

## DEVELOPMENT OF VOLUMETRIC MICRO-FLOW CALIBRATION SYSTEM USING FPGA FOR MEDICAL APPLICATION

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**Abstract** - To answer the need for traceability in micro flow area for medical industry, Flow Laboratory of Metrology LIPI in cooperation with Physics Department of University of Indonesia, developed a compact standard based on piston displacement concept. The standard consists of glass syringe and linear actuator controlled by Field Programmable Gate Array (FPGA). The volume generation uncertainty is 0.6% to 0.7% at 6.5 mL to 13.4 mL. Flow-rate uncertainty is 1.6% to 11.6% at 90.3 mL/hr to 1177.1 mL/hr.

**Keywords:** micro-flow, syringe pump, FPGA

### 1. INTRODUCTION

Traceability of measurement in medical industry is very important, to ensure quality of product or services provided by the industry. Research conducted by Indonesian Standardization Body (BSN) in 2013 discover that many measurement instrument used by Indonesia health industry is difficult to find traceability to SI unit, two among them are infusion pump and syringe pump [1].

Commonly, there are two methods to calibrate such instruments, first by gravimetric method using balance [2], second by volumetric method using burette or infusion pump analyzer [3]. The first method would be more expensive and difficult for some end user, such as hospital. Mostly they will choose the second method.

Then the next question is how to calibrate Infusion Pump Analyzer (IPA). This instrument basically replaces the traditional beaker and stopwatch, to modern way to measure liquid volume inside glassware using optical sensor and electronic timer [4]. It can not generate volume or flow, but passively measures changes of volume in certain time limit.

To calibrate this instrument, first it needs flow generator and second flow measurement device. And it will be better if standard that calibrates this instrument generates flow as well as measures it. So it will be a compact flow standard that can be used for laboratory calibration or in-situ calibration. For that reason, choice for type of flow standard to develop falls into piston operated volume apparatus [5]. In fact, syringe pump is also categorized into this type of instrument.

The next question is, if IPA is calibrated by a syringe pump, then is used to calibrate another syringe pump, how about measurement hierarchy? Well the syringe pump that is used to calibrate IPA will be calibrated using gravimetric method, so it can have higher accuracy than IPA.

Other issues in using syringe pump as standard are pulsation effect [6] and discontinuous flow generation. The pulsation issue can be overcome by using non rotating tip linear actuator [7], and controlling the motor movement based upon actuator speed information. The discontinuous flow generation can be overcome by developing parallel syringe pump [6]. This paper describes an attempt to build an accurate syringe pump as a volumetric micro flow calibration system for medical application.

### 2. PRINCIPLE OF OPERATION

For piston type flow generator, volume ( $\Delta V$ ) is generated by displacement ( $\Delta x$ ) of piston inside cylinder, and flow ( $Q$ ) is determined by volume divided by time ( $\Delta t$ ) when the piston displaces. That means the flow generated is proportional to speed of piston rod ( $v$ ).

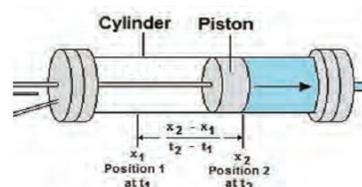


Fig.1. Volume generation by piston operated volume apparatus.

Temperature ( $T$ ) influences liquid density, as well as the cylinder and piston area ( $A$ ). So the volume and flow generation are also influenced by temperature, therefore the equations governing the syringe pump are:

$$\Delta V = \Delta x \cdot A(T) \quad (1)$$

$$Q_V = \frac{\Delta V}{\Delta t} = \frac{\Delta x}{\Delta t} \cdot A(T) = v \cdot A(T) \quad (2)$$

### 3. SYSTEM DESIGN

The system basically consists of linear actuator and a syringe. The Linear actuator is composed of motor that is connected to a gearbox which will become speed reducer. The gearbox is connected to a ball screw that converts rotational to translational movement; the ball nut is the mechanical component that pushes the plunger. To have a good linear movement, the ball nut is attached to linear guide. To measure linear displacement, a rotational encoder is coupled to the same gearbox to measure rotational movement of the gear, and then converts the information into linear displacement. For safety reason, two optic sensors is installed in upstream and downstream of the syringe to prevent the plunger keeps moving when it reaches upstream and downstream position. The digital information from the encoder and the optic sensors are read by a Field Programmable Gate Array (FPGA), which is used as an electronic controller. The main reason to choose FPGA is mainly due to its ability to perform parallel task, which is not possible for traditional microcontroller [8]. For this application the parallel task performed by the system is control the motor motion, as well as, measures its speed and plunger location. The FPGA control motor movement by Pulse Width Modulation (PWM) method, resolution of PWM is 16 bit. The FPGA is connected to a personal computer, so data can be sent to and manipulated in the computer. The syringe is made from glass so the expansion of liquid volume by pressure can be neglected. The capacity of syringe is 20 ml, and the expected flow rate is in the range of 100 ml/hr to 1000 ml/hr.



Fig.2. Metrology LIPI syringe pump system.

### 4. SYSTEM CHARACTERIZATION

Steps to characterize the system are as follows. First, calibration of the FPGA oscillator in Time and Frequency laboratory of Metrology LIPI. Because time measurement and PWM accuracy generated by FPGA is dependent on the accuracy of its oscillator. Second, the pulse width generated by FPGA is tested using a universal counter. This test will result in a transfer function that gives relation between count base on computer program with actual pulse width measured in time unit. This transfer function will be used for further development of computer program to control motor speed.



Fig.3. Metrology LIPI Universal Counter Stanford Research System SR620 with 1,3 GHz internal oscillator.

Table.1. FPGA internal clock frequency calibration result

No	FPGA Nominal Frequency MHz	Universal Counter SR260 Read MHz	Corection MHz		
			per unit	average	Uex
1	50	50,0000086	$8,6 \times 10^{-06}$	$8,8 \times 10^{-06}$	$1,9 \times 10^{-07}$
2	50	50,0000085	$8,5 \times 10^{-06}$		
3	50	50,0000083	$8,3 \times 10^{-06}$		
4	50	50,0000083	$8,3 \times 10^{-06}$		
5	50	50,0000084	$8,4 \times 10^{-06}$		
6	50	50,0000085	$8,5 \times 10^{-06}$		
7	50	50,0000087	$8,7 \times 10^{-06}$		
8	50	50,0000088	$8,8 \times 10^{-06}$		
9	50	50,0000098	$9,8 \times 10^{-06}$		
10	50	50,0000097	$9,7 \times 10^{-06}$		

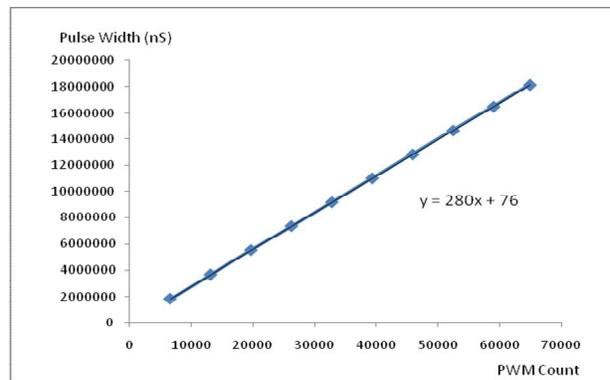


Fig.4. Transfer function between PWM count and generated pulse width.

The next step is to find relation between motor speed and gearbox rotational speed. This experiment is conducted by changing the PWM generated by the FPGA, and measuring rotary encoder pulse divided by time also using FPGA. This will help to determine at what PWM count, the desired gear rotational speed is achieved. After that, the actuator linear displacement is calibrated using dimensional method. The instrument for this method is a simple linear caliper that is traceable to Length Laboratory. The actuator is moved for certain speed, the linear displacement is measured by the caliper, the time is measured by the FPGA, and pulses coming from the encoder are also measured by the FPGA. The comparison of encoder pulse with distance measured by the caliper will give an instrument factor (FA).



Fig.5. Dimensional method to determine instrument factor.

Table.2. Relation between PWM count with Actuator Speed and Instrument Factor

No	PWM Count	Actuator Speed		Caliper Read mm	FA pulse/mm
		Hz	mm/min		
1	6554	8,5	2,8	38,4	210,4
2	6900	10	3,3	37,8	197,8
3	8100	13,3	4,4	37,9	195,3
4	10480	32,6	10,9	38,1	185,8
5	10650	41,3	13,8	38,2	184,2
6	11010	59,9	19,4	38,3	184,5
7	11700	72,7	24	38,5	182,5
8	12700	81,7	28,1	38,5	182,7
9	13700	98,4	33,3	38,6	182,2
10	14000	117,8	38,9	38,5	183,2
11	14800	129,3	43,3	38,6	179,3
12	15800	147,2	48,3	38,9	179,9

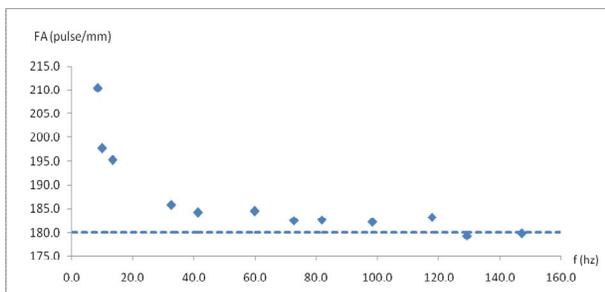


Fig.6. Instrument factor result.

This instrument factor will be used by the FPGA to determine the distance travelled by the actuator. This distance, multiplied by area of piston, will result in volume. So this instrument factor can also be used to determine volume. The area of piston is calculated based upon diameter of piston which is measured by the caliper. The volume of water displaced by plunger ( $\Delta V_{dim}$ ) is determined by multiplying pulse from the encoder ( $N_{RE}$ ) with area of the piston ( $A$ ) then divide it by the instrument factor ( $FA$ ). While the volumetric flow rate ( $Q_{dim}$ ) is calculated by multiplying frequency ( $f_{RE}$ ) with area and then divide it by the  $FA$ .

$$\Delta V_{dim} = \Delta x \cdot A(T) = \frac{N_{RE}}{FA} \cdot A(T) \quad (3)$$

$$Q_{dim} = \frac{\Delta V_{dim}}{\Delta t} = \frac{\Delta x}{\Delta t} \cdot A(T) \quad (4)$$

$$= \frac{N_{RE}}{FA} \cdot \frac{1}{\Delta t} \cdot A(T) = \frac{f_{RE}}{FA} \cdot A(T)$$

The last step is to calibrate the complete system consisting of linear actuator and syringe by using gravimetric method.



Fig.7. Gravimetric method to determine volume and flowrate

The equation to determine the volume of syringe is given by ISO/FDIS 8655-1 [5].

$$\Delta V_{20} = \frac{\Delta m}{\rho_b} \cdot \frac{\rho_b - \rho_u}{\rho_a - \rho_u} \cdot [1 - \beta_s (T_s - 20)] \quad (5)$$

$\Delta V_{20,0}$  : Volume of syringe at 20 °C (mL)

$\Delta m$  : Mass reading of water (gram)

$\rho_b$  : Density of weight that calibrate the balance, 8,0 g/cm<sup>3</sup>

$\rho_a$  : Density of water (g/cm<sup>3</sup>)

$\rho_u$  : Density of air (g/cm<sup>3</sup>)

$\beta_s$  : Thermal coefficient of glass (°C<sup>-1</sup>)

$T_s$  : Syringe temperature (°C)

Volumetric flow rate is calculated by dividing volume with time collection of water. The volume and flow rate from gravimetric measurement is compared to estimated value from calculation from (3) and (4).

Experiments were conducted by using two methods: 1) determining the velocity for varying velocities with a constant displacement; 2) determining the velocity for varying displacements with a constant velocity. The purpose of doing this is to see dependency of flow rate and volume setting [9]. Five different flow rates were applied; 100 ml/hr, 381 ml/hr, 550 ml/hr, 750 ml/hr and 1000 ml/hr. At each flow rate, the plunger moves at certain volume set. The volume was set at three different values; 100% and 50% from maximum volume. The maximum volume for the system after the entire component being assembled is 13 ml, although the syringe used is 20 ml.

Table.3. Volume Measured .by Gravimetric Method and FPGA

Setting		Gravimetric Method			FPGA Calculated		
Q mL/Hr	Volume mL	Volume mL	Uex mL	k	Volume mL	Uex mL	k
100	13	13,3	0,08	2,2	13,7	0,17	2,0
	6,5	6,2	0,04	2,2	6,3	0,05	2,1
381	13	13,4	0,09	2,2	12,7	0,08	2,1
	6,5	5,6	0,04	2,2	6,4	0,04	2,1
550	13	11,9	0,08	2,2	12,7	0,07	2,1
	6,5	6,1	0,04	2,2	6,4	0,04	2,1
750	13	12,6	0,08	2,2	12,8	0,07	2,0
	6,5	5,2	0,04	2,3	6,5	0,07	2,0
1000	13	12,5	0,08	2,2	12,9	0,08	2,0
	6,5	6,1	0,04	2,2	6,6	0,06	2,0

Table.4. Flow-rate Measured .by Gravimetric Method and FPGA

Setting		Gravimetric Method			FPGA Calculated		
Q mL/Hr	Volume mL	Q mL/Hr	Uex %	k	Q mL/Hr	Uex %	k
100	13	87,7	0,7	2,2	90,3	9,4	2,0
	6,5	92,7	0,7	2,2	95,1	5,7	2,0
381	13	295,3	0,9	2,2	279,2	23	2,0
	6,5	184,8	0,7	2,2	211,3	7,3	2,0
550	13	430,2	0,7	2,2	459,4	6,7	2,0
	6,5	417,6	0,8	2,2	443,0	14	2,0
750	13	776,7	0,7	2,2	788,0	6,1	2,0
	6,5	587,3	0,7	2,2	730,8	9,0	2,0
1000	13	1147,1	0,7	2,2	1177,1	3,2	2,0
	6,5	1027,8	0,7	2,1	1115,8	4,6	2,0

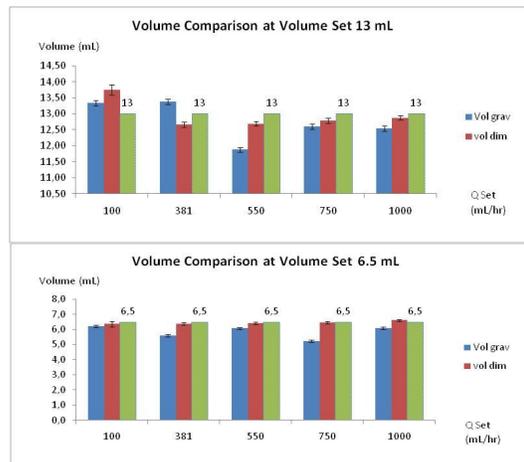


Fig. 7. Volume Comparison at Different Flow-rate and Volume.

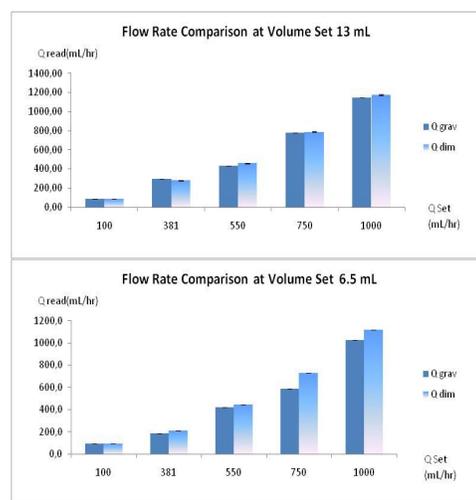


Fig. 8. Flow-rate Comparison at Different Flow-rate and Volume

The results show that the difference between volume measured by using gravimetric method and that calculated by using FPGA is large and varies in each flow rate. The difference is caused by improper gravimetric calibration method compared to other similar method developed in other NMI, such IPQ Portuguese [10]. The flow rate results show that big difference of flow rate between gravimetric method and FPGA occur above 750 mL/hr at 6.5 mL setting. At Table.2, it is shown that uncertainty from flow-rate calculated by FPGA is large. This means the variation of frequency from encoder during displacement of piston is large. This is caused by improper motion control of motor by FPGA. FPGA controls the motor by proportional method, a better method such as P.ID or Fuzzy Logic should be used to control the actuator speed.

## 5. CONCLUSION

The volumetric calibration system based on piston displacement method is able to reach the desired minimum and maximum flow-rate. But it still needs improvement regarding the gravimetric testing and motion control of actuator.

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