

Influence of various parameters on pressure drop during flow condensation in pipe Using Taguchi Approach

Lohith.N¹, H.B. Bhaskar²and Manu.S³

^{1, 2, 3}Assistant Professor, Department of Mechanical Engineering, Sri Siddhartha Institute of Technology, Tumkur, Karnataka, India

* Corresponding Author: lohithge@gmail.com

Abstract: The process parameters optimization is the essential step in Taguchi approach, which utilizes orthogonal array for maximizing the effect of controllable parameters and for minimizing the effect of uncontrollable process parameters. This study presents optimal parameters that influences on the flow condensation pressure drop in the pipe using Taguchi method. This investigation was carried out for optimization of pressure drop (ΔP) for flow condensation. The factors considered at three different levels are saturation temperature (T), Diameter (D), Mass flux (G). The L_{27} orthogonal array is employed and signal-to-noise (S/N) ratio and the analysis of variance, (ANOVA) are considered for identifying the best optimum conditions under larger is the better characteristic.

Keywords: Pressure drop, Diameter, Mass flux, ANOVA, Flow condensation, Taguchi approach.

1. Introduction

The two-phase frictional pressure drop is an important design parameter in many systems; therefore, it is required to predict accurately. Pressure drop depends on various factors including the flow geometries, flow mechanisms, interfacial shear stress and fluid properties. Various methods have been offered to find the frictional ΔP ; many studies have been conducted for horizontal or vertical upward flow as opposed to vertical downward flow. Many of the classical models make use of a two-phase multiplier to account for the differences from single-phase flow.

Webb and Ermis [1] investigated the effect of hydraulic diameters on ΔP and the heat transfer coefficient (HTC) during the flow condensation of R134a. Four different multi-port aluminium tubes were considered with hydraulic diameters of 0.44, 0.611, 1.33 and 1.564 mm. Good agreement obtained between their experimental data. They reported that correlation gives satisfactory results for small and large diameters and is valid for “shear controlled” condensation. S.N. Sapali et al., [2] experimentally investigated the pressure drop and the two-phase HTC of R-404A at various condensing temperatures in a micro-fin tube (8.96 mm ID) and smooth tube (8.56 mm ID). The experimental study was carried out at mean saturated condensing temperatures varying from 35°C to 60°C. The experimental results from both micro fin tubes and smooth tube showed the average HTC and ΔP increases with G, but decreases with increasing condensing temperature. Lee and Lee [3] developed a correlation for the two-phase frictional ΔP in horizontal rectangular channels with hydraulic diameter (D_h) $0.78 < D_h < 6.67$ mm. Experiments were conducted using a 20-mm wide test section with the channel height varying between 0.4 mm and 4 mm. The water and air superficial



velocities fluctuating from 0.03 to 2.39 m/s and from 0.05 to 18.7 m/s, respectively. The experimental facility was authenticated by comparing the single-phase friction factor for air to laminar and turbulent flow models. The two-phase ΔP model was developed by following the method of Lockhart and Martinelli [4]. The Chisholm parameter C showed poor agreement with the Lockhart and Martinelli model, especially for the laminar-laminar regime and the smallest channel size, in which the flow pattern is mostly plug or slug flow. As in Lockhart and Martinelli's model, the flow was classified into four regimes, but the value of C was modified to account for surface tension, channel size and flow rate. Their model was able to predict their data to within $\pm 10\%$ as well as predict the data from other horizontal and vertical studies to within $\pm 20\%$. Cavallini et al., [5] investigated HTC and ΔP during condensation of seven synthetic refrigerants. The working fluids investigated included pure HCFCs and HFCs as well as azeotropic and zeotropic mixtures. Models were developed from a data bank of 600 data points for condensation in 8 mm diameter horizontal tubes. In the data bank, the saturation temperature fluctuating from 30°C to 70°C and the G ranged from 100 to $750\text{ kg/m}^2\text{sec}$. The models were also compared to 1778 data points for HCFC and HFC refrigerants as well as 386 data points for CFC refrigerants. The data were grouped into flow regimes based on the dimensionless vapour velocity ($jv^* = xG / [gD_{pv}(\rho_l - \rho_v)]$) 0.5) and the turbulent-turbulent Martinelli parameter (X_{tt}). Based on flow regime transition criteria from the literature, flows with dimensionless vapour velocity > 2.5 were assigned to the annular flow regime. Below this value, wavy-stratified flow and slug flow were observed with a transition at $X_{tt} = 1.6$. The pressure drop model was developed using the Friedel [6] two-phase multiplier. It was observed that heat transfer correlations that use the Friedel pressure drop correlation such as Kosky and Staub [7] failed to adequately predict the data in the annular regime. They note that the Friedel correlation was developed to cover all flow regimes and therefore may not be best suited for the annular regime specifically. For the annular regime, a regression analysis was conducted on the data set to adjust the coefficients for the Friedel horizontal ΔP correlation. The resulting equation predicted the data with a mean deviation of -7% and a mean absolute deviation of 14% . Cavallini et al. [5] intended a similar model to account for factors such as entrainment, surface roughness and smaller diameters. Garimella et al., [8] studied horizontal condensation of R134a for tube diameters scaled from 0.5 to 4.9 mm at a saturation pressure of 1396 kPa (52.3°C). An experimentally validated multiple flow regime ΔP model was developed from these data and previous studies. Previous work by Coleman and Garimella [9] on flow regime identification was used to allocate appropriate flow regimes to the ΔP data. Distinct models were developed for intermittent/wavy flow and annular/mist/dispersed flow based on previous work by Garimella et al., [10], Garimella et al., [11], and Garimella [12]. The intermittent flow model included the offerings of the liquid slug, the film-slug interface and the slug-to-bubble transitions. A slug frequency model was developed for this regime. The annular model was developed by relating the measured interfacial shear stress to the agreeing single-phase friction factor. The data were grouped based on liquid-phase laminar ($Re_l < 2100$) and turbulent ($Re_l > 3400$) flow. Linear interpolation was used to determine the pressure drop in the transition region. Surface tension effects were considered by including the non-dimensional parameter ψ , as defined by Lee and Lee, in the expression for the interfacial friction factor. The model forecasted 82% of the experimental data to within $\pm 21\%$. It also showed the decrease in two-phase ΔP towards the single-phase gas value at high quality ($x \gtrsim 0.9$). Dalkilic et al., [13] measured the frictional ΔP during condensation of R600a (isobutane) and R134a. The tests with R600a were in horizontal circular tubes with a 4mm diameter and G scaled from 75 – $115\text{ kg/m}^2\text{sec}$. The tests with R134a were in vertical downward circular tubes with a diameter of 8.1 mm and G scaled from 300 to $400\text{ kg/m}^2\text{sec}$. All the experiments in this study were performed in the annular flow regime; therefore, the quality range for R600a was 0.45 – 0.9 while for R134a, it was 0.7 – 0.95. The measured frictional ΔP was compared with correlations in the literature. It was observed that the Cavallini et al. and Chen et al. [14] correlations predicted the vertical downward pressure drop in the R134a tests the best. Of these two, only the Chen correlation was also able to predict the R600a data. It was noted that the pressure drop during annular flow was independent of tube orientation. Kim and

Mudawar [15] compiled a database of 7115 frictional ΔP data points from 36 different bases to construct a universal correlation for frictional ΔP applicable to many different fluids, geometries and flow conditions. They note that a fundamental difference in two-phase flow patterns between boiling flows and adiabatic or condensing flows is the presence of entrained droplets in annular flow. Therefore, their database consisted of only adiabatic and condensing two-phase conditions, because the annular regime is usually dominant in mini- and microchannels. The diameters considered varies from 0.0695 to 6.22 mm, and the G considered was 4.0 to 8528 kg/m²sec. The majority of the data is for horizontal channels; however, one study (135 data points) with vertical upward flow was also included. They compared many common correlations with their database and noted that only a few were able to adequately predict the full body of data. Therefore, a new model was given as a modification to the Lockhart and Martinelli correlation. Because shear and surface tension effects are stronger than gravitational effects for mini- and microchannels, an expression for C was determined using dimensionless groups such as the Reynolds number, Suratman number, and density ratio. The resulting model showed good agreement with the data, having an average absolute deviation of 23.3% over the entire database. However, they note the need for mechanistic theoretical models in the future.

The Taguchi uses orthogonal arrays to organize the parameters that affects the process at different levels. Instead of testing all possible combinations like the factorial design, the Taguchi method tests pairs of combinations. This permits for the gathering of the necessary data to find which factors mostly distress product quality with a minimum amount of experimentation, thus saving resources and time. Another benefit is that optimal working conditions identified from the experimental work could be replicated in real applications [16–21]. Therefore, the present work aims at optimization for ΔP during flow condensation in pipe with the aid of taguchi method.

2. Taguchi Experiment: Design and Analysis

The simulation tests were carried out as per the standard L_{27} orthogonal array. The various factors taken for the calculation were Diameter in m, Saturation temperature in °C and Mass flux in kg/m²sec. Each factor was provided with three levels as displayed in Table 1.

Table 1. Factors and Levels for flow condensation in pipe.

Factors	Unit	Level 1	Level 2	Level 3
Diameter-D	m	0.001	0.002	0.003
Saturation Temperature-T	°C	50	55	60
Mass Flux-G	Kg/m ² sec	100	200	300

Pressure gradient in Table 2 are calculated using the Garimella et al., [8] correlation, which is given as follows

$$\frac{\Delta p}{L} = \frac{1}{2} f_t \frac{G^2 x^2}{\rho_v \alpha^{2.5} D} \quad (1)$$

Table 2. Orthogonal array (L27) of Taguchi and Signal to noise ratio for pressure drop.

L ₂₇ test	D (m)	T (°C)	G (kg/m ² sec)	ΔP(kPa/m)	S/N ratio
1	0.001	50	100	2.798176	8.9375
2	0.001	55	100	2.564267	8.179263
3	0.001	60	100	2.354683	7.438649
4	0.001	50	200	8.77044	18.86043
5	0.001	55	200	8.037288	18.10219
6	0.001	60	200	7.380381	17.36158
7	0.001	50	300	17.10994	24.66497
8	0.001	55	300	15.67966	23.90673
9	0.001	60	300	14.39812	23.16612
10	0.002	50	100	1.192302	1.527722
11	0.002	55	100	1.092633	0.769485
12	0.002	60	100	1.003329	0.028871
13	0.002	50	200	3.737081	11.45065
14	0.002	55	200	3.424685	10.69241
15	0.002	60	200	3.144777	9.951798
16	0.002	50	300	7.290536	17.25519
17	0.002	55	300	6.681095	16.49695
18	0.002	60	300	6.135033	15.75634
19	0.003	50	100	0.723876	-2.80672
20	0.003	55	100	0.663364	-3.56496
21	0.003	60	100	0.609146	-4.30557
22	0.003	50	200	2.268874	7.116207
23	0.003	55	200	2.079211	6.35797
24	0.003	60	200	1.909272	5.617355
25	0.003	50	300	4.426264	12.92075
26	0.003	55	300	4.056257	12.16251
27	0.003	60	300	3.72473	11.4219

3. Results and discussion

3.1. Signal to Noise (S/N) ratio analysis

This response analysis gives determination of control parameters like D, T and G on pressure drop. The parameter with high S/N ratio yields optimal quality with low variance using MINITAB. Pressure drop value feature chosen was “larger is the better” kind and similar kind of response was used for signal to noise ratio as shown under.

The S/N ratio for the response for larger-the-better characteristic is analysed using the equation 2 for the entire test.

$$\text{i.e. } \frac{S}{N} = -10 \log_{10} \left(\frac{1}{n} \sum \frac{1}{y^2} \right) \quad (2)$$

The S/N ratio values are determined by using Equation 2. The S/N ratio response was inspected by means of 27 tests and displayed in Table 2. The main effect plots of S/N ratios and Means for

ΔP are revealed in figure 1 and figure 2. The table and plots demonstrates highest-pressure drop of 17.10994 kPa/m attained for D of 0.001m, T of 50°C and G of 300 kg/m²sec. From the results of response table of S/N ratio, it is obvious that Mass flux G exhibited highest contribution, Diameter D exhibited medium contribution and Saturation Temperature T exhibited very less contribution on pressure drop.

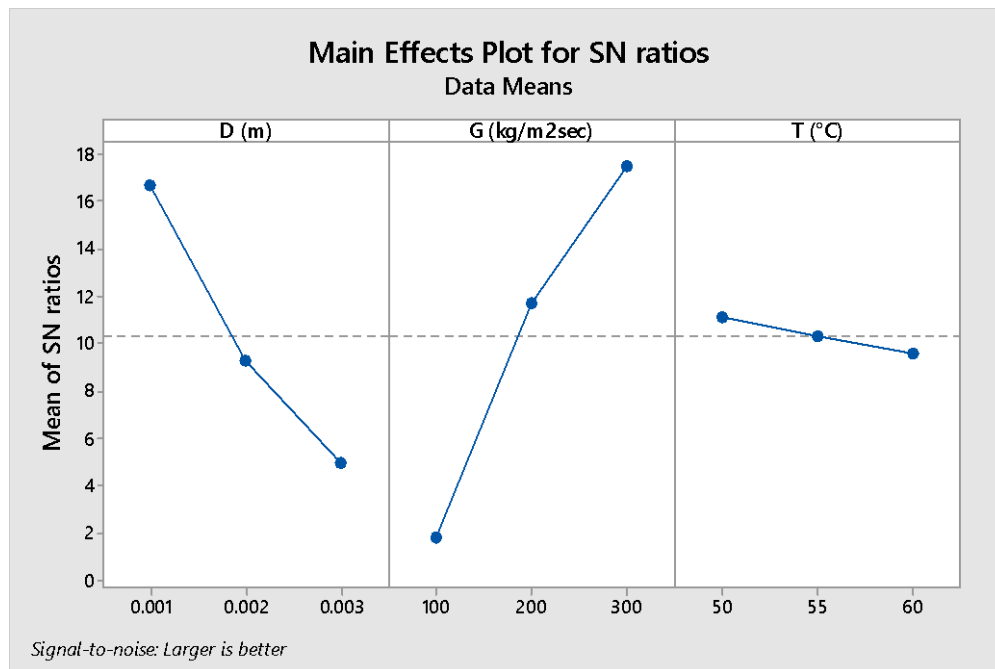


Figure 1 Effect plot for SN ratios on Pressure drop

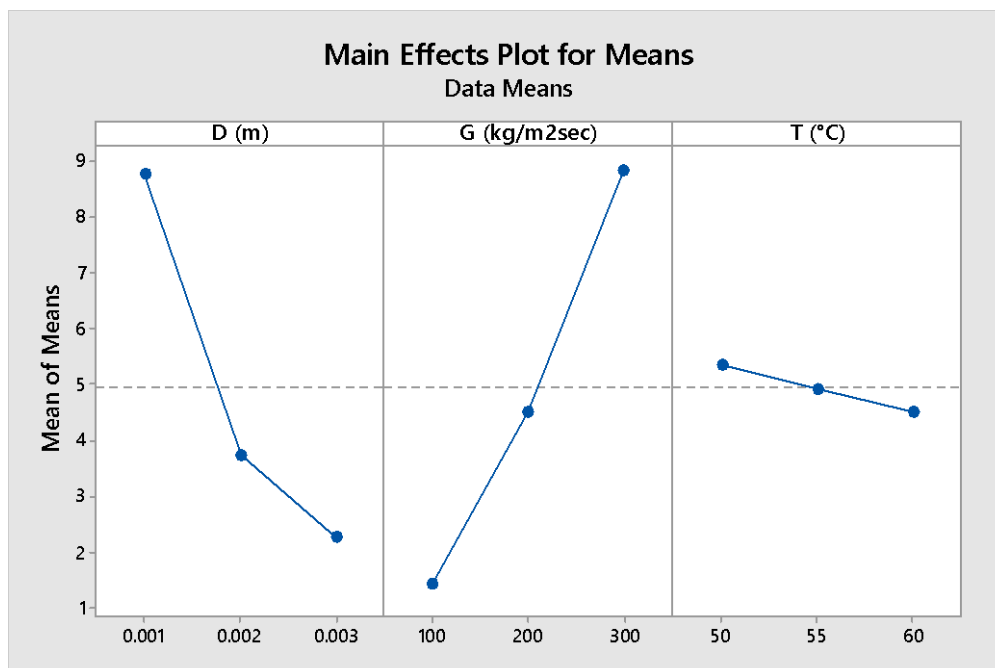


Figure 2 Effect plot for Means on Pressure drop.

Table 3. Response for pressure drop.

Response Table for Signal to Noise Ratios			
“Larger is better”			
Level	D (m)	G (kg/m ² sec)	T (°C)
1	16.735	1.800	11.103
2	9.325	11.723	10.345
3	4.991	17.528	9.604
Delta	11.744	15.727	1.499
Rank	2	1	3
Response Table for Means			
Level	D (m)	G (kg/m ² sec)	T (°C)
1	8.788	1.445	5.369
2	3.745	4.528	4.920
3	2.273	7.389	4.518
Delta	6.515	7.389	0.851
Rank	2	1	3

3.2. Analysis of Variance (ANOVA)

ANOVA is a statistically built, objective judgement-making tool for identifying any dissimilarities in the average performance of groups of items that were verified. ANOVA aids in analysing the importance of all-required factors and their interactions by matching the average square against an estimate of the experimental errors at specific confidence levels. This analysis was conducted for a level of significance of 5% (that is the level of confidence of 95%). Table 4 displays the ANOVA results.

Table 4. ANOVA results for pressure drop parameters.

Source	DF	Seq SS	Adj SS	Adj MS	F value	P value	% Contribution
D (m)	2	210.126	210.126	105.063	2139.76	0.000	38.68
G (kg/m ² sec)	2	247.920	247.920	123.960	2524.63	0.000	45.63
T (°C)	2	3.261	3.261	1.631	33.21	0.000	0.59
D (m)*G (kg/m ² sec)	4	79.211	79.211	19.803	403.31	0.000	14.57
D (m)*T (°C)	4	1.042	1.042	0.261	5.31	0.022	0.18
G (kg/m ² sec)*T(°C)	4	1.229	1.229	0.307	6.26	0.014	0.22
Error	8	0.393	0.393	0.049			
Total	26	543.182					100

It can be observed from the ANOVA analysis (table 4) that the diameter, mass flux and saturation temperature have the influence on pressure drop. The last column of table 4 shows the percentage contribution of each parameter on the total variation representing their degree of impact on the result. The mass flux (45.63%) and diameter (38.68%) have great influence on the pressure gradient while the saturation temperature has minimum contribution (0.59%). The interaction between Mass flux and Diameter, Diameter and Saturation temperature, and Mass flux and Saturation temperature showed 14.57%, 0.18% and 0.22% contribution respectively on Pressure drop.

4. Conclusion

From the study, conclusions drawn are,

- Mass flux put forth significant effect on Pressure gradient, tailed by Diameter and Saturation temperature exhibited lower effect.
- The analysis of variance indicates that the mass flux (45.63%) and diameter (38.68%) have significant influence on the pressure drop and the saturation temperature has minimum contribution (0.59%).
- The interaction between Mass flux and Diameter was 14.57%, whereas Diameter and Saturation temperature, Mass flux and Saturation temperature will influence very less (0.18% and 0.22% respectively).
- Maximum pressure drop obtained was 17.10994 kPa/m for D of 0.001m, T of 50°C and G of 300 kg/m²sec. The results indicated that the Mass flux influences more on ΔP .

References

- [1] Webb and Ermis (2001), "Effect of Hydraulic Diameter on Condensation of R-134a in Flat, Extruded Aluminium Tubes", *Journal of Enhanced Heat Transfer*, **Vol.8**, pp. 77–90.
- [2] S.N. Sapali, Pradeep a.Patil (2009) "Two-phase condensation heat transfer coefficients and pressure drops of r-404a for different condensing temperatures in a smooth and micro-fin tube". *International Journal of Engineering Science and Technology* **Vol.1 (2)**, 2009, pp.43-58.
- [3] Lee, H. J. and S. Y. Lee (2001), "Pressure Drop Correlations for Two-Phase Flow within Horizontal Rectangular Channels with Small Heights," *International Journal of Multiphase Flow* **Vol. 27(5)** pp. 783-96.
- [4] Lockhart, R. W. and R. C. Martinelli (1949), "Proposed Correlation of Data for Isothermal Two-Phase Two-Component Flow in a Pipe," *Chem. Eng. Prog. Symp. Series* **Vol. 45** pp. 39-47.
- [5] Cavallini, A., D. Del Col, M. Matkovic and L. Rossetto (2009), "Frictional Pressure Drop during Vapour–Liquid Flow in Minichannels: Modelling and Experimental Evaluation," *International Journal of Heat and Fluid Flow* **Vol. 30(1)** pp. 131-39.
- [6] Friedel, L. (1979), "Improved Friction Pressure Drop Correlation for Horizontal and Vertical Two Phase Flow," *3R International* **Vol. 18(7)** pp. 485-91.
- [7] Kosky, P. G. and F. W. Staub (1971), "Local Condensing Heat Transfer Coefficients in the Annular Flow Regime," *AIChE Journal* **Vol. 17(5)** pp. 1037-43
- [8] Garimella, S., A. Agarwal and J. D. Killion (2005), "Condensation Pressure Drop in Circular Microchannels," *Heat Transfer Engineering* **Vol. 26(3)** pp. 28-35.
- [9] Garimella, S., Agarwal, A., Coleman, J.W. (2003), "Two-Phase Pressure Drops in the Annular Flow Regime in Circular Microchannels," *International Congress of Refrigeration*, Washington D.C.
- [10] Garimella, S. and T. M. Bandhauer (2001), "Measurement of Condensation Heat Transfer Coefficients in Microchannel Tubes," *Proc. 2001 International Mechanical Engineering Congress and Exposition*, pp. 1-7.
- [11] Garimella, S., J. D. Killion and J. W. Coleman (2002), "Experimentally Validated Model for Two-Phase Pressure Drop in the Intermittent Flow Regime for Circular Microchannels," *Journal of Fluids Engineering, Transactions of the ASME* **Vol. 124(1)** pp. 205-214.
- [12] Garimella, S., J. D. Killion and J. W. Coleman (2003), "An Experimentally Validated Model for Two-Phase Pressure Drop in the Intermittent Flow Regime for Noncircular Microchannels," *Journal of Fluids Engineering, Transactions of the ASME* **Vol. 125(5)** p. 887.
- [13] Dalkilic, A. S. and S. Wongwises (2010b), "New Experimental Approach on the Determination of Condensation Heat Transfer Coefficient Using Frictional Pressure Drop and Void Fraction Models in a Vertical Tube," *Energy Conversion and Management* **Vol. 51(12)** pp. 2535-47.

- [14] Chen, I. Y., K. S. Yang, Y. J. Chang and C. C. Wang (2001), "Two-Phase Pressure Drop of Air-Water and R-410a in Small Horizontal Tubes," *International Journal of Multiphase Flow* **Vol. 27(7)** pp. 1293-99.
- [15] Kim, S.M and I. Mudawar (2012), "Universal Approach to Predicting Two-Phase Frictional Pressure Drop for Adiabatic and Condensing Mini/Micro-Channel Flows," *International Journal of Heat and Mass Transfer* Vol. **55(11-12)** pp. 3246-61.
- [16] R.N .Kackar, 1985, Offline quality control, parameter design and Taguchi method, *J.Qual.Technol.***17** 176–209.
- [17] M.S. Phadke, R.N .Kackar, D.V. Speeney, M.J. Grieco, 1983, Offline quality control in integrated fabrication using experimental design, *Bell Syst. Tech. J.* **62** 1273–1309.
- [18] G. Taguchi 1987, *Taguchi Techniques for Quality Engineering*, Quality Resources, New York.
- [19] P.J.Ross 1988, *Taguchi Techniques for Quality Engineering*, McGraw Hill, New York.
- [20] M.S.Phadke 1989, *Quality Engineering Using Robust Design*, Prentice Hall, New Jersey.
- [21] R.K. Roy 2001, *Design of Experiments Using the Taguchi Approach*, John Wiley and Sons Inc., Hoboken, NJ.