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Optimization analysis of the inkjet using the Taguchi method

Taguchi metodu kullanılarak mürekkep püskürtülmesinin optimizasyon analizi

Burak TÜRKAN[1*]

[1]Machinery Program, Gemlik Asım Kocabıyık Vocational School, Bursa Uludag University, Bursa, Turkey.
burakt@uludag.edu.tr

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Abstract

Inkjet printers are effective tools for combining high resolution with acceptable velocity and low cost output. In this study, the incompressible Navier-Stokes equations were used to investigate the weight change of the inkjet droplets for the two-phase flow. For the ink color black, red and blue, for the nozzle inlet radius 0.02, 0.03 and 0.04mm, and for the inlet velocity 0.2, 0.4 and 0.6 m/s were taken. Taguchi analysis was performed, and it was seen that the most effective parameter on ink weight was the inlet velocity. It has been determined that the optimum conditions for weight maximization are black color, 0.02mm nozzle radius and 0.6 m/s inlet velocity. After determining the optimum conditions, droplet flow analysis was numerically carried out with the Comsol program to detect the change in different colored inks. It showed that the droplet fluid amount was greater and the time it took to reach the target area was shorter for inks with higher density and viscosity.

Keywords: Comsol, Droplet, Inkjet, Taguchi.

Öz

Mürekkep püskürtmeli yazıcılar, yüksek çözünürlüğü kabul edilebilir bir hızla birleştirmek ve düşük maliyet ile çıktı almak için etkili araçlardır. Bu çalışmada, iki fazlı akışda mürekkep püskürtmeli damlacıkların ağırlık değişimini araştırmak için sıkıştırılamaz Navier-Stokes denklemleri kullanıldı. Mürekkep rengi için siyah, kırmızı ve mavi, kanal giriş yarıçapı için 0.02, 0.03 ve 0.04 mm ve giriş hızı için 0.2, 0.4 ve 0.6 m/s alınmıştır. Taguchi analizi yapılmış ve mürekkep ağırlığı üzerinde en etkili parametrenin giriş hızı olduğu görülmüştür. Ağırlık maksimizasyonu için optimum koşulların siyah renk, 0.02 mm kanal yarıçapı ve 0.6 m/s giriş hızı olduğu belirlenmiştir. Optimum koşullar belirlendikten sonra farklı renkli mürekkeplerdeki değişimi tespit etmek için Comsol programı ile sayısal olarak damlacık akış analizi incelenmiştir. Daha yüksek yoğunluk ve viskoziteye sahip mürekkepler için damlacık sıvı miktarının daha fazla olduğu ve hedef alana ulaşma süresinin daha kısa olduğu görülmüştür.

Anahtar kelimeler: Comsol, Damlacık, Mürekkep püskürtme, Taguchi.

1 Introduction

Injecting little drops of fluid from a nozzle on the surface of a piece of paper refers to the working basis behind inkjet technology. Designers can study various parameters to investigate the characteristics of a printer. For example, they change the geometric and kind of inkjet to obtain drops of various volumes. The speed and resolution of the final images are the basis of a printer. The velocity at which ink is injected through the nozzle significantly affects the size and speed of the sprayed droplets. It is important to create a simulation model for understanding fluid flow. These printers are used for diagnostics, analysis and drug research [1].

Examining the properties of the ink with the screen imaging method is difficult. Therefore, it is possible to examine how the ink droplets flow by using computational fluid dynamics (CFD). For this, both Newtonian and non-Newtonian inks have been developed [2]-[4]. Messerschmitt [5] Xu and Willenbacher [6] used high speed video imaging technologies to examine the separation process of ink as droplets. They defined 3 main regions. These are the pre-injection zone, the attachment zone up to the detachment position, and the ink spreading and settling zone. Yang and Liu [7] conducted experiments using different velocities to test the adhesiveness values of ink. They showed that the ink maintained a higher adhesiveness value at higher velocities. Referencing to Kapur [8], Riemer [9] and Messerschmitt [5] studies, they obtained a CFD model to calculate the ink volume. Yu Sakai Sethian [10] developed a simulation model in order to test the drop size and motion in inkjet printers. They obtained a numerical solution by modeling the flow at the printer head of the inkjet printer. Aleinov et al. [11] and Sou et al. [12] have developed new methods to calculate fluid motion behavior and volume using numerical solution methods to solve the Navier-Stokes equations. Chorin [13] studied the flow velocity field with incompressible Navier-Stokes equations. Uner and Gurcum [14] examined the conductive ink applications in electronics, textiles and applications made with inkjet printing techniques separately. It has been determined that the porous structure and flexible form of the textile surface negatively affects the efficiency of the printed circuit. Thus, several simulation studies have been carried out in the literature [15]-[17].

In this study, the parameters affecting the weight of the ink droplet were analyzed using both numerical and Taguchi statistical data analysis methods. Statistically, the effects of 3 parameters were investigated in detail. In the inkjet nozzle modeled according to these data, the aim was to evaluate the velocity, weight and visual flow results of the ink drop after leaving the nozzle at the same time. The basis here is to determine the priority design parameters correctly in the printer design and to consider the optimization study in the light of this information. It is also discussed that the density of

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[*] Corresponding author/Yazışılan Yazar

the ink has a significant effect on flow performance as well. In addition, the physical properties of the liquid and the importance of the sprayer design were investigated using the inkjet.

2 Material and method

Figure 1 indicates the geometry of the inkjet analyzed in this study. Due to the symmetry, our model is designed in 2D. Ink is injected in 10 microseconds, allowing the ink to flow out of the nozzle. When the injection process is finished, a drop of ink leaves the system and tries to reach its target point.

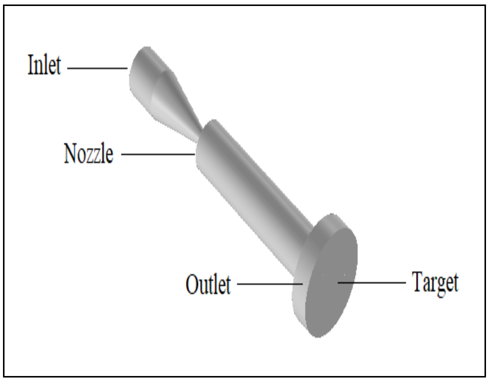

Figure 1. Geometry.

2.1 The Taguchi method

In this study, the Taguchi method was used to optimize the parameters affecting the ink mass (ink color, inlet radius and entry velocity). As the number of factors affecting the ink mass increases, the number of experiments to be performed increases as well. This also increases costs and makes implementation difficult. Therefore, the Taguchi method, which is efficient to apply in multi-factor situations, can be used. In this method, first, an orthogonal array suitable for the total degrees of freedom (TDF) obtained by summing the DF (degrees of freedom) values for each parameter should be selected.

In this study, 3 levels were chosen for each of the 3 parameter values. The TDF value for each parameter was obtained by subtracting 1 from the levels of the parameters. There are a total of 6 TDF for 3 levels of 3 parameter values (Table 1). For the ink color black, red and blue, for the nozzle inlet radius 0.02, 0.03 and 0.04 mm, and for the inlet velocity 0.2, 0.4 and 0.6 m/s were taken. The numbering of samples showing the levels of ink mass parameters and the experimental layout chosen using the Taguchi L9 orthogonal array are given in Table 2. The results obtained from the experiment are converted to the S/N (signal to noise) ratio in the Taguchi method. The signal-to-noise (S/N) ratio is used in data analysis to allow control of the response and reduce the variability associated with the response. In the Taguchi method, there are three performance criteria for the S/N ratio: minimum (smaller-the better), maximum (larger-the-better) and average (nominal-the-best). In this study, the maximum mass objective function is defined. Equation 1 is used for maximum performance values [18].

$$\mathrm{S/N}_{max} = -10log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{{y_i}^2}\right) \qquad (1)$$

Where, n is the number of tests and y_i is the number of experimental data observed for the performance characteristics.

Table 1. Parameters used in the study and their levels.

Parameter	DF (Level no 1)	Level 1	Level 2	Level 3
Ink color	2	black	red	blue
Nozzle radius (mm)	2	0.02	0.03	0.04
Inlet velocity (m/s)	2	0.2	0.4	0.6
Total DF	6			

Table 2. Selected parameters and levels using the Taguchi orthogonal $L9$ array.

Orthogonal array	Experiment no	Ink color	Nozzle radius (mm)	Inlet velocity (m/s)
111	1	black	0.02	0.2
122	2	black	0.03	0.4
133	3	black	0.04	0.6
212	4	red	0.02	0.4
223	5	red	0.03	0.6
231	6	red	0.04	0.2
313	7	blue	0.02	0.6
321	8	blue	0.03	0.2
332	9	blue	0.04	0.4

2.2 Mathematical modeling for numerical analysis

2.2.1 Convection of the fluid

The following equation defines the relocation of the rebooted level set function:

$$\frac{\partial\emptyset}{\partial t} + u.\nabla\emptyset + \gamma\left[\left(\nabla\left(\emptyset(1-\emptyset)\frac{\nabla\emptyset}{|\nabla\emptyset|}\right)\right) - \varepsilon\nabla.\nabla\emptyset\right] = 0 \qquad (2)$$

Where, $\varepsilon = h_c/2$ can be taken, h_c is the mesh size in the region through which the droplet passes. The restart amount is γ. The following expression is used for density and viscosity change. [19]-[21];

$$\rho = \rho_{air} + (\rho_{ink} - \rho_{air})\emptyset \quad \mu = \mu_{air} + (\mu_{ink} - \mu_{air})\emptyset \qquad (3)$$

2.2.2 Transport of mass and momentum

Ink and air can be took into account uncompressed. Navier-Stokes equations;

$$\rho\left(\frac{\partial u}{\partial t} + u.\nabla u\right) - \nabla.\left(\mu(\nabla u + \nabla u^T)\right) + \nabla p = F_{st} \quad (\nabla.u) = 0 \qquad (4)$$

Here, ρ refers to density (kg/m^3), p pressure (Pa), u the velocity (m/s), μ the dynamic viscosity (N·s/m^2), F_{st} the surface tension force [19]-[21]. The surface tension force is calculated as;

$$F_{st} = \sigma\delta\kappa n \qquad (5)$$

Where, σ is the surface tension coefficient (N/m), n is the interface. The normal to the interface;

$$n = \frac{\nabla\emptyset}{|\nabla\emptyset|} \qquad (6)$$

While the delta function is approached by;

$$\delta = 6|\emptyset(1-\emptyset)||\nabla\emptyset| \qquad (7)$$

2.3 Numerical study

A 2D axisymmetric model was used to obtain the amount of mass in the inkjet process. Since it can be modeled axisymmetrically, only half of the planar intersection is taken into account in the numerical method (Figure 2). Boundary conditions are taken constant inlet velocity, outlet pressure=0, axial symmetry wall and no slip walls.

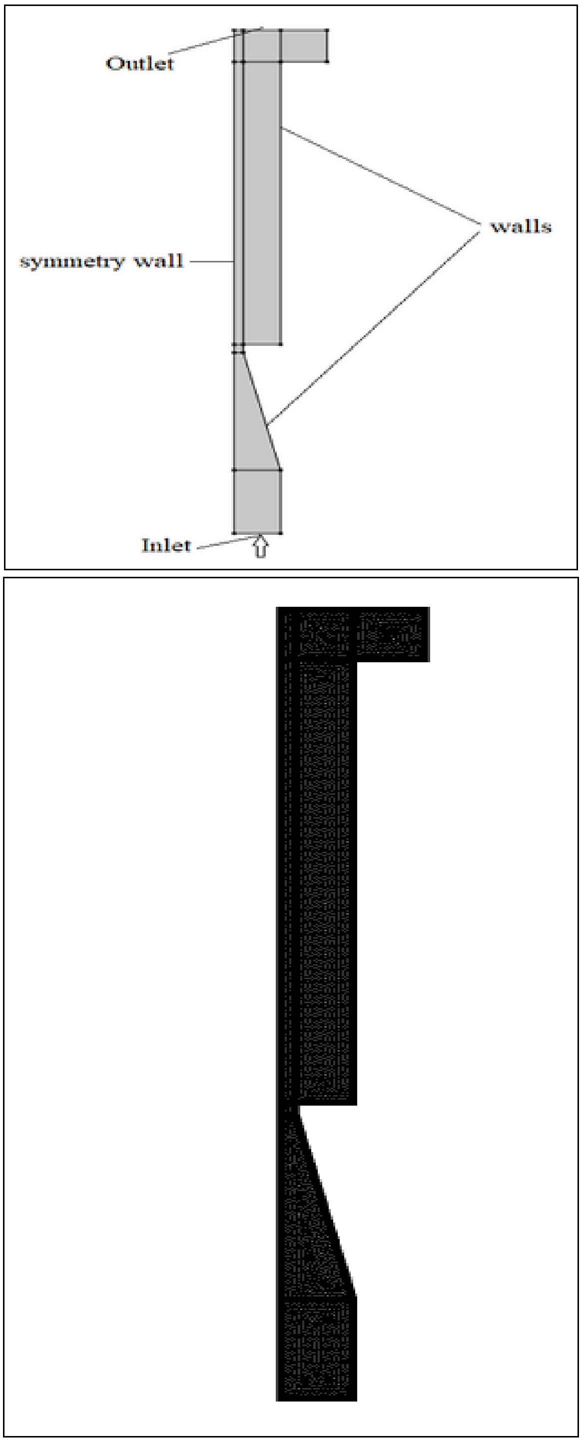

Figure 2. Model and mesh structure used in the analysis.

The assumptions made to simplify the model;

- There is no heat generation in the product,
- The fluid is incompressible and laminar,
- During inkjet gravity was taken into account,
- Throughout the analysis, the thermophysical properties of the air and the ink were considered constant.

First a mesh independence study was carried out on the sprayer modeled for the numerical study. As a result, 8149 elements were selected in the model structure. The partial differential equations are solved as time dependent under the 0.001 relative tolerance and 0.0001 absolute tolerance criteria using the Comsol Multiphysics 5.3 [21] program to describe mass change and velocity in the sprayer.

Table 3. Mesh independence study.

Number of element	Ink weight	Difference (%)
4891	7.34e-11	0.95
8149	7.27e-11	0.13
57026	7.26e-11	

As presented in Table 3, several number of element (4891, 8149 and 57026) were generated. The minimum difference was obtained with the 8149 elements, therefore, all the simulations were performed 8149 number of element. The thermophysical properties of the air and ink used in the analysis are given in Table 4.

Table 4. Thermophysical parameters of air and ink.

	Density (kg/m^3)	Dynamic viscosity (Ns/m^2)
Air	1.225	1.789 10^{-5}
Black ink	1074.3	0.005751
Red ink	1012.5	0.001114
Blue ink	1008.1	0.001123

3 Findings and discussion

3.1 Model verification

The numerical results by Tofan et al. [22] were used to verify the results of the model used in this study. The chang in droplet velocities of both studies are given in figure 3 and it can be seen that the results are highly compatible. There was an average of 8.7% difference between the two studies. Therefore, the numerical method was used in this study.

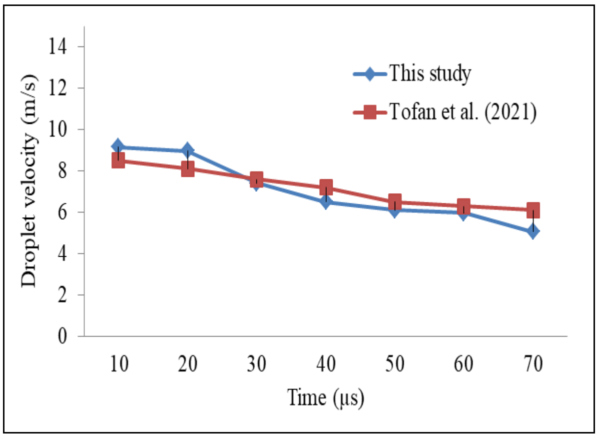

Figure 3. Comparison of the this study with the given results in literature.

3.2 Application of the Taguchi analysis to ink weight

Different ink weight values calculated for 9 different experiments were entered into the Minitab 18 program. Then, ANOVA analyzes were performed using the Taguchi method

(Table 5). It shows the ink weight values and calculated S/N ratios for the duration of 70µs. According to the average S/N ratio analysis given in Figure 4, the highest weight value (optimum condition) was achieved at a nozzle diameter of 0.025 mm and an inlet velocity of 0.6 m/s for the black colored ink which had the largest average S/N ratios. The lower nozzle diameter and air velocity increased the amount of ink.

It can be said that the effect seen with the reduction of the nozzle diameter form 0.04mm to 0.02 mm can also be seen with the velocity transition from 0.2 m/s to 0.6 m/s. Output values for the S/N ratios and rank values according to the effect of the 3 parameters are given in Table 6. Accordingly, it has been determined that the inlet velocity has the first ranking, the nozzle diameter the second ranking and the ink color the third ranking.

Table 5. Ink weight and calculated S/N ratio for the 70µs analysis.

Orthogonal array	Ink weight $\times 10^{10}$ (kg)	S/N ratio	Standard deviation
111	0.72000	-2.85503	0.010000
122	1.35000	2.60620	0.010000
133	1.52000	3.63650	0.010000
212	1.48000	3.40484	0.010000
223	2.18000	6.76895	0.010000
231	0.000163	-75.7566	0.000001
313	2.25000	7.04348	0.010000
321	0.00320	-49.9055	0.000100
332	0.01300	-37.7727	0.001000

Table 6. Response table for signal to noise ratios.

Level	ink color	Nozzle radius (mm)	Inlet velocity (m/s)
1	1.129	2.531	-42.839
2	-26.878	-13.510	-10.587
3	-21.861	-36.631	5.816
Delta	28.007	39.162	48.655
Rank	3	2	1

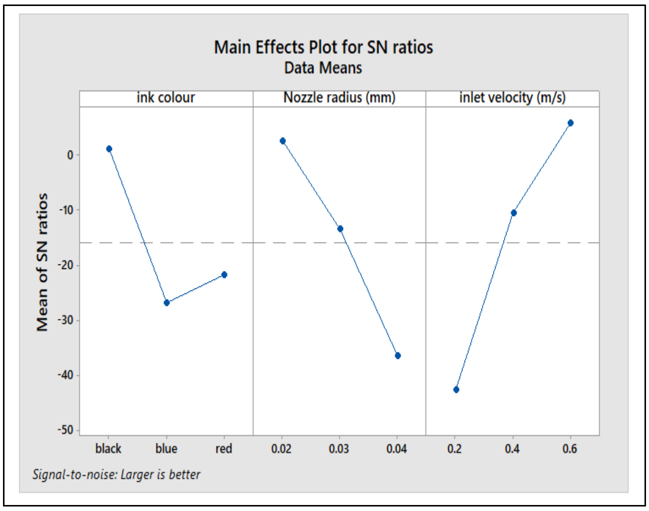

Figure 4. S/N ratios of different parameters (ink color, nozzle radius and inlet velocity).

ANOVA is a statistical method in which the results are widely applied to define the percentage contribution of each parameter. The ANOVA method allows us to test the importance of all main factors and their interactions with each other. In this study, the ANOVA method was applied to define the contribution of each of the parameters affecting the ink weight, using their average values. With the ANOVA results given in Table 7, the contribution rates of the parameters on the ink weight were obtained. These percentage rates are given in Figure 5. At the end of the 70µs analysis, it was found that the inlet velocity effect was 49%, the nozzle radius effect was 31% and the ink color effect was 18%. According to this result, the order of importance for the parameters affecting the ink weight can be seen as inlet velocity> nozzle radius> ink color. Considering the ink weight for the inkjet, the most important parameter is the inlet velocity. While the average S/N ratio decreases with the increasing nozzle radius, the average S/N value increases with the increasing inlet velocity.

Table 7. Analysis of variance for the S/N ratios.

Source	*DF*	*Seq SS*	*Adj SS*	*Adj MS*	*F*	*P*
ink color	2	1338.1	1338.1	669.07	7.25	0.12
Nozzle radius (mm)	2	2325.6	2325.6	1162.78	12.6	0.07
inlet velocity (m/s)	2	3676.6	3676.6	1838.30	19.9	0.04
Residual Error	2	184.6	184.6	92.29		
Total	8	7524.9				

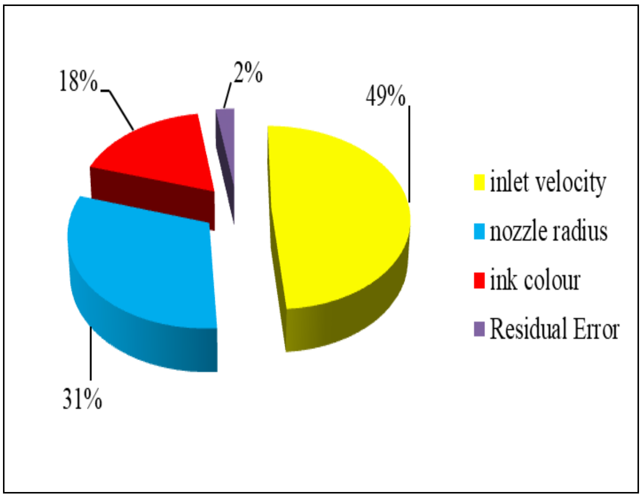

Figure 5. Effect percentages of different parameters (ink color, nozzle radius and inlet velocity) on ink weight.

Optimum conditions with the maximum amount of ink reaching the target point for the inkjet were achieved with black ink, a nozzle diameter of 0.025 mm and an inlet velocity of 0.6 m/s. Considering that different ink colors will be used for the same inkjet, the effect of the colors was examined visually. Numerical analyzes were performed to obtain flow images of different colored inks within the inkjet for 10-30-50-70 µs time periods. According to the results given in Figure 6, the drop flow of the red and blue inks are similar to each other with high diffusivity, while with the black ink the drop has more weight when reaching the target.

Figure 7 shows the analysis results of the velocity change values of the drops belonging to different ink colors for 10-30-50-70 µs time periods. According to the results given here, it is seen that the change in the velocity value of the black ink drop is lower than the red and blue ink in all velocities. The changes in the velocity values of the red and blue inks are close to each other. At the end of the 70µs period, the maximum velocity values of inside of ink drop were obtained as 16.55, 18.23 and 18.25 m/s for the black, red and blue inks, respectively.

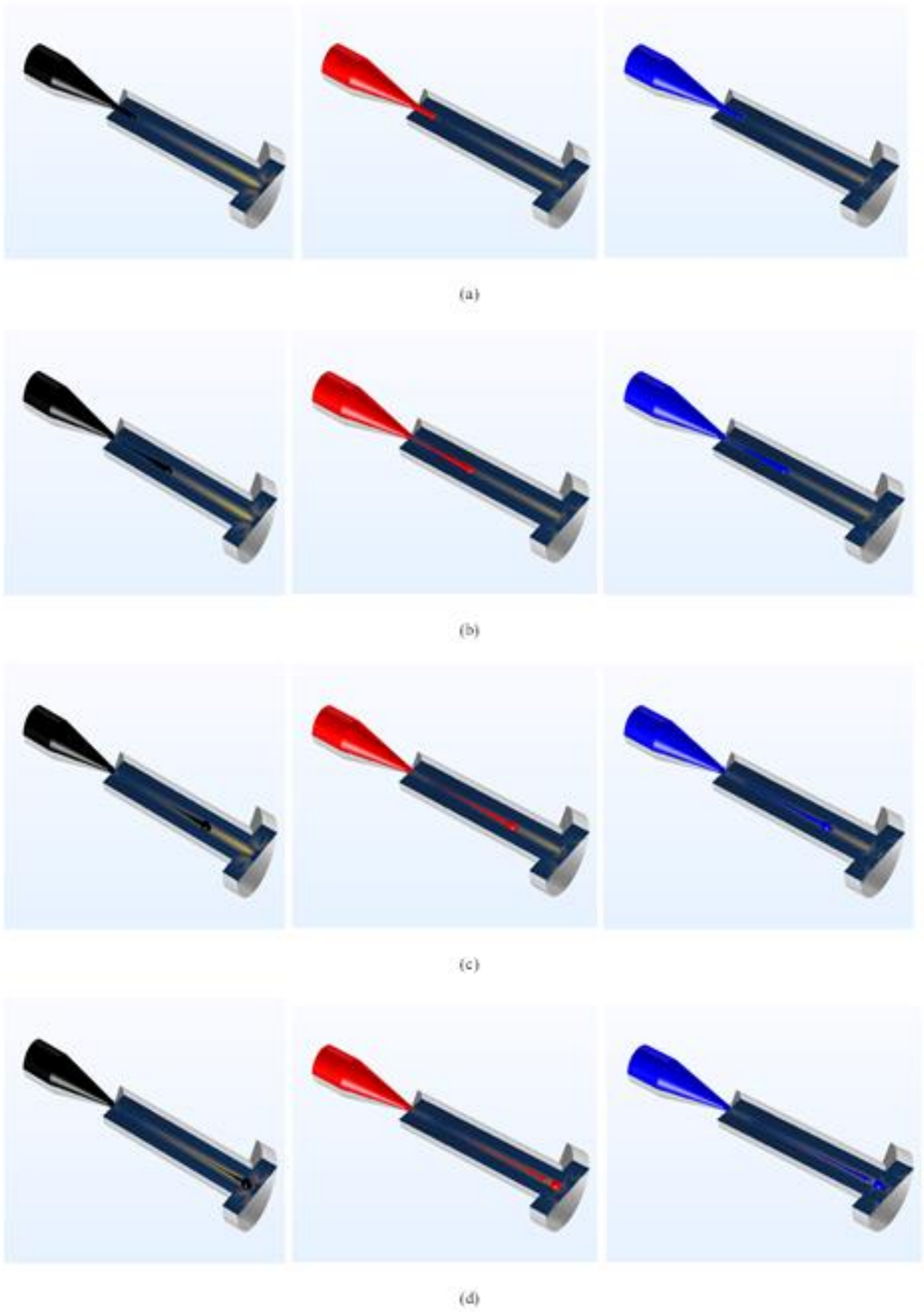
(a)
(b)
(c)
(d)

Figure 6. Ejection of different colored ink droplets from the simulation. (a): 10 µs. (b): 30 µs. (c): 50 µs. (d): 70 µs.

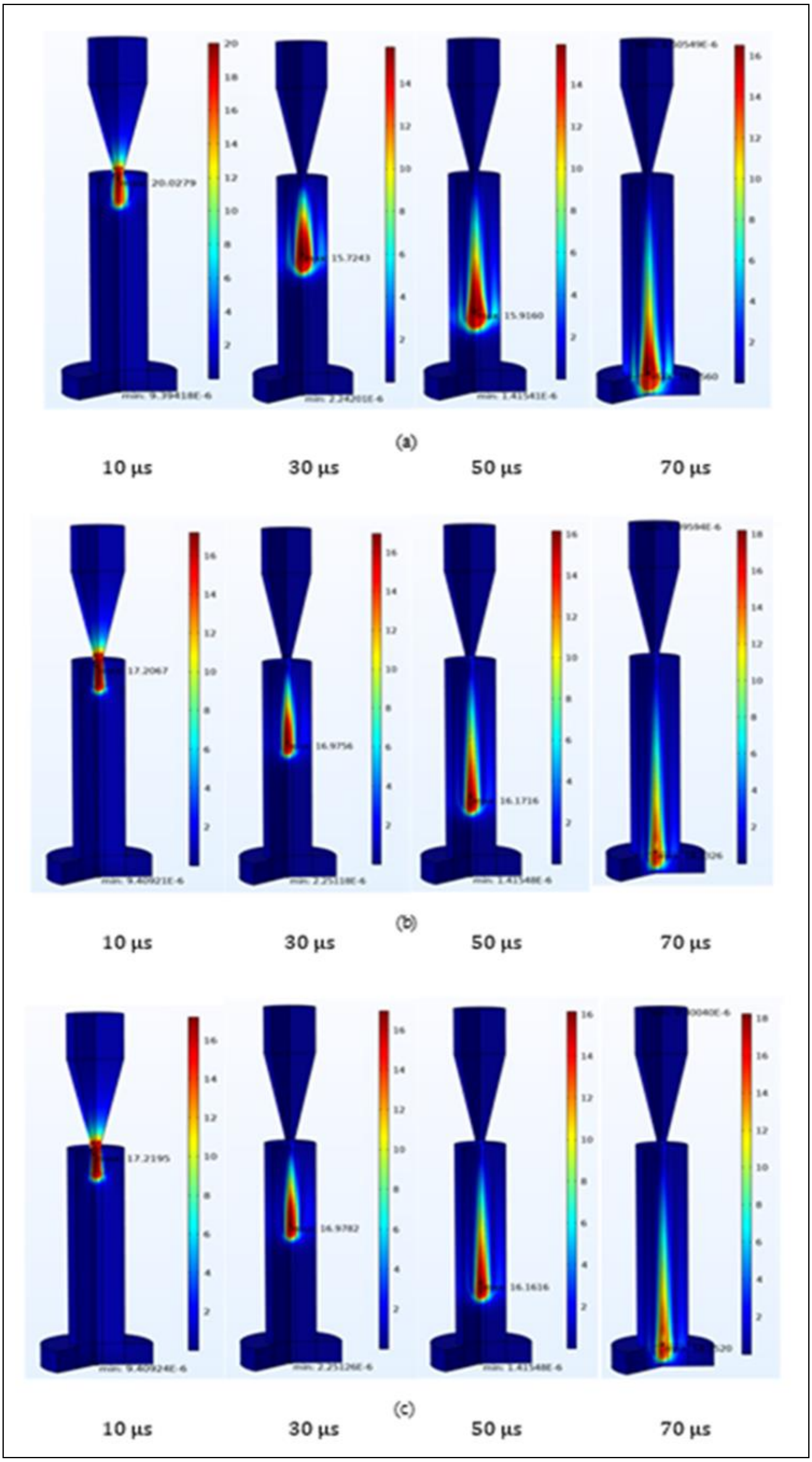

Figure 7. Variation of velocity values of drops of different ink colors in the inkjet for different time (10-30-50-70 µs) periods. (a): Black. (b): Red. (c): Blue.

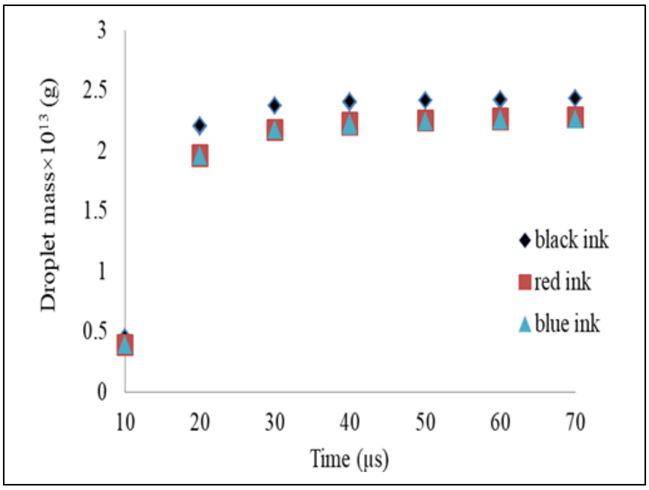

Figure 8. Weight change graph obtained according to analysis results for different inks.

According to the results of the analysis made for different ink colors in Figure 7, it was visually obtained that the black ink had more drops. In Figure 8, the comparison of different ink colors by measuring their weight values for different time periods is given as a graph. Accordingly, it can be said that although all 3 inks have an equal weight at the beginning, the weight value of the black ink exceeds $2 * 10^{-13}$ g after 20 microseconds and reaches the inkjet target point with 15.6% more weight than the other colors.

4 Conclusion

The lower inkjet inlet velocity is expected to reach higher velocities as the diameter of the nozzle decreases, but this causes the effect of the other parameter to be ignored. The most important result of this study is the numerical analysis of the effects of the inlet velocity, nozzle radius and ink density, and the optimization process by determining the effect rates with the Taguchi method. Therefore, this approach necessitates the consideration of different factors for the case.

When a low nozzle radius and a high inlet velocity is chosen, it has been observed that the black ink drop reaches the target point without dispersing.

Since the density and dynamic viscosity of the black ink were higher, the droplet dispersion was less. Therefore, it is important to increase the density for different colors of ink solvents.

The ink reaching high speeds without dispersing in the inkjet is also important in terms of time, cost and quality. The numerical study and obtaining the optimization analysis with the Taguchi statistics provide valuable information for academic and industrial usage.

It has been determined that the most effective parameter that brings the most ink to the target point in a short time period is the inlet velocity with a 49% effect.

5 Author contribution statements

Within the scope of this study, Burak TÜRKAN contributed to the formation of the idea, design and literature review, evaluation of the results obtained, provision of the materials used and examination of the results; writing and supervision of the article in terms of content.

6 Ethics committee approval and conflict of interest statement

"There is no need to obtain permission from the ethics committee for the article prepared". "There is no conflict of interest with any person/institution in the article prepared".

7 References

[1] Yeh JT. "A VOF-FEM Coupled inkjet simulation". *Proceedings of ASME FEDSM'01*, New Orleans, Louisiana, 29 May–1 June 2001.

[2] Riemer DE. "The direct emulsion screen as a tool for high resolution thick film printing". *Electronic Component Conference Proceedings,* Washington, DC, USA, 10-12 May 1971.

[3] Riemer DE. Ein Beitrag Zur Untersuchung Der Physikalisch Technischen Grundlagen Des Siebdruckverfahrens. PhD Thesis, Technische Universitat Berlin, Germany, 1988.

[4] Potts SJ. Phillips C, Jewell E, Clifford B, Lau YC, Claypole T. "High-speed imaging the effect of snap-off distance and squeegee speed on the ink transfer mechanism of screen-printed carbon pastes". *Journal of Coatings Technology and Research,* 17(2), 447-459, 2020.

[5] Messerschmitt E. "Rheological considerations for screen printing inks". *Screen Print,* 72(10), 62-65, 1982.

[6] Xu C, Willenbacher N. "How rheological properties affect fine-line screen printing of pastes: A combined rheological and high-speed video imaging study". *Journal of Coatings Technology and Research,* 15(6), 1401-1412, 2018.

[7] Yang Y, Liub F. "Study on the relationships between offset ink tack value and its viscosity, the separation velocity". *Advanced Materials Research,* 332-334, 1704-1708, 2011.

[8] Kapur N, Abbott SJ, Dolden ED, Gaskel PH. "Predicting the behavior of screen printing". *IEEE Transactions on Components, Packaging, and Manufacturing Technology,* 3(3), 508-515, 2013.

[9] Riemer DE. "The theoretical fundamentals of the screen printing process". *Microelectronics International,* 6(1), 8-17, 1989.

[10] Yu JD, Sakai S, Sethian JA. "A coupled level set projection method applied to ink jet simulation". *Interfaces and Free Boundaries,* 5(1), 459–482, 2003.

[11] Aleinov ID, Puckett EG, Sussman M. "Formation of droplets in microscale jetting devices". *Proceedings of ASME FEDSM'99.* San Francisco, California, 18-23 July 1999.

[12] Sou A, Sasai K, Nakajima T. "Interface tracking simulation of ink jet formation by electrostatic force". *Proceedings of ASME FEDSM'01*, New Orleans, Louisiana, 29 May-1 June 2001.

[13] Chorin AJ. "Numerical solution of the navier-stokes equations". *Mathematics of Computation,* 22(104), 745-762,1968.

[14] Uner I, Gurcum BH. "Conductive ink applications on electronic textiles". *Pamukkale University Journal of Engineering Sciences,* 25(7), 794-804, 2019.

[15] Yayla S, Ayça S, Oruç M. "A case study on piezoelectric energy harvesting with using vortex generator plate modeling for fluids". *Renewable Energy, Elsevier,* 157(C), 1243-1253, 2020.

[16] Yayla S, Kamal K, Bayraktar S, Oruc M. "Two phase flow separation in a horizontal separator by inlet diverter plate in oilfield industries". *International Journal of Mechanical and Production Engineering (IJMPE)*, 5(10), 7-10, 2017.

[17] Oruç M, Yayla S. "Experimental investigation of oil-in water separation using corrugated plates and optimization of separation system". *Separation Science and Technology*, 57(5), 788-800, 2022.

[18] Taguchi G. *Introduction to Quality Engineering*. 1st ed. Tokyo, Japan, Asian Productivity Organization, 1990.

[19] Olsson E, Kreiss G. "A conservative level set method for two phase flow". *Journal of Computational Physics,* 210(1), 225-246, 2005.

[20] Yue P, Feng J, Liu C, Shen J. "A diffuse-interface method for simulating two-phase flows of complex fluids". *Journal of Fluid Mechanics,* 515(1), 293-317, 2004.

[21] Comsol Multiphysics 4.3. *Comsol Multiphysics Reference Manual*. 1st ed. Stockholm, Sweden, Comsol AB, 2012.

[22] Tofan T, Kruggel-Emden H, Turla V, Jasevičius R. "Numerical modeling of the motion and interaction of a droplet of an inkjet printing process with a flat surface". *Applied Sciences,* 11(2), 527-541, 2021.