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Application of Box-Behnken experimental design to optimize the magnetic actuation parameters' for driving fluid in micro pump

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ABSTRACT – Microfluidics pump technology characterized by the parameters of pump components and fluids at the submillimetre scale, has shown considerable promise for improving diagnostics and biology research. The main work of this paper is applying Box-Behnken design to optimize actuator model focuses on the flow rate in electromagnetic actuation pump. The objective of the current study is to develop an extraction method for assessing pump output parameters using response surface methodology (RSM) optimization. A three-level three-factor Box-Behnken design (BBD) was applied for investigating the interactions between the critical variables including frequency, voltage and location to achieve the desired flow rate. Analysis of variance indicated that the proposed quadratic model successfully interpreted the experimental data with coefficients of determination of R^2 = 0.55 and adjusted R^2 = 0.15. Through this model, we can predict and control the flow rate output under different conditions. It may explain about biofluids interaction with vessels wall such as actuator, which give rise to the flow characteristic of the transport role and functionality.

1. INTRODUCTION

The circulatory system is a compound of blood that compromise blood vessels and heart that plays an important role in the human body. It is operated throughout of the body by transporting nutrients to the outlying parts and assists in inhalation of oxygen and exhalation of the waste products like carbon dioxide via lungs [1]. Once the circulation system fails, it will cause the rest of the organs in the body to malfunction. The primary part that will be affected is the heart. As a result, the chronic heart disease will lead to the heart failure. An importance of heart is a situation in which the heart unable to pump sufficient blood throughout the body [2]. This is because the pumping force of the heart is not enough to perform the circulatory operation. A heart transplants maybe the best option if all the conventional method fails. However, many patients died and suffered while waiting for heart transplant due to lack of donor [3]. In United States of America, there is only heart assists device namely as New Generation Heart Mate II that had been approved by the United States Food and Drug Administration to be applied as a temporary supporting system before heart donation process take place as well as for destination therapy or long-term [4]. Micropumps becomes an essential component of microfluidic transport systems from biology and medicine to space exploration and microelectronics cooling, drug delivery, such as the delivery of insulin, hormonal and pain management drugs [5]. Microfluidic transport requirements such as these can sometimes be met by taking advantage of passive mechanisms, most notably surface tension [6–9]. For other applications, macroscale pumps, pressure/vacuum chambers and valves provide adequate microfluidic transport capabilities [10–13]. Depending on the working principle, micropumps can be classified into displacement type and dynamic type [14,15] categories. This classification distinguishes the reciprocating micropump and the continuous flow micropump [16–18]. In terms of the micropump geometry, an additional classification distinguishes these devices into the categories that have and those that do not have a check-valve [19], or those that are based on the design parameters, such as the size, rate, and power density [20,21]. The objective of the current study was to develop and validate an extraction method for assessing pump output parameters using response surface methodology (RSM) optimization. The RSM was first introduced to optimize chemical reaction conditions and process parameters, and it has been successfully used as an optimizing technique in analytical method development [22,23].

2. METHODOLOGY

RSM designs allows us to estimate interaction and even quadratic effects, and hence give us the idea of the (local) shape of the response surface under investigation. Box-Behnken design is having the maximum efficiency for an RSM problem involving three factors and three levels. Also, the number of runs required is less compared to a central composite design. The proposed Box-Behnken design requires 15 runs for modeling a response surface. Randomization ensures that the conditions in one run neither depend on the conditions of the previous runs nor predict the conditions in the subsequent runs. Randomization is essential for drawing conclusions from the experiment, in correct, unambiguous and defensible manner. Process parameters for the study had three levels given as Voltage (V), Pinch location(mm) and Frequency (Hz). The levels were ranged based on the preliminary experiment-trial and sourced from the available literatures. Adopting Box–Behnken designs can sharply reduce the number of experimental sets without decreasing the accuracy of the optimization compared with traditional factorial design methods.

Details of the experimental runs with the set of input parameters that were conducted are given in Table 1.

Table 1 Experiment input parameters.

Part	Parameter	
Elastic tube	Outer Diameter, mm	30.0
	Thickness, mm	1.0; 3.0
	Length, mm	200; 260
Actuator	Length, mm	150.0
	Diameter, mm	10.0
	Thickness, mm	10.0
Electrical DC motor available	Voltage, V	2.0 to 6.0

The material and equipment of the experiment were set up and connected as shown in Figure 1. Then the elastic tube of 200mm long and 1mm thickness is joined into the circuit. The water pipe was completely filled into the whole circuit via T-tubing barb. The pincher location was set placed about 20mm from the left side of the elastic tube. Before started the experiment, the voltage of DC motor was set up to 2.0V. The electrical power supply was switched on to let the pincher press the elastic tube. When the pincher presses the elastic tube section, the water inside the rigid tube will flow through the flow meter. The flow rates of the flow meter were recorded. After that, repeat the step using of 3mm thickness of elastic tube with different applied voltage of 3.0, 4.0, 5.0 and 6.0 V respectively. Lastly, the steps are repeated by using 260mm length of elastic tube.

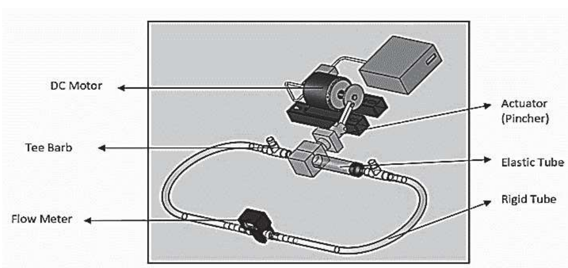

Figure 1 Experimental setup.

3. RESULTS AND DISCUSSION

Analysis of variance results for acquired model. Experiments were performed using the Box–Behnken experimental design. The predicted value (P-Value) is shown along with the experimental conditions in Table 3. Based on the model analysis in the first part, a quadratic model was chosen to fit the data. The relationship between the flow rate and the three chosen factors is shown in Eq. 1:

Regression Equation in Uncoded Units

$$\text{Flow rate} = 221 - 0.35 X_2 - 161 X_1 + 0.209 X_3 + 0.00632 X_2 * X_2 + 40.1 X_1 * X_1 - 0.000069 X_3 * X_3 - 0.504 X_2 * X_1 + 0.000321 X_2 * X_3 - 0.0615 X_1 * X_3 \quad (1)$$

A normal plot of residuals between the normal probability (%) and the internally studentized (resulting from the division of a *residual*) residuals was also obtained. In this way, the residuals can be checked to determine how well the model satisfies the assumptions of ANOVA, and the internally studentized residuals can be used to measure the standard deviations separating the experimental and predicted values. Figure 2 shows the relationship between the normal probability (%) and the internally studentized residuals. The straight line means that no response transformation was required and that there was no apparent problem with normality.

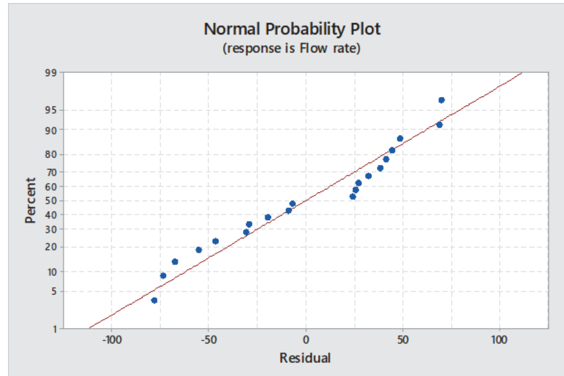

Figure 2 Normal plot of residuals showing the relationship between normal probability (%).

4. CONCLUSION

Box Behnken design was successfully adopted and the experiments were designed choosing the input variables for the levels selected. With minimum number of experiments, data was collected, and the models were developed. Response Surface Models evolved for responses show the effect of each input parameter and its interaction with other parameters, depicting the trend of response. A quadratic model was proposed to describe the relationship between the flow rate and three input variables. Analysis of variance indicated that the proposed quadratic model successfully interpreted the experimental data with coefficients of determination of $R^2 = 0.55$ and adjusted $R^2 = 0.15$. With reduced number of experimental runs, fairly convincing, logical and acceptable results have been obtained, which can be followed for getting solution to the desired requirements.

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