IJCTA, 9(39), 2016, pp. 271-280

Estimation of Liquid Temperature from Analysis of Liquid Level Sensor Characteristics

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Abstract : This paper presents a technique of liquid temperature measurement using estimators. The objective of the proposed work is to design an estimator for measuring the liquid temperature in a process tank by analyzing the behavior of available capacitive level sensor (CLS). Input output characteristics of the capacitive level sensor is analyzed for variation in liquid level and temperature. An observer is designed using the principle of regression analysis to compute the relation between the capacitive level sensor outputs for variations in liquid temperature. Kriging estimator are used as observer to compute the unknown liquid level and temperature from the output of capacitance level sensor. The designed temperature measurement technique is validated by performing the experiment in simulation and on practical setup. Results obtained by the technique shows successful implementation of proposed estimator

Keywords : Capacitive level sensor, Kriging estimator, observer, soft sensor, temperature.

1. INTRODUCTION

Measurement of processes parameters is a main requirement in industries to know the vital parameters of the process like temperature, pressure, level, flow, viscosity etc. These parameters can be measured through variation in any electrical component as resistance, inductance, capacitance, time etc. Liquid level measurement is one of the main parameter to be measured in process industries to about 15% of total measurement instruments.

Many researchers have reported work in the area of level measurement and some of the works are reported here. Measurement of liquid level using optical fiber is discussed in [1]. Measurement of level of sea water is discussed in [2] using image processing algorithms. Liquid level measurement using coreless multimode fiber is reported in [3]. Measurement of liquid level using combination of Bragg grating and no core fiber is reported in [4]. Application of polymer optical fiber for the measurement of liquid level dynamically is discussed in [5]. Measurement of both temperature and liquid level simultaneously using optic interferometer is reported in [6]. In [7], a method for measurement of low conductive fluid level using inductive sensor is reported. In [8], implementation of level measurement process for adaptive liquid level measurement technique using capacitance level sensor is discussed.

Temperature is also one of the vital parameter to be measurement in a process industry. Several researchers have contributed for design and implementation of various technique for the measurement of temperature. A temperature measurement using fiber optic is discussed in [9] based on sensitivity of wavelength towards temperature variations in the range of 25-75 °C. In [10], a model based method for detection of solid body temperature without disturbing the process is discussed. Temperature measurement using ultrasound is discussed in [11] where velocity of ultrasound wave is measured and the temperature of the fluid is calculated based on the relationship between temperature and ultrasound velocity. Temperature measurement of fuel bed is c discussed in [12] using thermocouple under three levels of the

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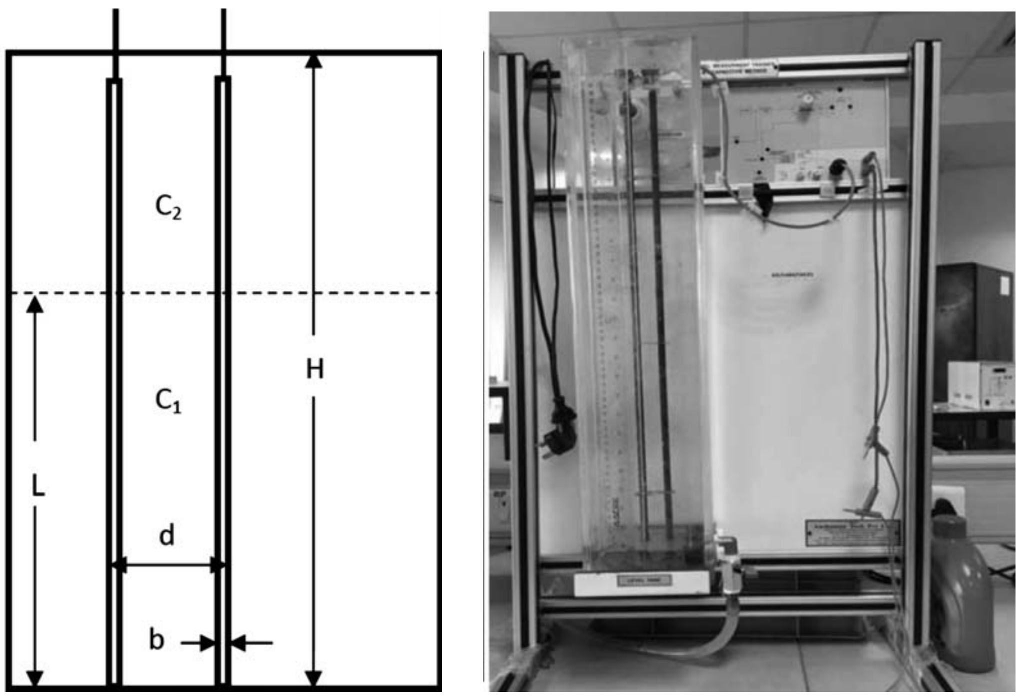
combustion process. Temperature measurement using 2 probe method is reported in [13] for measurement of temperature in the range of 300-1000 kelvin. Heating surface temperature measurement near the source of temperature using micro-thermocouple is reported in [14]. Temperature measurement using fiber optic interferometer is discussed in [15]. In [16], measurement of inside temperature of building using Bayesian estimation method is discussed.

In this work it is considered to use a capacitive level measurement device for the measurement of level. As from the principles of capacitance level sensors it is known that its output would be reactive to temperature. This relation is estimated to compute the liquid level and temperature in the proposed work.

2. EXPERIMENTAL SETUP

Figure 1 shows the experimental setup for measurement of liquid level. A parallel plate capacitor is used in this setup for measurement of liquid level and is immersed in the tank. Capacitance of a parallel plate capacitor is given by



(*a*) (*b*)

Figure 1: (*a*) Schematic of CLS, (*b*) experimental setup

$$C = \frac{\in_0 \in_r A}{d} \tag{1}$$

Where

C – Capacitance

$\in_0$ – Permittivity of vacuum

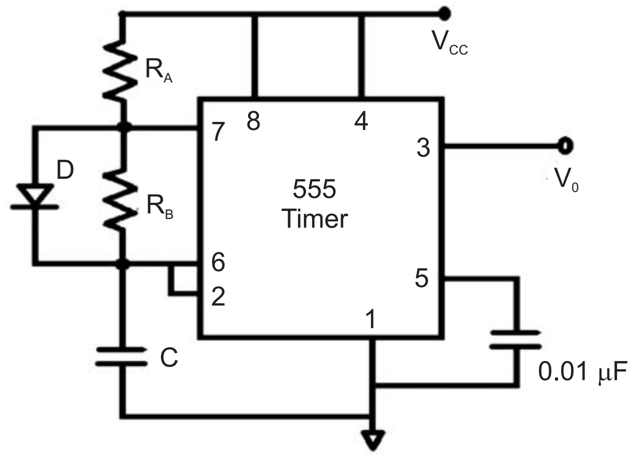
$\in_r$ – Relative permittivity

A – overlapping area of plates

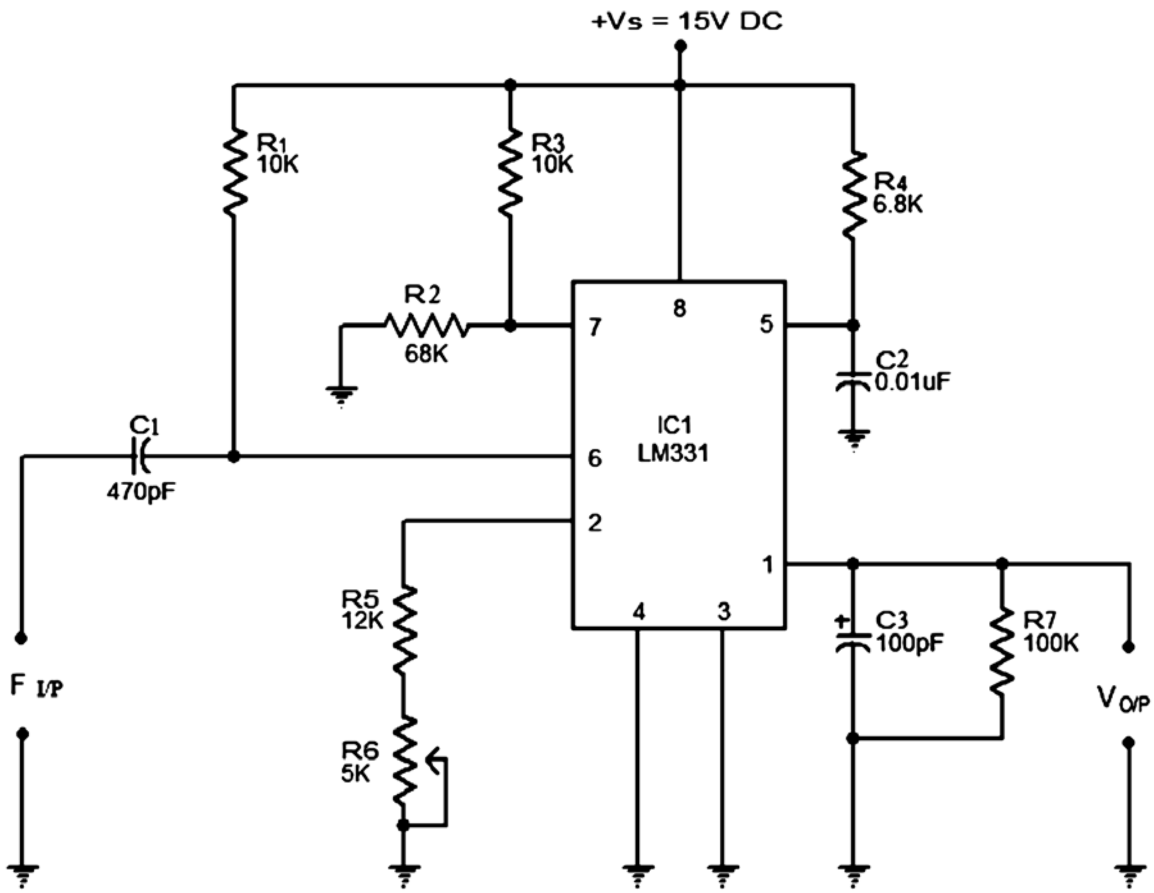
d – Distance between the plates.

Here water acts as the dielectric medium between the plates. When the tank is empty, air will be the dielectric medium between the parallel plates and relative permittivity will be 1. When the water level starts increasing, two parallel capacitance will be formed, one with dielectric medium as air and other with water. As the liquid level rises, area of capacitor with water as dielectric increases thus increasing its capacitance. On the other side, surface area of capacitor with air as dielectric reduces and thus is the capacitance. The effective capacitance will be the function of height which is given by eq. (2).

$$C = \frac{2\pi \in_0 \in_r}{\ln\left[\frac{d}{b} - \sqrt{\left[\frac{d}{b}\right]^2 - 1}\right]} L + \frac{2\pi\varepsilon_0}{\ln\left[\frac{d}{b} - \sqrt{\left[\frac{d}{b}\right]^2 - 1}\right]} (H - L) \quad (2)$$



(*a*)



(*b*)

Figure 2: (*a*) Capacitance to frequency converter (*b*) Frequency to voltage converterh

Capacitance change from the CLS should be converted to an active signal for further computation. For converting capacitance to a standard voltage value a combination of 555 timer and differential amplifier are used. Figure 2 (*a*) shows the circuit used to convert capacitance to frequency using a 555 astable multi-vibrator. The relation between the capacitance and obtained frequency is given in eq. (3)

$$f_{i/p} = \frac{1}{\ln(2)(R_A + 2R_B)C}\,\text{Hz} \tag{3}$$

Frequency to voltage converter circuit is designed to covert the frequency into voltage which is as shown in figure 2(b). The relation between obtained voltage and frequency is shown in eq. (4) and eq. (5).

$$V_{O/P} = \left(\frac{V_T}{R_5 + R_6}\right) \times R_7 \times 1.1 \times R_4 \times C_2 \times F_{1/P}\ \text{V} \tag{4}$$

$$V_{O/P} = \left(\frac{R_7}{R_5 + R_6}\right) \times 2.09 \times R_4 \times C_2 \times F_{1/P}\,\text{V} \tag{5}$$

3. PROBLEM DESCRIPTION

To understand the working of the capacitance level measurement process and analyze its characteristics an experimentation is carried on. The output obtained from the level measurement technique for variation in input liquid level is characterized and plot in Fig. 3.

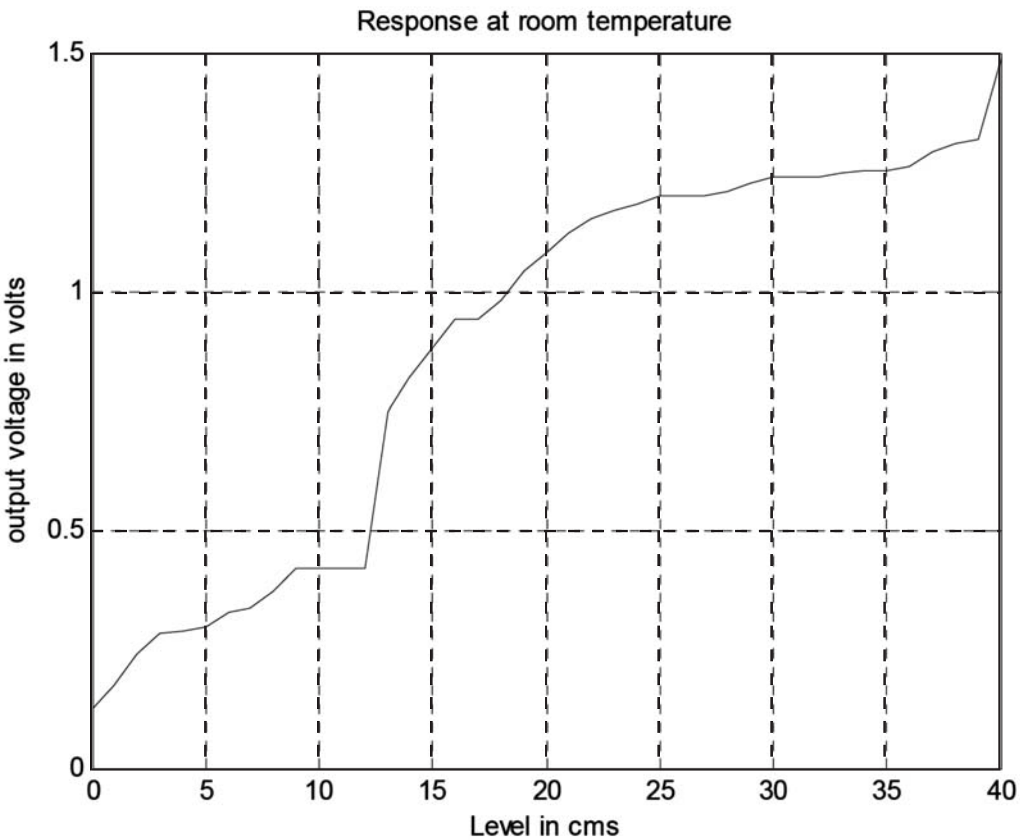


Figure 3: Output of level measurement technique for variation in liquid level

From the figure it is clear that the output of level measurement process is nonlinear. The experiment was carried on at a room temperature of about 28 0C. Now to analyze the behavior of the process measuring instruments, it is subjected to test for varying input level and liquid temperature in the ranges of 20 0C to 50 0C. Results obtained is plot in Fig. 4. From the figure we observe that the output voltage of the level measurement system varies with changes in liquid level and also with temperature of liquid.

From these obtained characteristics of capacitive level measurement it is clear that, on analyzing the output we can correlate it with both temperature and liquid level. Thus objective of the work is proposed to detect the temperature of the liquid by estimating its relation with the obtained output of level measurement technique along with accurate measurement of liquid level.

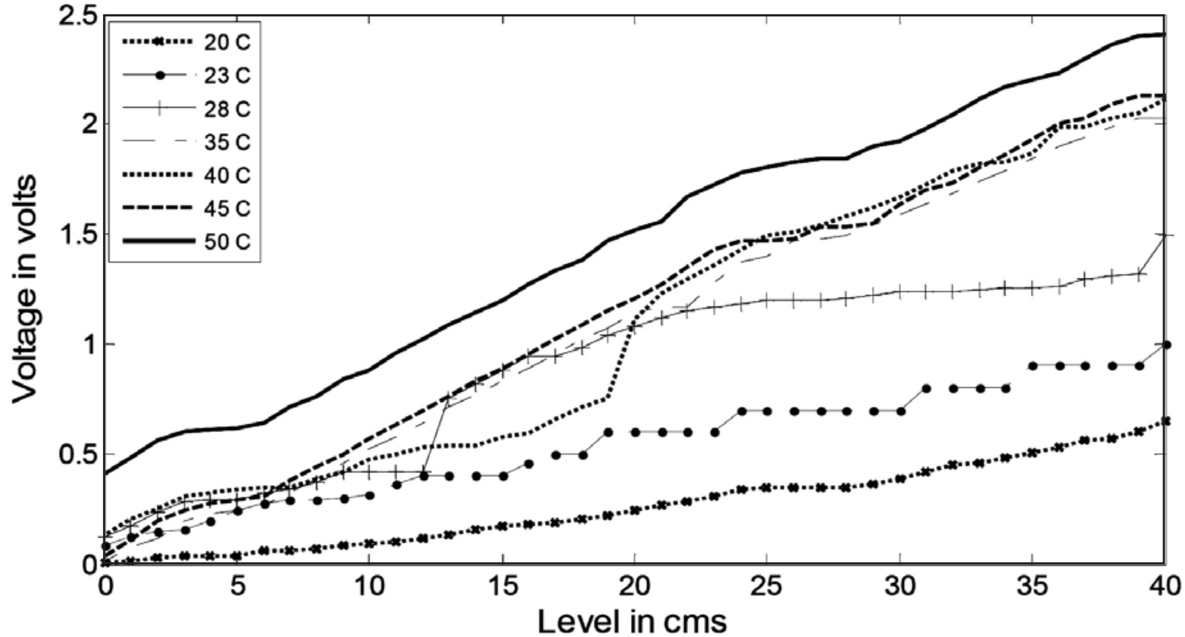


Figure 4: Response of level measurement technique for different water temperatures

4. ESTIMATOR DESIGN

From the above figure it is clear that the capacitive level sensor output varies with liquid level as well as the temperature. The proposed work aims at design of an estimator to compute the temperature of liquid using the data obtained from capacitive level sensor. A non-parametric regression model is considered to design the observer. In the first stage of designing an estimator, output obtained from level sensor for a particular liquid level for variation in liquid temperature is plot.

4.1. Interpolation of level relation

From the empirical equations given in eq. (2), eq. (3), and eq. (5) it is seen that the relation between liquid level and voltage output of frequency to voltage converter is proportional. But in real life the output is prone to deviate from the equations and the graph in Fig. 4 and Fig. 5, shows that the relation is not the same as empirical equations. So, an interpolation of obtained voltage signal for varying liquid level is obtained by polynomial equation/ smoothing spline variable technique and is represented in Fig. 6, 7, and 8.

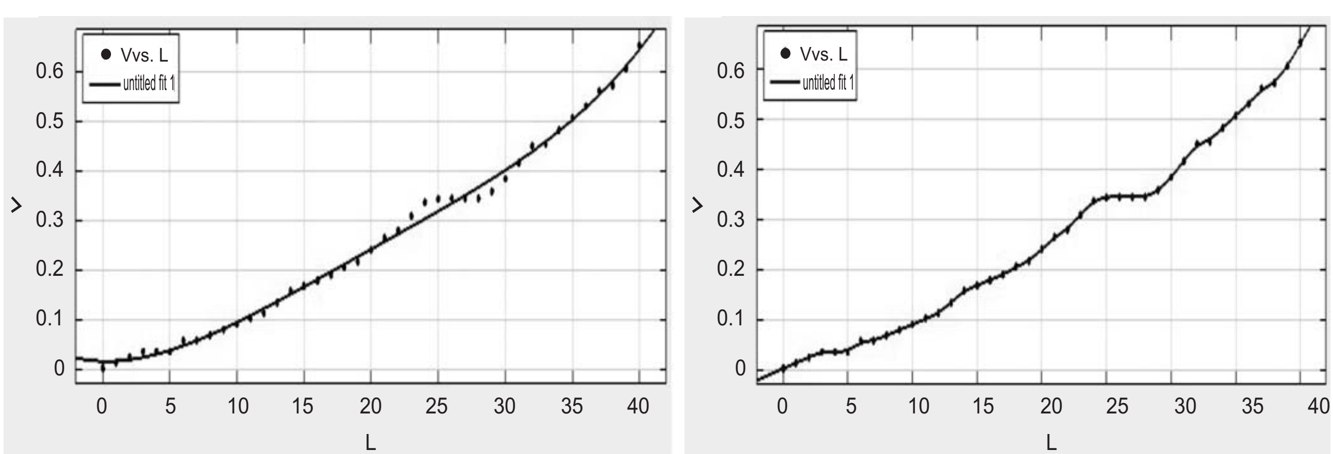


Figure 5: Curve fit graph at liquid temperature of 20 °C using (*a*) spline and (*b*) polynomial

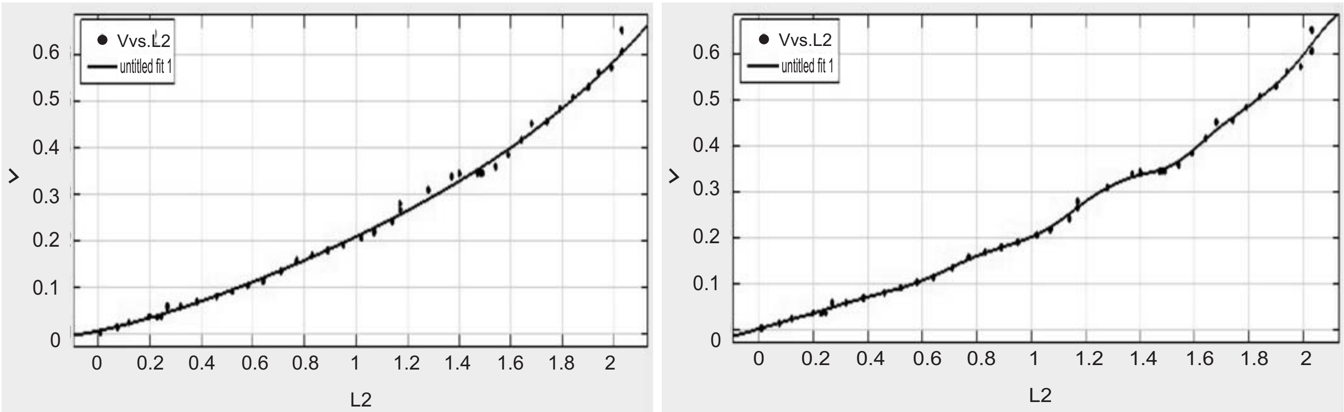


Figure 6: Curve fit graph at liquid temperature of 35 °C using (*a*) spline and (*b*) polynomial

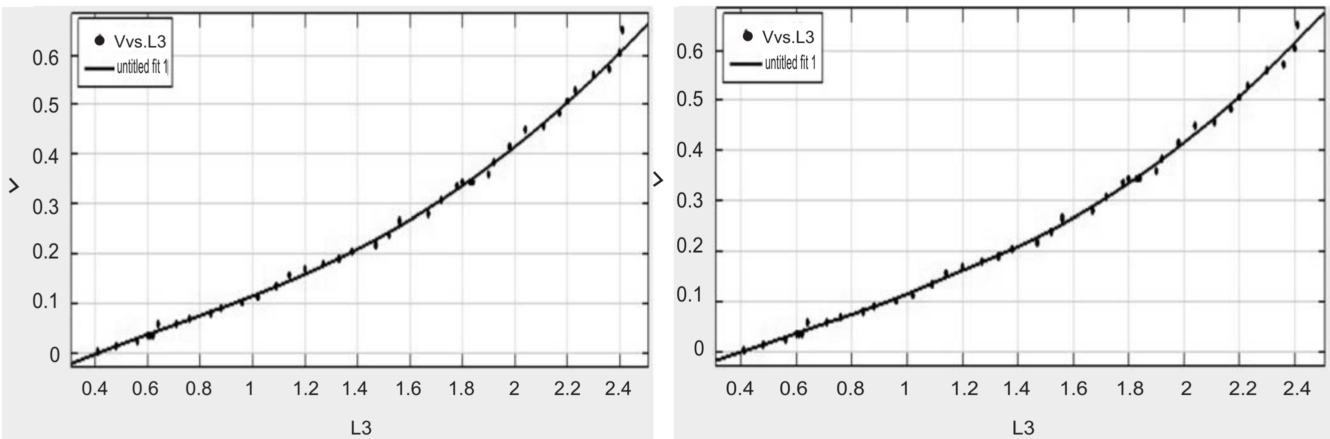


Figure 7: Curve fit graph at liquid temperature of 50 °C using (*a*) spline and (*b*) polynomial

Polynomial equation obtained after the process of curve-fit is as represented in eq. (6), (8), and (9) for different values of temperature like 20 °C, 35 °C, and 50 °C respectively.

$$V(L) = 5.351x10^{-7} L^4 - 4.153x\ 10^{-5} L^3 + 0.001215L^2 - 0.0006988L + 0.0165 \quad (6)$$

$$V(L) = 0.02243L^4 - 0.06681L^3 + 0.1307L^2 + 0.116L + 0.00604 \quad (7)$$

$$V(L) = -0.0135L^4 + 0.0996L^3 - 0.1651L^2 + 0.290L - 0.1001 \quad (8)$$

4.2. Interpolation of temperature relation

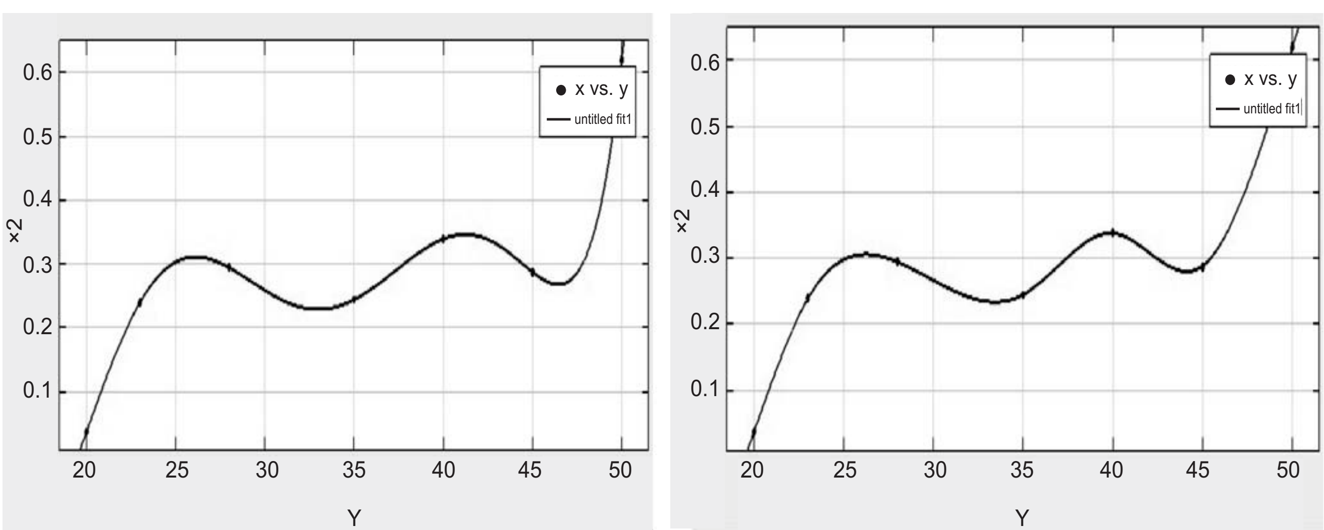


Figure 8: Curve fit graph at liquid level of 5 cm using (*a*) spline and (*b*) polynomial

In this process, the relation between capacitor level sensor outputs for varying temperatures is analyzed to compute the polynomial equation/ smoothing spline variable. These relations are computed by fitting the relations between obtained output of capacitance level sensor and temperature. Figure 8, 9, and 10 (*a*) and (*b*) shows the output obtained after the curve-fit technique carried on using polynomial equation and spline smoothing respectively.

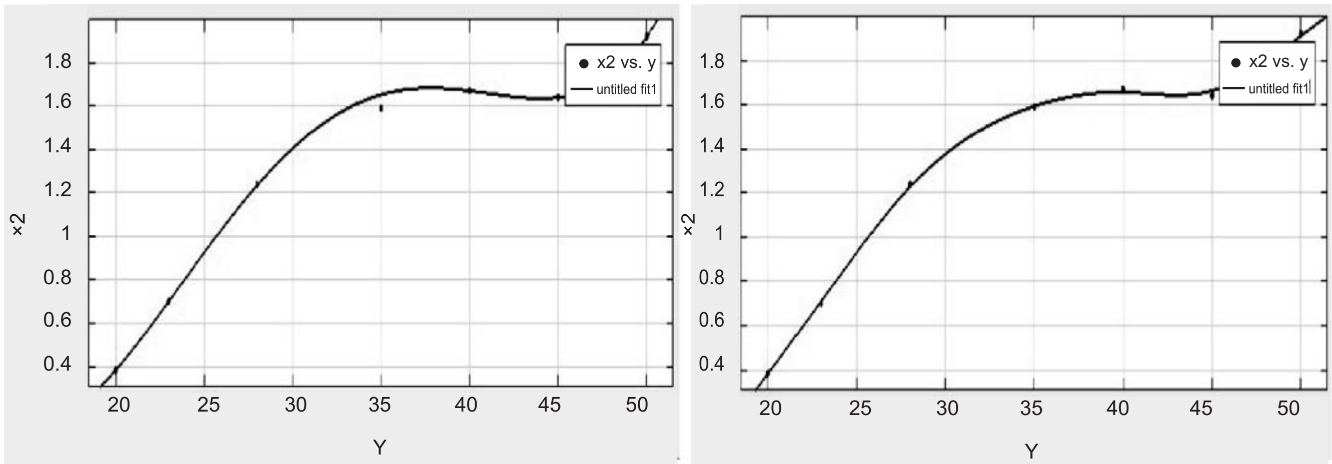


Figure 9: Curve fit graph at liquid level of 30 cm using (*a*) spline and (*b*) polynomial

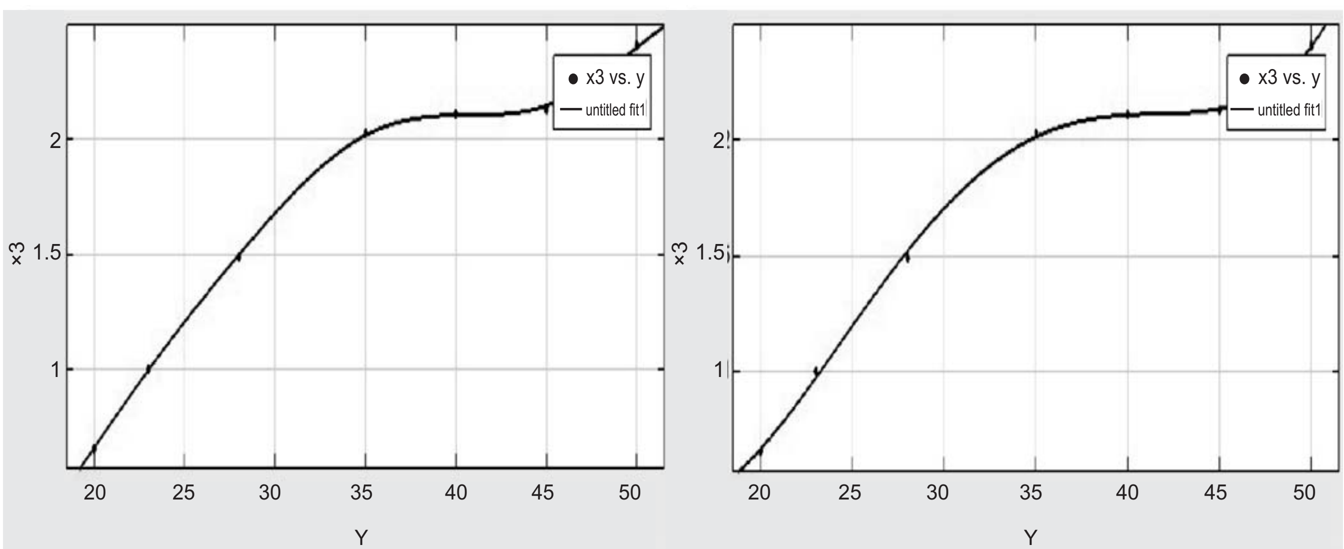


Figure 10: Curve fit graph at liquid level of 40 cm using (*a*) spline and (*b*) polynomial

The polynomial equation obtained after performing the curve fit algorithm can be represented as

$$V(T) = -2.39x10^{-6}\,T^5 + 4.193x10^{-4}T^4 - 0.02839T^3 + 0.926T^2 - 14.48T + 87.09 \quad (9)$$

$$V(T) = 1.17x10^{-5}T^4 - 0.001527T3 + 0.06878T^2 - 1.203T + 7.249 \quad (10)$$

$$V(T) = 1.07x10^{-5}T^4 - 0.00142T^3 + 0.06529T^2 - 1.164T + 7.45 \quad (11)$$

Equation (9), (10), and (11) shows the polynomial representation of relation between temperature and voltage for a constant value of liquid level like 5cms, 30cms and 40 cms respectively.

4.3. Data Association

In this stage, the relation obtained by both voltage to liquid level and voltage to temperature are compared to evaluate each of the terms. Kriging estimator is made use to obtain the same. Kriging estimator is used to compute weights based on regression of observed values of surrounding data points according to spatial covariance values [17-20].

In the proposed work we have two relations one relating signal conditioning voltage to liquid level for varying temperatures and other voltage output to liquid temperature at constant level. Kriging estimator is used to compute the liquid temperature and liquid level using the voltage data. Basic Kriging estimator is given as

$$V^{*} - V(T) = \sum_{\alpha=1}^{m(u)} \lambda_{\alpha}[V(L_{\alpha}) - V(T_{\alpha})] \quad (12)$$

The objective of the equation is to determine the weight λ_{α}, to minimize variance of the estimator.

$$\sigma_E^2 = Var\{V^{*} - V(T)\} \quad (13)$$

The random field V(T) can be decomposed into residual and trend components, *i*.e.

$$V(T) = R(u) + m(u) \quad (14)$$

Computation of temperature and level is further carried on by applying Kriging with a trend (or universal Kriging), where a linear or higher order trend in (L, T) coordinates of data points is fit to the local mean in the neighborhood of the estimation point.

Once the obtained voltage is decomposed into two component functions in terms of liquid level and temperature, interpolation equations computed earlier is used to determine the unknown liquid level and temperature.

5. RESULTS AND CONCLUSION

Once the estimator is designed it should be tested with practical data to evaluate the performance. For testing, the range of liquid level is considered from 0 to 40 cm and changes in liquid temperature is between 20 °C to 50 °C. Tests are conducted with variations in both liquid level and temperature under static conditions results obtained is tabulated in Table 1. The percentage of error for the estimated outputs of level and temperature is plot in Fig. 11.

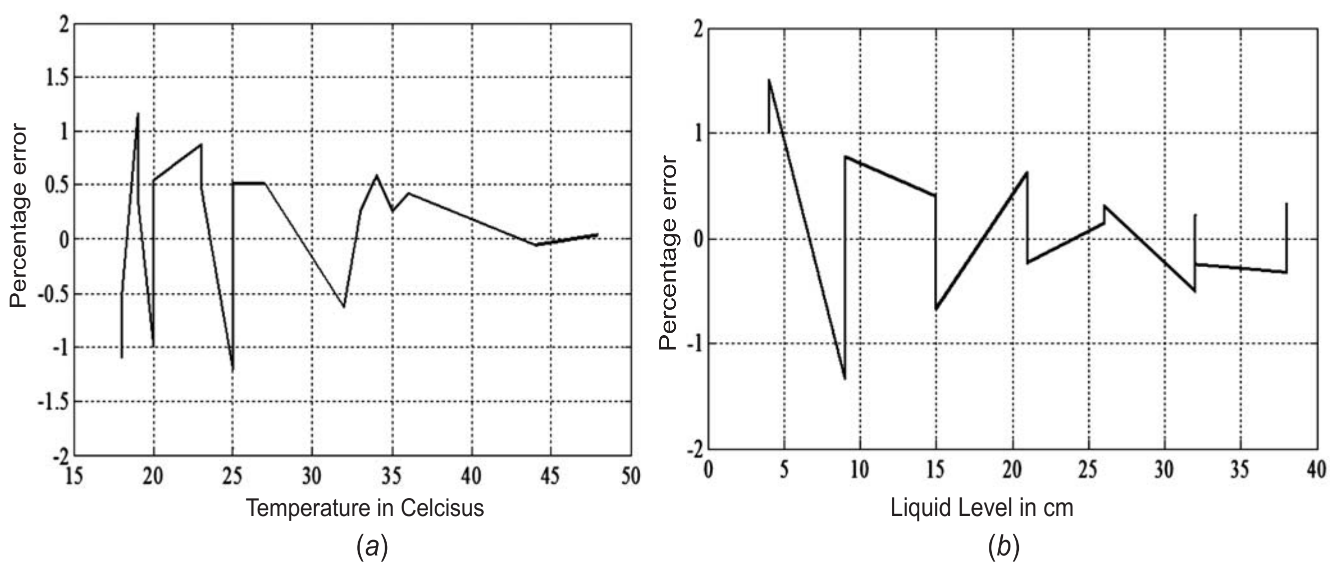


Figure 11: Percentage error obtained for measurement of a) temperature and b) liquid level

6. CONCLUSION

Liquid level process is one of the most commonly seen process in any industry like pharmaceutical, refineries, cement, power, food, etc. In most of the level processes it is seen that it is subjected to many external influences, of which temperature and humidity are common. These parameters often cause a severe change in process performance. This paper made an attempt to design a liquid level measurement technique which could also estimate the temperature of liquid along with liquid level. For this, an interpolated signal of voltages for changes in temperature and liquid level was subjected to Kriging regression analysis.

The results obtained from the proposed technique shows that the technique was able to compute the level of liquid and temperature accurately with a % root mean square error of 0.78%, which is practically acceptable.

Table 1
Real life experimentation results

Sl. No.	*Actual*		*Measured*		*% error for measurement*	
	Level in cm	*Temp in °C*	*Level in cm*	*Temp in °C*	*Level*	*Temp*
1.	4.00	20	3.96	20.2	1.00	-1.00
2.	4.00	23	3.94	22.8	1.50	0.87
3.	9.00	34	9.12	33.8	-1.33	0.59
4.	9.00	18	8.94	18.2	0.67	-1.11
5.	9.00	25	8.93	25.3	0.78	-1.20
6.	15.00	25	14.94	24.87	0.40	0.52
7.	15.00	32	15.10	32.2	-0.67	-0.63
8.	21.00	19	20.87	18.93	0.62	0.37
9.	21.00	35	21.01	34.91	-0.05	0.26
10.	21.00	48	21.05	47.98	-0.24	0.04
11.	26.00	44	25.96	44.02	0.15	-0.05
12.	26.00	36	25.93	35.85	0.27	0.42
13.	26.00	20	25.92	19.89	0.31	0.55
14.	32.00	23	32.16	22.89	-0.50	0.48
15.	32.00	33	31.93	32.91	0.22	0.27
16.	32.00	18	32.08	18.09	-0.25	-0.50
17.	38.00	19	38.12	18.78	-0.32	1.16
18.	38.00	27	38.02	26.86	-0.05	0.52
19.	38.00	48	37.87	47.98	0.34	0.04

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