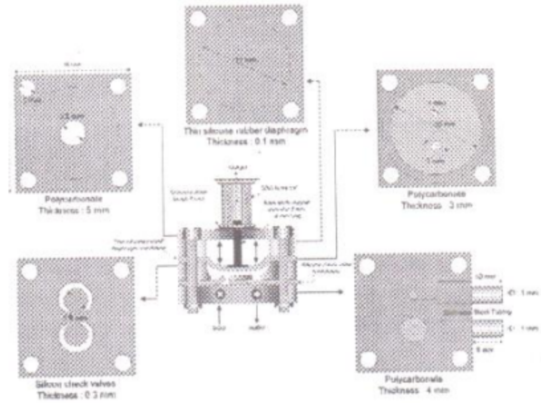

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The pump body consisted of polycarbonate for the first layer, a thin silicone rubber diaphragm membrane for the second layer, polycarbonate as pump main volume for the third layer, polymer (silicone) valves for the fourth layer, and polycarbonate body and tubing connection as the fifth layer.

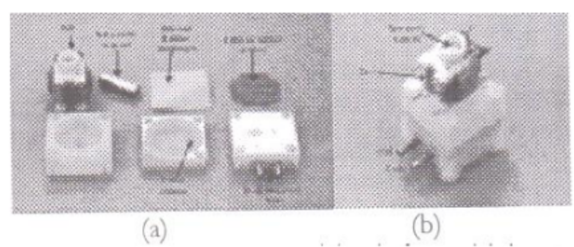

Figure 3. Photograph of a planar miniaturised pump (a) showing pump components (b) assembled system (dimensions 18 mm long, 18 mm wide, 25 mm high)

Commercially available polycarbonate was used for the pump body because of its very high resistance to impact damage. Polycarbonate is resistant to aqueous solutions of acids, aliphatic hydrocarbons, paraffin, alcohol (except methanol), animal and vegetable fats and oils. but is attacked by alkalis, ammonia, and aromatic and chlorinated hydrocarbons [10]. Standard tubes (Tygon Cole-Palmer Instrmnent Co.) were used for the fluid interface while Loc-tite 406 epoxy glue was used to attach the tubing and the diaphragm membrane.

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In order to achieve reliable flow in a FIA system, which may contain numerous reagent streams, a pulse free or rippleless, constant flow characteristic must he maintained. To meet these requirements the author firstly incorporated two single pumps into a dual pump unit. The outcome of using dual pump is illustrated in Figtue 4.

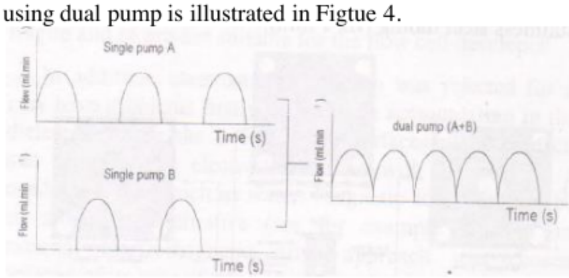

Figure 4. A first step towards rippleless flow using dual pumps at 90-degree phase difference to each other

Further, two of these 'dual pump' structures were then incorporated in a single pumping assembly as the final system, a photograph of the pump components and the completed pump assembly is shown in Figure 5. The pump body consisted of a five layer sandwich: polycarbonate body for the first layer (29.5x29.5x5 mm), thin silicone rubber diaphragm membrane for the second layer (29.5x 29.5x0.1 mm), polycarbonate as pump main volume for the third layer (29.5 x 29.5 x 3 mm), polymer (silicone) valves for the fourth layer (29.5x29.5x0.3 mm), and policarbonate as tubing connection for the fifth layer (29.5x29.5x4 mm).

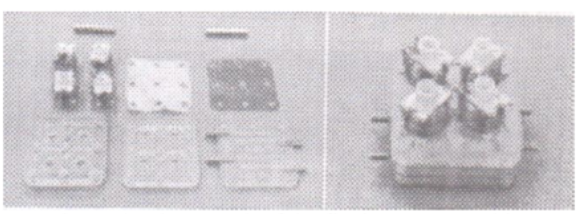

Figure 5. Photograph of the final pump assetnbly

2.5 Electronic controller

The design and objectives of the electronic controller were to maintain a constant and rippleless flow, control or set the pump speed (flow rate). The electronic controller consisted of a 4-phase clock generator for the pumps. The circuit consists of an astable multivibrator, synchronously clocking the pair of D fip flops. The timing diagram of pump operation is shown in Figure 6.

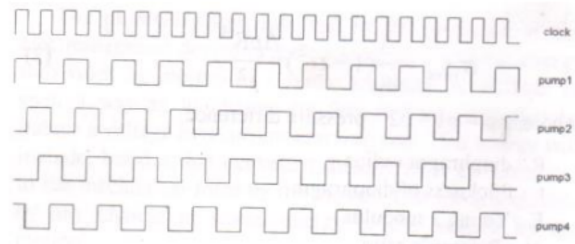

Figure 6. Timing diagram of 4-phase pump operation

III. EXPERIMENTAL RESULTS

The miniaturised 4-phase pump has been evaluated and has the following specifications :

- electronically controlled flow rate to maintain constant, rippleless flow
- the developed pump was self priming under the applied conditons.
- low power consumption (about 10 watt)
- DC power supply (7.5 to 11 volts, square wave signal compared to piezoelectrically driven pumps wich need about 100 V).
- flow rate 1.5 to 3.5 ml min^{-1} which is higher than silicon type micropumps
- simple to operate
- chemical inertness : polycarbonate body and silicon based valve membrane
- pumps analyte in the liquid state
- dimensions : 29.5 mm long x 29.5 mm wide x 25 mm high
- low maintenance and
- low cost

Figure 7. shows the flow rate as a function of the different actuation frequencies at ± 7.5 volts (squarewave) for single unit, dual unit, and four unit pumps. The flow rate increased with the frequency of the applied voltage.

The flow rate of the dual unit pump was approximately twice that of the single unit. Flow rate of the four unit and dual unit pumps reached a maximum around 11 Hz and that of the single unit pump, around 10 Hz.

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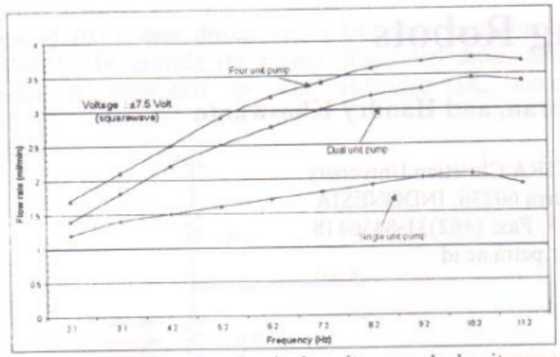

Figure 7. Pumping rates of a single unit pump, dual unit pump, and four unit pump

For correct operation of a pump, air bubbles should be removed from the pump system. The existence of air bubbles inside the pump degrades pumping performance since most of the energy coming from the diaphragm deflection can be lost in the compression of the air bubbles. The single unit and dual unit pumps developed did not show self-priming under the test conditions (10 cm pump head), however, the four unit pump was self-priming.

During a test period in which the voltage and frequency were held constant, the rate of flow of liquid through the pump was measured. As expected, constant flow was produced in the dual unit and four unit pumps (4-phase) during application of squarewave voltages in the intended range (7.5 to 11 volts peak).

IV. CONCLUSIONS

Design aspects of the planar miniaturised pump developed specially for the author's flow cell are discussed, together with the structure, materials, and fabrication process. The miniaturised electromagnetic pumps described in this research were purpose-designed for the flow injection analysis measurement. However, it is possible they could also be employed in other microanalytical applications.

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