Chapter 6
Experimental Analysis of 3D Printed Microfluidic Device for Detection of Adulteration in Fluids

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Abstract In the field of analytical chemistry and bio-engineering, various technologies have been developed for a variety of applications and microfluidics is one of the promising technologies. Microfluidics can be combined with 3D printing mode so as to solve various types of problems. The usage of fluid is increasing gradually both in the household as well as in industrial applications. Due to increasing demands of fluid, the adulteration of fluids is also increasing gradually so as to meet the demand. Due to the addition of adulterants the properties of conventional fuel and biofuel are highly affected. In the case of a household, milk adulteration is one of the major issues which are affecting the individual's health. This paper deals with different designs of 3D printed optical microfluidic device which has the capability to measure the presence of adulterant based on the variation of viscosity in blending of biofuel and adulterants present in milk.

Keywords Microfluidic device · 3D printer · Adulteration

6.1 Introduction

The fluid term indicates the matter of state which can be divided into two parts: gas and solid [1]. Applications of these fluids are ranging for a wide range, industrial and day to day activities. Fluids for industries ranging from lubricants, fuel, engine oils, biofuels, machinery oils and drilling fluids whereas in day-to-day household actives the major fluids used include water, milk, honey, brewed liquids, etc. [2–4]. These fluids undertake or perform an act with respect to their usage. In order to check the accuracy of fluids, it has to endure several tests and measurements. Test performed for accuracy testing depend on the physical and chemical properties [5, 6].

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G. Anand et al. (eds.), *Nanotechnology for Energy and Water*,
Springer Proceedings in Energy, https://doi.org/10.1007/978-3-319-63085-4_6

Among available devices to perform accuracy test depending on the physical property of fluids, the main issues came across are precision, price, reliability, durability, and dimension of the testing device [7, 8]. The available devices to test adulteration in these fluids cannot be operated by a common man. The testing of fluid mainly depends on the viscous property of the taken fluid. Viscosity is a property that represents the resistance of a fluid to flow. Viscosity can also be defined as the thickness or internal resistance present between the layers of flowing fluid. The importance of measuring viscosity is for both application industrial and research [9–14].

Microfluidics has emerged as a technology that is an applicable wide range of applications like analytical chemistry, bioengineering, and electro-analytical chemistry [15]. The purity of milk, biofuel blending and to check fuel adulteration, microfluidics devices can be used when integrated with a proper measurement and analysis platform.

In this paper, we report a 3D printed lab-on-a-chip microfluidic device [16] for detecting the biofuel blending and milk adulteration by real-time monitoring of the variations in their viscosity [17]. The device is very easy to operate and determines the interface shifting of the sample fluid which is immiscible with the reference fluid in a common channel. This micro-viscometer is printed by using acrylate ink [18] and it has many advantages like low cost, high accuracy, and robustness. The simple and versatile design makes it compatible for the use in applications wherein fluid viscosity plays a vital role [19]. The blending of diesel with bio-diesel and the adulteration of milk with commonly used adulterants was tested using this device for various ratios and the device was found to be highly accurate in its output.

6.2 Materials and Method

6.2.1 Hagen Poiseuille Flow Equation

Hagen Poiseuille flow equation given in Eq. (6.1) which supports in finding out the viscosity of the unknown fluid depending on reference fluid which is flowing inside the common channel. The variables like pressure differential, fluid velocity and length of the channel to be constant, the width occupied by the unknown fluid would vary based on the reference fluid flowing inside the channel [19, 20].

According to Hagen-Poiseuille's law for laminar flow in a rectangular channel:

$$Q = \frac{\Delta P b h^3}{12 L \mu} \tag{6.1}$$

Here, 'ΔP' is the difference in pressure between the inlet and outlet in Pascals, 'b' is the width of the channel in meters, 'h' is the height of channel in mm, 'L' is the length of the channel in mm, 'μ' is the fluid velocity inside the channel in ml/min.

6.2.2 Design and 3D Printing of the Microviscometer

Microviscometer was designed using computer aided design (CAD) software Rhinoceros 5.0. The 3D geometry of the device is designed by using CAD software as shown in Fig. 6.1. The channel width is kept at 1 mm in X, Y and Z planes. The X-Y geometry of microviscometer is represented in Fig. 6.2. The dimension of the device is defined in mm scale.

Here for experimental analysis three factors of dimension are being varied like 'b' is the width of the channel, 'h' is the height of channel and 'L' is the length of the channel. The values of these factors are optimized by using Taguchi analysis method. The 3D printed microviscometer device used in this experiment is shown in Fig. 6.3 and printed by using MiiCraft 3D printer. So, using this Miicraft 3D printer around 20 devices of varying dimensions like width, height and length were printed to perform the adulteration test analysis outcome.

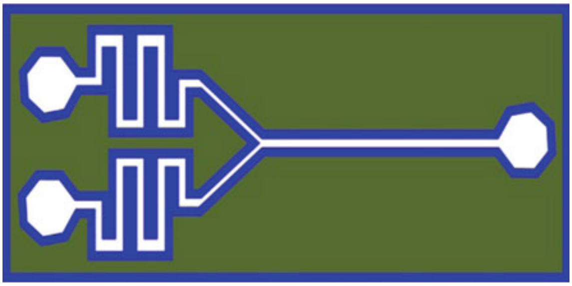


Fig. 6.1 3D geometry of microviscometer using rhinoceros ver. 5.0

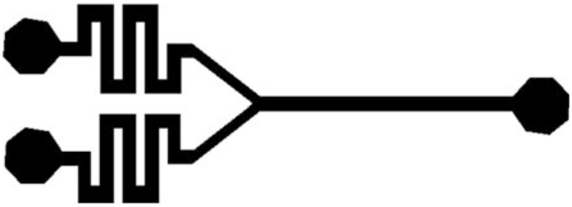


Fig. 6.2 X-Y geometry of the microviscometer (in mm)

Fig. 6.3 3D printed output of the microviscometer

6.2.3 Taguchi Method

Taguchi method is applicable to signal-to-noise (SN)-ratio for testing quality characteristics by approaching the ideal value. Taguchi's SN-Ratio is defined in basically on three conditions which are as follows (i) Taguchi's SN-Ratio for smaller-the-better where quality characteristics is usually an undesired output. (ii) Taguchi's SN-Ratio for larger-the-better where quality characteristics is usually a desired output. (iii) Taguchi's SN-Ratio for nominal-the-best where quality characteristics is usually a nominal output. Out of these three conditions, SN-Ratio for smaller-the-better and SN-Ratio for larger-the-better are opted to perform the optimization process. And finally, the one which is selected is based on Analysis of variance (ANOVA) which is giving less ANOVA error. So, using Taguchi method 3 parameters are being varied and the device is tested so as to perform in an optimized way when used for its real-time application.

6.2.4 Taguchi Experiment

For Taguchi experiment here three dimensions and three different values are taken which is shown in Table 6.1 and dimension defined are in millimeter (mm).

Here, Q is constant which is equal to 4.5 µl/min, and ΔP is equal to 1 atm (1 atm = 101325 Pa). As three parameters are defined for analysis along with three levels of values so for optimization process L9 Orthogonal Array will be created. Below Fig. 6.4 shows the Minitab screen for the starting step of Taguchi analysis and Create Taguchi Design tab is selected.

L9 Orthogonal Array (3**3) is created which is shown in Fig. 6.5 where Factors are 3 and these 3 factors are performed 9 times (Runs: 9) for analysis. Here in Taguchi design, 'C1' is a column for Length, 'C2' is a column for Height, 'C3' is a column for Width, and 'C4' is a column for Viscosity which is 'Response Column'.

Now, Taguchi's SN-Ratio for smaller-the-better where quality characteristics is usually an undesired output is performed by using SN- Ratio Eq. (6.2).

$$\eta = -10\, Log_{10} \frac{1}{n} \in \frac{1}{Y^2} \tag{6.2}$$

Taguchi analysis is done in respect of viscosity versus Length, Height, Width. Here Fig. 6.6 illustrates the main effects plot for SN- ratio. From this plot, optimal results for the defined factors can be determined. The factor values obtained from graph defines the dimension of the device to test the adulterant precisely.

Table 6.1 Factors and levels defined throughout design of experiments

S.No.	Factors (mm)	A	B	C
1	Height	1	2	3
2	Length	25	30	35
3	Channel width	0.3	0.6	0.9

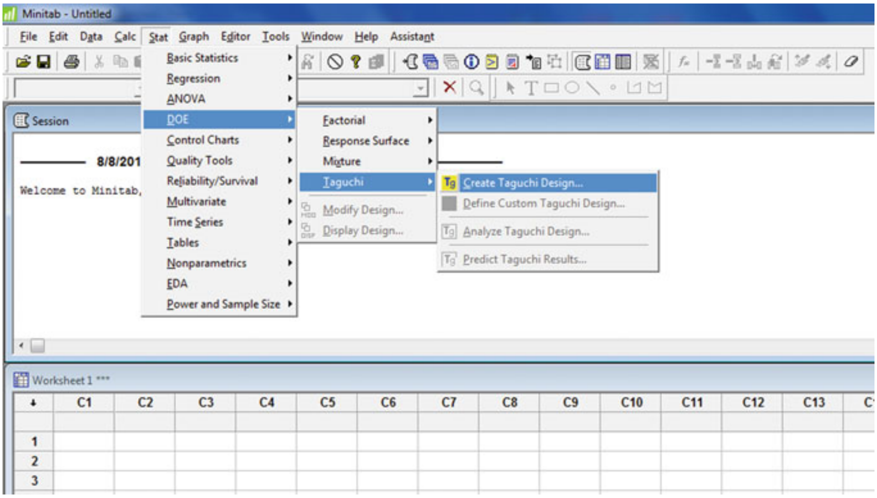
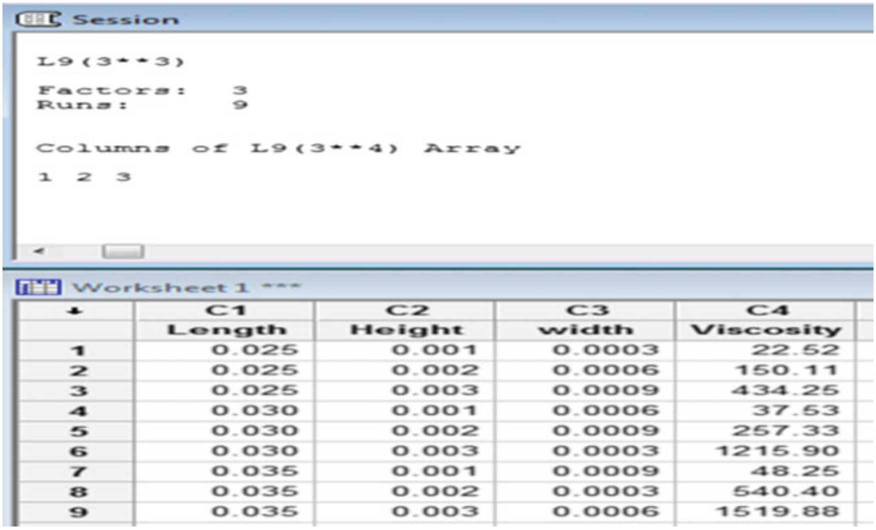


Fig. 6.4 Minitab screen representing initial step of taguchi method



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L9(3**3)

Factors:   3
Runs:      9

Columns of L9(3**4) Array

1 2 3
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↓	C1 Length	C2 Height	C3 width	C4 Viscosity
1	0.025	0.001	0.0003	22.52
2	0.025	0.002	0.0006	150.11
3	0.025	0.003	0.0009	434.25
4	0.030	0.001	0.0006	37.53
5	0.030	0.002	0.0009	257.33
6	0.030	0.003	0.0003	1215.90
7	0.035	0.001	0.0009	48.25
8	0.035	0.002	0.0003	540.40
9	0.035	0.003	0.0006	1519.88

Fig. 6.5 Minitab screen representing L9 orthogonal array taguchi design

For the validation of Taguchi method opted ANOVA test is performed so as to check the ANOVA error.

ANOVA is an analysis of variance and it is an algebraic method which controls factors that are defined. ANOVA is used to conclude the percentage of contribution of each control factors to disclose their effect on the quality characteristics (Table 6.2).

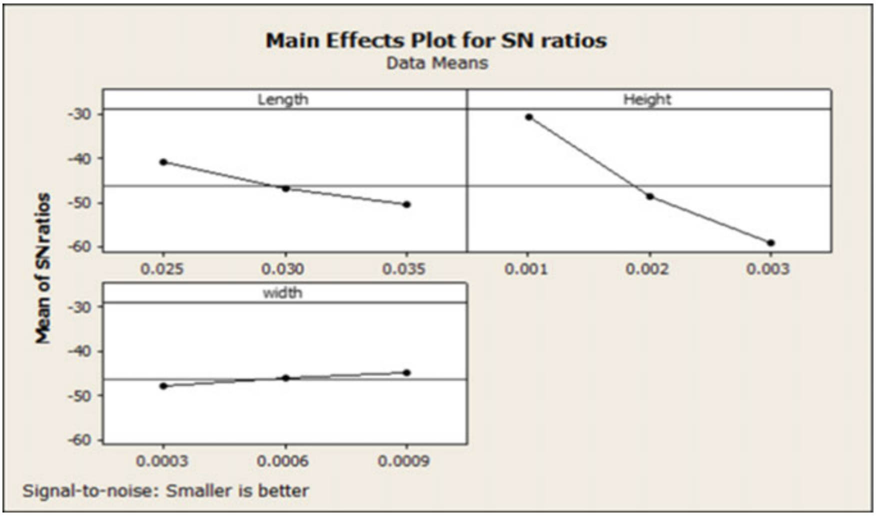

Fig. 6.6 Main Effects Plot for SN

Table 6.2 Response table for signal to noise ratios using smaller is better

Level	Length	Height	Width
1	−41.11	−30.74	−47.80
2	−47.13	−48.80	−46.22
3	−50.65	−59.36	−44.88
Delta	9.54	28.63	2.92
Rank	2	1	3

The increase in SN-ratio determines the increase in control factor. It can be used to investigate the different factors along with the degree of freedom (DF), the Sequential sum of square (Seq SS), Adjusted Sum of the square (Adj SS), Sequential mean square (Seq MS) and last column indicates the P-value for each control parameters. The row ensuring least P value was added more to the response involved and the control factor having high value than F value is insignificant.

During ANOVA test a general linear model has plotted Viscosity versus Length, Height, Width. Figure 6.7 shows normal probability graphs of residuals and figures attained shows that nearly all the normal probability graph follows a straight line outline. Table 6.3 shows detailed values of 3 parameters during ANOVA analysis (Table 6.4).

Linear regression calculation was used to compare the control factors (Length, Height, Width) and output response is viscosity.

$$R - Sq = 95.65\% \quad R - Sq(adj) = 82.61\%$$

R-Sq is the percentage of the response variable variation that is explained by a linear model.

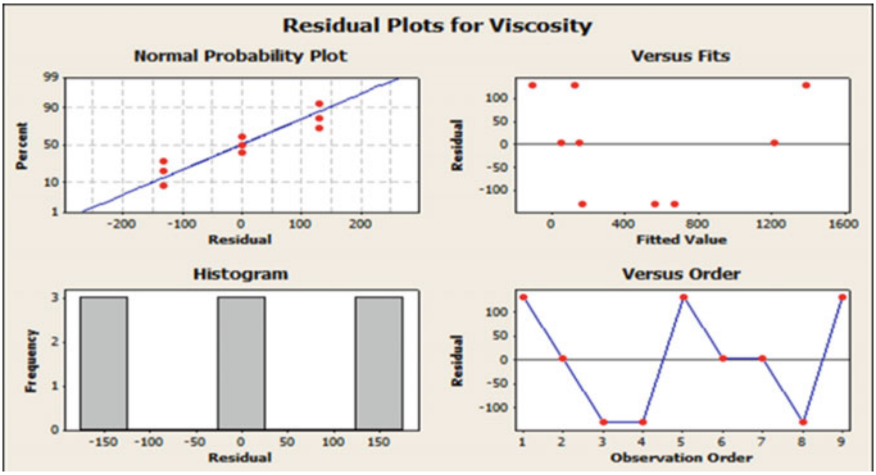

Fig. 6.7 Residual plots for viscosity

Table 6.3 ANOVA values for three parameters

Factor	Type	Levels	Values
Length	Fixed	3	0.025, 0.030, 0.035
Height	Fixed	3	0.001, 0.002, 0.003
Width	Fixed	3	0.0003, 0.0006, 0.0009

Table 6.4 Analysis of variance for viscosity which is generated using adjusted SS for tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Length	2	381030	381030	190515	3.69	0.213
Height	2	1668569	1668569	834285	16.14	0.058
Width	2	224553	224553	112276	2.17	0.315
Error	2	103387	103387	51694		
Total	8	2377540				

6.3 Conclusion

The device designed with a varying parameter can be used for detection of adulteration of fluid in real time application with high accuracy. As Taguchi method, SN-Ratio for smaller-the-better is tested and it defines that it always predicts values which we are tending to see in the worst aspect of things or we believe that the worst will happen. Validation of Taguchi method is done by using ANOVA analysis with less error. Here, linear regression calculation finally defines that the values considered satisfying the test analysis.

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