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Optimization of the Paper Permeability Tester using Robust Design

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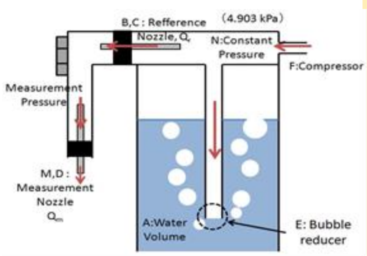
Graphical abstract



Abstract

This paper is using practical case study of robust design engineering. Effect of control factors and optimum condition is studied to design a more robust Paper Permeability Tester. In this study, robustness means decreasing uncertainty that is validity of measurement results with the Tester. Robustness is required to ensure the reliability for the measurement results in the field of the measurement tester. Thus, orthogonal array L_{18} is employed and the optimum condition was obtained for decreasing the measurement dispersion. Experiment reproducibility of Signal-to-Noise Ratio and sensitivity were confirmed within 20%. SNR value is linearly depends on air permeance value. When the value of air permeance is small, it tends to provide small SNR. Flow rate in nozzle was considered as a major cause. Stability of flow in the nozzle is significant to design the Tester to be more robustness. In a case of a flow under the rapidly, SNR is small due unstable flow. Sensitivity with nozzle diameter was dramatically large. Nozzle specification tolerance was found to have strong influence on measurement result.

Keywords: Permeability tester; permeance; robust parameter design; signal-to-noise ratio; tolerance design

Abstrak

Kajian ini menggunakan kaedah kejuruteraan kualiti robust. Kesan parameter boleh kawal dan kondisi optimum dianalisiskan untuk membentuk apparatus pemeriksa kebolehtelapan kertas yang mantap (robust). Dalam kajian ini, kemantapan apparatus adalah penting untuk memastikan reliabiliti data pengukuran terjamin. Oleh itu, reka bentuk orthogonal L_{18} digunakan dan kondisi optimum digunakan untuk mengurangkan penyebaran variasi data. Kebolehulangan eksperimen menggunakan nisbah *signal-to-noise* (SNR) dan kesensitifan dikenalpasti dalam lingkungan 20%. SNR adalah berkadar langsung dengan nilai ketelapan udara. Apabila nilai ketelapan udara kecil, maka SNR berpotensi ke arah nilai yang kecil. Kadar aliran dalam muncung dianggap sebagai pengaruh utama terhadap fenomena ini. Kestabilan aliran dalam muncung adalah siknifikan untuk mencipta pemeriksa kebolehtelapan kertas yang mantap. Dalam kes aliran yang perlahan, SNR adalah kecil disebabkan oleh ketidakstabilan aliran dalam muncung. Nilai sensitiviti dalam diameter muncung adalah sangat besar. Spesifikasi tolerans muncung didapati sangat mempengaruhi keputusan pengukuran data.

Kata kunci: Pemeriksa kebolehtelapan kertas; ketelapan*; robust parameter design;* nisbah *signal-to-Noise;* reka bentuk tolerans

1.0 INTRODUCTION

Air permeance of paper is assessed as related printing characteristic. Recently, demand for the Paper Permeability Tester is increased due to its variety of functional materials which are high quality paper and porous films. Although the Paper Permeability Tester is standardized by Japanese Industrial Standards (JIS) [1] and ISO [2], the reliability in the test results is pointed out as necessary, parallel with the demand of Paper Permeability Tester. The tester has an uncertainty in its test results. Reducing uncertainty in the result will increase the accuracy of tester. Therefore, the main purpose of this study is optimizing the Tester to ensure the reliability in test results using robust parameter design.

2.0 EXPERIMENTAL

2.1 Paper Permeance

Paper Permeability and its test are standardized by JIS. Value of paper permeability, air permeance, is defined by taking the time at which constant air volume passed through the specimen [2]. The permeability is evaluated as one of alternative characteristics of printability. If there are many holes passing the air in the specimen, value of paper permeance is low.

2.2 Tester

Oken type Paper Permeability Tester which is better than Gurley Type Paper Permeability Tester [3] was used in this study. Figure 1 shows a schematic diagram of the Oken Tester. Air is pushed out from the compressor goes into a chamber where air is kept at static pressure, 4.903(kPa) (500 mmAq), by a water column. The air coming from unit pressure chamber goes into a measurement chamber through an inlet nozzle which is called reference nozzle, and constant air is passed through the specimen. Measurement nozzle in this study is used as a specimen instead of paper to calibrate the Permeability Tester in this study. Measurement nozzle length and reference nozzle are referring to the same nozzle part. However, the location of the nozzle being installed is at different part of the system, thus serving different function and label. Measurement nozzle is installed outside the pressure chamber (factor label as *M*, *D*) and reference nozzle is installed inside the pressure chamber (factor label as *B*,*C*). Flow rate of the reference nozzle, Q_r, and measurement nozzle, Q_m, are determined by means of the following equation.

$$Q_m = \frac{\pi}{8\mu}(P_c - P)\frac{R^4}{L} \tag{1}$$

$$Q_r = \frac{\pi}{8\mu}P\frac{r^4}{l} \tag{2}$$

$$T = \frac{1.28\times10^4 \mu L}{\pi P_c D^4} \tag{3}$$

where μ is the viscosity coefficient of air; P_c is value of unit pressure in the chamber; P is value of pressure in the measurement chamber; r is the inside radius of the reference nozzle; l is the length of the reference nozzle; R is the inside radius of the measurement nozzle; L is the length of the measurement nozzle; Permeance, T, is determined by the ratio between Q_r and Q_m.

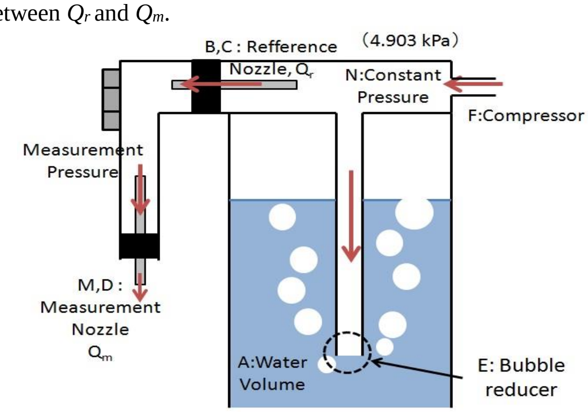


Figure 1 Paper permeability tester

2.3 P-diagram and Factors

P-diagram was obtained by Equations (1), (2), (3), and Figure 1. Measurement nozzle length is related to the measurement result in linear relation between nozzle length and Permeance. Therefore, measurement nozzle length which is the input signal is related linearly to Permeance which is the output, Y, by a function in Permeability Tester, Equation (3). Figure 2 shows the relation between Measurement Nozzle Length and Air permeance. The condition of flow was considered only for laminar flow, depicted as a solid line in Figure 2. Meanwhile, turbulent area where measurement nozzle length is shorter than 30 mm is ignored. Therefore, a Linear Equation method [4] was used to calculate SNR and sensitivity with dynamic response, Equations (4) and (5). M is distance from an average of input signal levels. Reference point which is the average of input signal level is 50 mm. The reason why Linear Equation method is used is because of the unknown whether the zero intercepts is reached when the turbulent area is ignored since only laminar flow is taken into measurement.

Constant pressure in the chamber always fluctuate, therefore, noise factor was determined.

$$\eta = 10\log\frac{\left(\frac{1}{r_0 r}\right)(S_\beta - V_e)}{V_e} \tag{4}$$

$$S = 10\log\frac{S_\beta - V_e}{r_0 r} \tag{5}$$

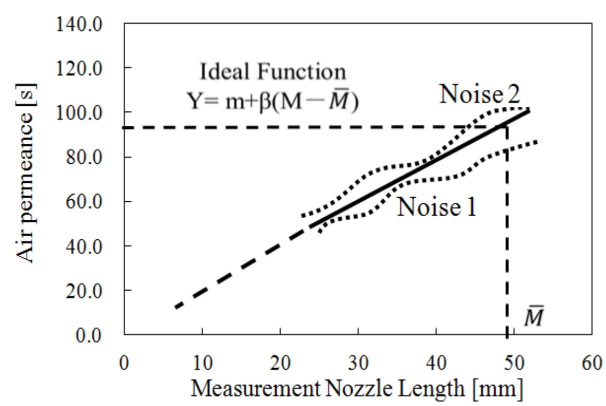


Figure 2 Ideal function for the tester

Six control factors were determined from the principal of Oken Tester. Level of input signal, noise factor, and each factor were summarized in Table 1, 2, and 3. Factor *A*; Value of water has not been defined in detail. Effect of value of water need to be found if the Tester should weight saving. Factor *B*, *C*, and *D*; Value of permeance depends on Reference Nozzle Length, Reference Nozzle Diameter, and Measurement Nozzle Diameter. Effects of these factors and optimum condition should be investigated to design a more robustness Tester using Taguchi Method with L_{18}.

Level of Reference Nozzle Length, Reference Nozzle Diameter, and Measurement Nozzle Diameter was determined under laminar flow where nozzle length is assumed in optimum condition around 40-55(mm). Factor *E*; bubble reducer is a plastic material to reduce amount of bubble inside of the Tester. The installed position of the bubble reducer is changed in three levels; that are upper, middle, and lower position from standard point set in this study. The different position will affect the length of the metallic pipe, thus, the pressure is kept constant.

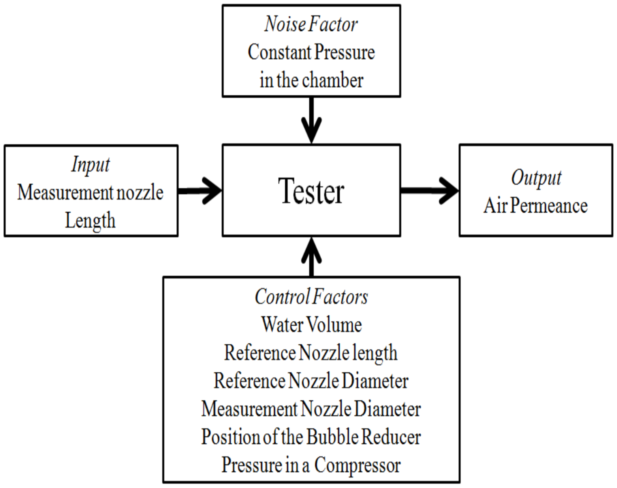


Figure 3 P-diagram

Table 1 Level of input signal

Signal Factor	Level 1	Level 2	Level 3	
Measurement Nozzle Length	45	50	55	mm
M (Distances from an Average)	-5	0	5	

Table 2 Level of noise factor

Noise Factor	Level 1	Level 2	
Pressure	4.80	4.90	kPa

Table 3 Level of control factors

	Control Factors	Level 1	Level 2	Level 3	
A	Water Volume	Nomal	-55		cm^3
B	Reference Nozzle Length	45	50	55	mm
C	Reference Nozzle Diameter	0.33	0.41	0.51	mm
D	Measurement Nozzle Diameter	0.33	0.41	0.51	mm
E	Position of Bubble Reducer	2	0	-2	mm
F	Pressure in Compressor	0.005	0.01	0.02	MPa

3.0 RESULTS AND DISCUSSION

Signal-to-Noise Ratio, SNR, and sensitivity were calculated by using data below. For instance, SNR and sensitivity calculation for run 1 is shown in the following equation.

S_T is the total sum of square of air permeance measurement data to calculate the total variation around the mean in run 1:

Table 4 Data of run 1

M 1		M 2		M 3	
N1	N2	N1	N2	N1	N2
101.0	100.7	109.8	109.0	120.0	119.0

$$S_T = y_{11}^2 + y_{12}^2 + y_{21}^2 + y_{22}^2 + y_{31}^2 + y_{32}^2 - S_m \quad (6)$$
$$= 101.0 + 100.7 + 109.8 + 109.0 + 120.0 + 119.0 - 72490$$
$$= 72840$$

S_m is the mean of run 1:

$$S_m = \frac{\left(\sum y_{ij}\right)}{kr_0} = 72490 \quad (7)$$

S_β is the variation caused by the linear effect of signal:

$$S_\beta = \frac{1}{r_0 r}[y_1\left(M_1 - \overline{M}\right) + y_2\left(M_2 - \overline{M}\right) + \cdots + y_k\left(M_k - \overline{M}\right)]^2 \quad (8)$$
$$= \frac{1}{100}[101.0 \times (45 - 50) + \cdots + 119.0 \times (55 - 50)]^2$$
$$= 347.82$$

S_e is the error variation:

$$S_e = S_T - S_\beta - S_m = 1.67 \quad (9)$$

V_e is the error variance:

$$V_e = \frac{S_e}{4} = 0.42 \quad (10)$$

Thus, SNR is calculated as:

$$\eta = 10 \log \frac{\left(1/100\right)(347.82 - 0.42)}{0.42}$$
$$= 9.21 \quad dB$$

The sensitivity is calculated as:

$$S = 10 \log \frac{347.82 - 0.42}{100}$$
$$= 5.41 \quad dB$$

Figure 4 shows an example of the ideal function with which permeance is related to factor levels linearly in the graph of run 1. Permeance in noise1 is larger than noise2 in each level.

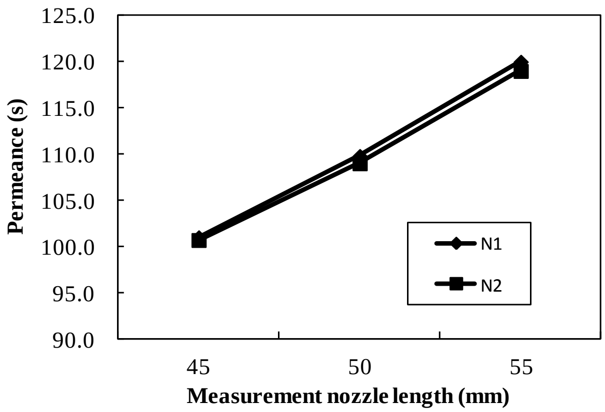


Figure 4 Ideal function graph for Run 1

Table 5 Result for the experiment

	A	B	C	D	E	F	M 1		M 2		M 3			
							N1	N2	N1	N2	N1	N2	SNR	Sensitivity
1	1	1	1	1	1	1	101.0	100.7	109.8	109.0	120.0	119.0	9.21	5.41
2	1	1	2	2	2	2	106.0	104.0	122.0	120.0	132.0	130.0	1.74	8.27
3	1	1	3	3	3	3	100.3	98.0	109.0	108.0	117.0	116.0	4.50	4.77
4	1	2	1	1	2	2	93.5	93.0	102.8	101.5	112.0	111.0	9.37	5.22
5	1	2	2	2	3	3	88.4	87.0	102.0	100.0	111.0	109.0	2.49	6.94
6	1	2	3	3	1	1	91.8	90.4	100.0	98.0	107.5	105.5	2.73	3.73
7	1	3	1	2	1	3	37.8	37.4	45.0	44.5	48.0	48.3	-0.50	0.42
8	1	3	2	3	2	1	32.6	31.8	35.6	34.7	38.8	38.0	1.52	-4.18
9	1	3	3	1	3	2	455.0	448.0	500.0	499.2	525.0	528.0	0.96	17.47
10	2	1	1	3	3	2	17.5	16.7	19.3	18.5	21.4	20.4	-3.09	-8.49
11	2	1	2	1	1	3	228.0	227.0	252.0	247.0	272.0	268.0	5.20	12.55
12	2	1	3	2	2	1	257.0	255.0	295.0	294.0	320.0	319.0	4.01	16.04
13	2	2	1	2	3	1	41.8	40.5	48.5	47.4	53.0	51.6	0.46	0.91
14	2	2	2	3	1	2	35.5	34.7	38.9	37.7	42.5	41.3	0.04	-3.39
15	2	2	3	1	2	3	518.0	510.0	560.0	550.0	604.0	600.0	4.81	18.88
16	2	3	1	3	2	3	15.7	14.8	17.3	16.5	18.8	18.2	-3.41	-9.86
17	2	3	2	1	3	1	199.0	197.0	214.0	213.0	233.0	232.0	8.27	10.75
18	2	3	3	2	1	2	223.0	220.0	255.0	250.0	274.0	268.0	0.47	13.85

Table 5 is Result for the Experiment. High SNR above an average, 2.71 (dB), is almost obtained around 100 (s). On the other hand, low SNR below an average is around under 50 (s). It seems that SNR depends on a measurement range where is a ratio of a flow in measurement nozzle and reference nozzle.

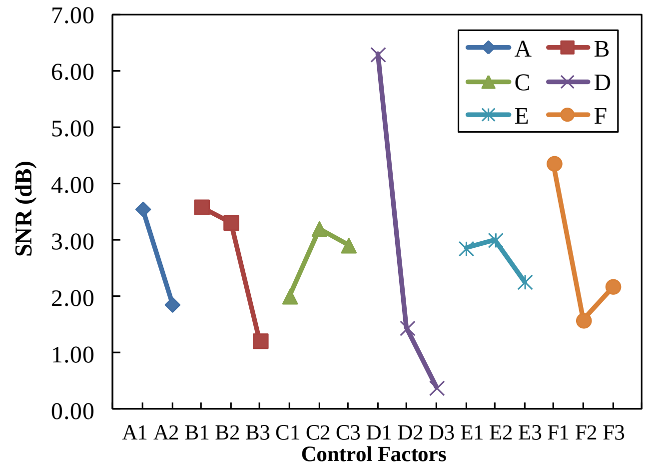


Figure 5 Factor effect plot for SNR

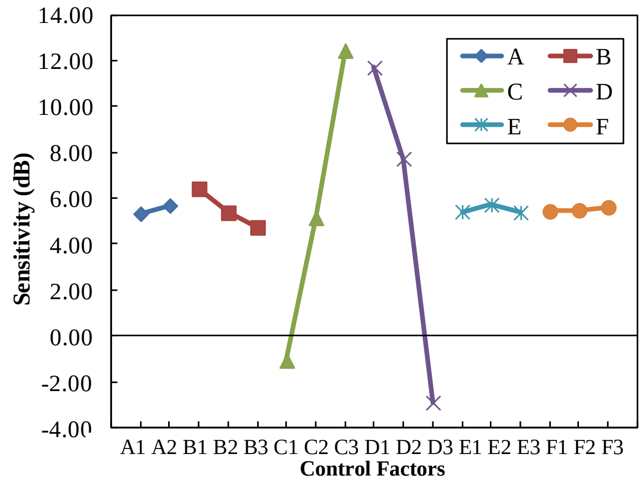


Figure 6 Factor effect plot for Sensitivity

Figure 6 Factor effect plot for Sensitivity Figure 5 shows the value of SNR, and Figure 6 shows the value of sensitivity obtained by L_{18}. Although initial condition is $A_1B_1C_2D_2E_2F_2$, optimum condition was obtained at $A_1B_1C_2D_1E_3F_1$, as circled in Figure 4.

Table 6 and *7* show a comparison of SNR and sensitivity. Both of SNR and sensitivity in estimation and confirmation have good reproducibility. dB gain difference in reproducibility of SNR was 21.3% and sensitivity was 9.68%.

Figure 7a and 7b show the ideal function graph for confirmation experiment which consists of initial and optimum condition respectively. Good improvement is shown in optimum condition $A_1B_1C_2D_1E_3F_1$ with SNR 8.08(dB) less than 30% reproducibility.

Table 6 SNR comparison

SNR	Estimation	Confirmation	
Optimum condition	9.69	8.08	
Initial condition	2.05	2.07	
Gain	7.64	6.02	[dB]
Gain difference	21.3%		

Table 7 Sensitivity comparison

Sensitivity	Estimation	Confirmation	
Optimum condition	27.65	12.76	
Initial condition	23.72	8.45	
Gain	3.93	4.31	[dB]
Gain difference	9.68%		

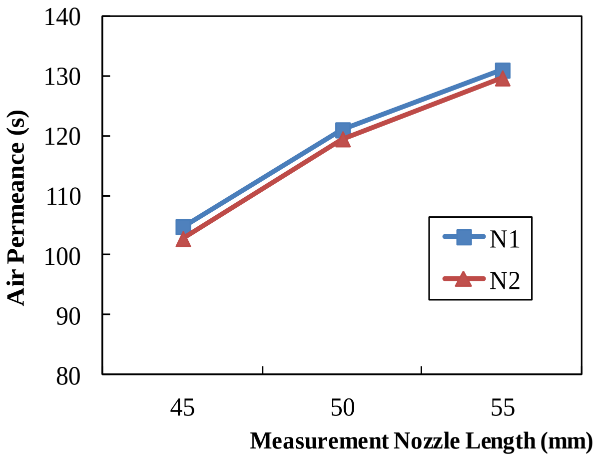


Figure 7(a) Ideal function graph of initial condition

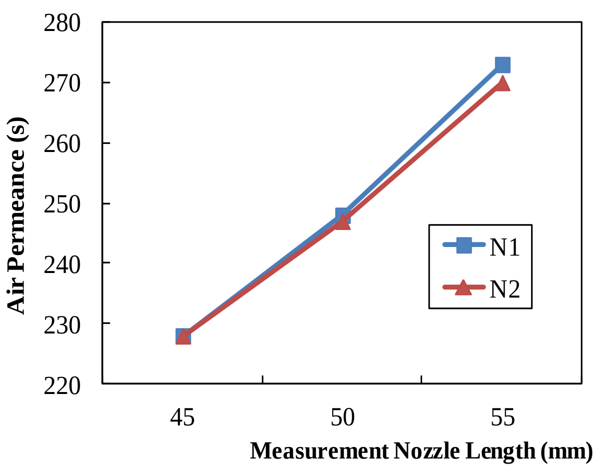


Figure 7(b) Ideal function graph of optimum condition

Sensitivity of *C* and *D* is remarkable. There are three reasons why sensitivity for factor *C* and *D* is large. Firstly, tolerance of nozzle diameter is wide approximately 10% from specification. Flow in a nozzle was greatly influenced by this wide tolerance of nozzle diameter. Robust design for tolerance diameter should be established for nozzle flow robustness.

Secondly, SNR depends on range of measurement. Air permeance is taken from the ratio of flow rate. Thus, related factors to the reference nozzle flow rate, *B* and *C*, are affecting other factors. When the value of air permeance is small, SNR tends to be small. An ideal condition of measurement is in same range, for instance around 100(s).

Finally, specification of the nozzle relates to flow rate in the nozzle. Flow rate in a nozzle is focused on as an effect for SNR. Since relation between flow rate in a nozzle and constant pressure in a chamber which is noise factor is linear, stabilizing flow in a nozzle represents being more robust. Relation between flow rate and differences of pressure obeys the law of Hagen-Poiseuille in the case of laminar flow in both nozzles. In addition, law of continuity can be applied to the flow system when flow speed is small [3]. Thus, the flow will be stable when the certain value is given in the nozzle flow rate. Then, the nozzle's flow rate used in the experiments is evaluated with Equations (1) and (2). Table 8 and 9 show the flow rate in a reference nozzle and measurement nozzle respectively.

Table 8 Flow rate in reference nozzle (cm^3/s)

Q_r	M 1		M 2		M 3		
	N1	N2	N1	N2	N1	N2	SNR
1	1.38	1.39	1.25	1.27	1.13	1.14	9.21
2	3.21	3.27	2.81	2.86	2.53	2.57	1.74
3	7.90	8.06	7.16	7.25	6.51	6.60	4.50
4	1.36	1.37	1.23	1.25	1.12	1.13	9.37
5	3.31	3.36	2.95	3.00	2.68	2.73	2.49
6	7.80	7.92	7.12	7.25	6.53	6.65	2.73
7	2.01	2.03	1.94	1.96	1.89	1.90	-0.50
8	4.87	4.92	4.77	4.82	4.66	4.71	1.52
9	0.58	0.60	0.48	0.49	0.42	0.42	0.96
10	2.69	2.72	2.67	2.70	2.65	2.68	-3.09
11	1.03	1.04	0.86	0.88	0.74	0.76	5.20
12	2.21	2.25	1.79	1.81	1.53	1.54	4.01
13	2.16	2.18	2.08	2.10	2.01	2.03	0.46
14	5.25	5.31	5.12	5.18	4.98	5.04	0.04
15	0.52	0.53	0.43	0.44	0.37	0.37	4.81
16	2.22	2.24	2.21	2.23	2.20	2.22	-3.41
17	1.11	1.13	0.96	0.97	0.83	0.84	8.27
18	2.41	2.46	1.98	2.03	1.71	1.76	0.47

Table 9 Flow rate in measurement nozzle (cm^3/s)

Q_m	M 1		M 2		M 3		
	N1	N2	N1	N2	N1	N2	SNR
1	1.37	1.38	1.14	1.16	0.94	0.96	9.21
2	3.03	3.14	2.30	2.38	1.92	1.98	1.74
3	7.88	8.22	6.57	6.72	5.57	5.69	4.50
4	1.45	1.47	1.20	1.23	1.00	1.02	9.37
5	3.75	3.87	2.89	3.00	2.41	2.50	2.49
6	8.50	8.76	7.12	7.40	6.07	6.30	2.73
7	5.32	5.42	4.31	4.40	3.94	3.94	-0.50
8	14.93	15.47	13.39	13.89	12.00	12.39	1.52
9	0.13	0.13	0.10	0.10	0.08	0.08	0.96
10	15.39	16.27	13.86	14.59	12.40	13.14	-3.09
11	0.45	0.46	0.34	0.36	0.27	0.28	5.20
12	0.86	0.88	0.61	0.62	0.48	0.48	4.01
13	5.16	5.39	4.28	4.43	3.79	3.94	0.46
14	14.79	15.29	13.16	13.75	11.71	12.21	0.04
15	0.10	0.10	0.08	0.08	0.06	0.06	4.81
16	14.14	15.14	12.77	13.52	11.69	12.19	-3.41
17	0.56	0.57	0.45	0.46	0.35	0.36	8.27
18	1.08	1.12	0.78	0.81	0.63	0.66	0.47

When the flow in a reference nozzle, Q_r, is 0.8-1.4 (cm^3/s), SNR tends to be large. On the other hand, when the flow rate in a measurement nozzle, Q_m, is more than 10 (cm^3/s), SNR is lower than zero.

■4.0 CONCLUSION

Optimum condition for the Paper Permeability Tester was obtained by using orthogonal array L18. Reproducibility of gain with SNR and sensitivity was confirmed. Difference of SNR dB gain was 21.3% between estimation and confirmation.

According to Figure 6, factor C and D are the most sensitive factor and best to adjust to desired value. Tolerance of nozzle diameter had influenced the result of measurement. Tolerance of specification of nozzle diameter and nozzle length is required to make the paper permeability tester more robust. High flow rate in a nozzle is not robust. Stability of a flow is needed to get reliable measurement result with the Tester.

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