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Optimization of Vortex Tube Design Parameters Using the Taguchi Method

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Anahtar Kelimeler

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Sıcaklık farkı, Varyans Analizi (ANOVA)
Hesaplamalı Akışkanlar Dinamiği (HAD)
Regresyon analizi

Graphical/Tabular Abstract (Grafik Özet)

In Figure A, case 21 shows a central velocity of ≤120 m/s, while case 26 reaches a minimum of 150 m/s. The low-velocity region causes a temperature drop before the cold exit, confirming the effectiveness of Taguchi optimization. Şekil A'da vaka 21'de merkezde ≤120 m/s, vaka 26'da ise minimum 150 m/s hız gözlenmiştir. Düşük hız bölgesi, soğuk çıkış öncesi sıcaklık düşüşüne neden olarak Taguchi optimizasyonunun etkinliğini doğrulamaktadır.

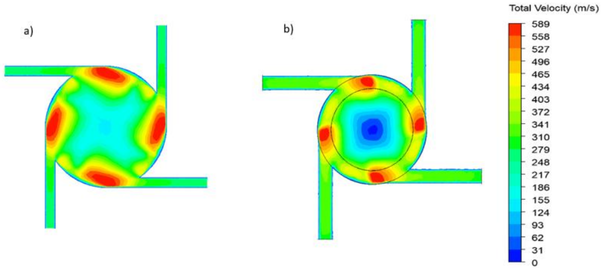

Figure A: Comparison of the velocities in the inlet region of a) Run 21 and b) the Run 26 / ***Şekil A:*** Giriş bölgesindeki hızların karşılaştırılması: a) Çalışma 21 ve b) Çalışma 26

Highlights (Önemli noktalar)

- *The impact of four key design parameters on VT performance was analyzed using the Taguchi method. / Taguchi yöntemi kullanılarak VT performansı üzerinde dört temel tasarım parametresinin etkisi analiz edildi.*
- *A 40.3% improvement in $COP_{cooling}$ was achieved with the optimized design. / Optimize edilmiş tasarımla $COP_{cooling}$ değerinde %40,3'lük bir iyileşme sağlandı.*
- *The nozzle number (N) was identified as the most influential factor on $COP_{cooling}$. / $COP_{cooling}$ üzerinde en etkili faktör olarak meme sayısı (N) belirlendi.*

Aim (Amaç): *This study aims to optimize VT design parameters using the Taguchi method to enhance cooling performance. / Bu çalışma, soğutma performansını artırmak amacıyla VT tasarım parametrelerini Taguchi yöntemiyle optimize etmeyi amaçlamaktadır.*

Originality (Özgünlük): *The study demonstrates the effectiveness of the Taguchi approach in VT optimization by analyzing different design parameters, addressing a gap in the literature. / Çalışma, farklı tasarım parametrelerini analiz ederek VT optimizasyonunda Taguchi yaklaşımının etkinliğini göstermekte ve literatürdeki boşluğu doldurmaktadır.*

Results (Bulgular): *The optimized VT achieved a 40.3% higher COPcooling, with nozzle number having the highest impact. / Optimize edilmiş VT, COPcooling değerinde %40,3 daha yüksek performans gösterirken, en büyük etki nozul sayısından kaynaklanmıştır.*

Conclusion (Sonuç): *The findings confirm that the Taguchi method is a reliable method for VT optimization, enhancing energy efficiency. / Bulgular, Taguchi yönteminin VT optimizasyonunda güvenilir bir method olduğunu ve enerji verimliliğini artırdığını doğrulamaktadır.*

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Abstract

In this study, the optimization of a vortex tube (VT) with a fixed tube diameter and boundary conditions was conducted to improve four different design factors: the value of the conical valve angle (α), the number of nozzles (N), the cold flow exit diameter ($D_{cold\ exit}$), and the nozzle inlet diameter (D_{nozzle}), to improve the Cooling Coefficient of Performance ($COP_{cooling}$). For each identified factor, five different levels were assigned, and an L_{25} orthogonal series was constructed using the Taguchi approach. The 3D-designed cases were subjected to numerical analysis in the ANSYS Fluent software program using the standard k-epsilon turbulence model. The effect levels of the design parameters were determined using the Analysis of variance (ANOVA) method. Furthermore, after obtaining an empirical equation with $COP_{cooling}$ as the dependent variable through Regression analysis, a confirmation test was conducted. The results indicated that the order of influence of the five parameters on $COP_{cooling}$ was N> D_{nozzle}> $D_{cold\ exit}$ > α, with the N parameter having the strongest impact on the $COP_{cooling}$ in the VT, while the α parameter had the least effect. Additionally, the optimal VT showed a 40.3% improvement in $COP_{cooling}$ when compared to a VT with initial geometric parameters. The findings indicate that using the Taguchi approach for VT geometry optimization significantly enhanced performance.

Taguchi Yöntemi Kullanılarak Vorteks Tüpü Tasarım Parametrelerinin Optimizasyonu

Makale Bilgisi

Araştırma makalesi
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Öz

Bu çalışmada, sabit tüp çapı ve sınır koşulları ile bir vorteks tüpünün (VT) optimizasyonu, Soğutma Performans Katsayısını ($COP_{cooling}$) iyileştirmek amacıyla dört farklı tasarım faktörünün belirlenmesiyle gerçekleştirilmiştir: konik vana açısı (α), nozul sayısı (N), soğuk akış çıkışı çapı ($D_{cold\ exit}$) ve nozul giriş çapı (D_{nozzle}). Her belirlenen faktör için beş farklı seviye atanmış ve Taguchi yaklaşımı kullanılarak bir L_{25} ortogonal serisi oluşturulmuştur. 3D tasarlanmış analizler, ANSYS Fluent yazılımında standart k-epsilon türbülans modeli kullanılarak sayısal analizlere tabi tutulmuştur. Tasarım parametrelerinin etki seviyeleri, Varyans Analizi (ANOVA) yöntemiyle belirlenmiştir. Ayrıca, $COP_{cooling}$ bağımsız değişkeni ile regresyon analizi yoluyla ampirik bir denklem elde edildikten sonra, bir doğrulama testi gerçekleştirilmiştir. Sonuçlar, $COP_{cooling}$ üzerindeki beş parametrenin etki sırasının N > D_{nozzle} > D_{cold} > α olduğunu göstermiştir; burada N parametresi VT içindeki $COP_{cooling}$ üzerinde en güçlü etkiye sahipken, α parametresi en düşük etkiye sahiptir. Ayrıca, optimum VT'nin, başlangıçtaki geometrik parametrelere sahip bir VT ile karşılaştırıldığında $COP_{cooling}$ değerinde %40.3'lük bir iyileşme sağladığı belirlenmiştir. Taguchi yaklaşımının VT geometri optimizasyonunda kullanılması, performansı önemli ölçüde artırmıştır.

1. INTRODUCTION (GİRİŞ)

The vortex tube (VT), invented in the early 20th century and used in various applications, separates a compressed stream into hot and cold flows based on tangential inlet and high pressure. It has been observed that the gas, introduced tangentially at the inlet, initiates a rotational flow or vortex within the system, effectively segregating into distinct hot and cold streams [1]. In 1947, in Germany, George J. Ranque and Rudolf Hilsch were the first to study the flow separation occurring within the tube both numerically and empirically [2].

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A standard VT, as shown in Figure 1, consists of four main components: one or more tangential inlet nozzles, a vortex chamber, a cold exit, and a control valve at the hot exit of the tube. The compressed gas, typically air in open systems [3], is introduced into the system through tangential inlet nozzles, where it advances to the vortex chamber. Here, the gas creates a vortex and the primary flow, referred to as peripheral flow, continues along the hot tube. Hot air exits from the end of this tube and hits the control valve, then moves along the tube as a secondary flow and exits through the cold hole as VT output.

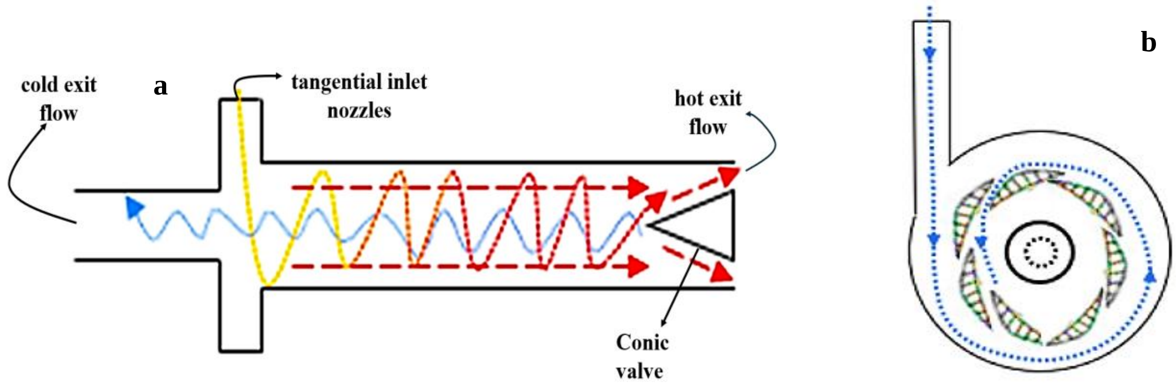

Figure 1. VT schematic view of a) longitude view and b) front view (VT'nin şematik görünümü: a) boyuna görünüm ve b) ön görünüm)

Due to its low efficiency, the VT is primarily used in spot cooling applications. Despite being less well-known than conventional cooling devices, the VT is a simple device without moving parts, making it inexpensive to manufacture and environmentally friendly. Thus, with its growing popularity in spot cooling, chemical analyses, and moderate-temperature chromatographic applications in recent years, there has been an increase in research on VT, focusing primarily on geometric and material influences, experimental and numerical methods, and optimization techniques for performance enhancement.

The impact of geometric and material properties on vortex tube performance plays a critical role in determining their efficiency and effectiveness. These properties directly influence the energy separation process within the internal structure, enhancing the potential to optimize cooling and heating capacities, which in turn facilitates broader industrial application of VTs. Studies by Hartnett and Eckert [4] investigated swirl flow characteristics, and Kurosaka's exploration of acoustic effects due to temperature differences in VTs [5], provide a foundational understanding of the physical phenomena within vortex tubes. Takahama's [6] work on optimizing geometric parameters demonstrated that maximum temperature differences were achieved with specific nozzle-to-tube diameter ratios (L/D) (0.2) and nozzle area to tube area ratios (0.08 to 0.17). Takahama and Yokosawa [7] further expanded this research by examining the effects of altering tube lengths and angles, finding a notable 10% impact on temperature separation. This indicates the sensitivity of VT performance to geometric changes. Dinçer et al. explored the impact of different inlet pressures on the performance of the vortex tube [8]. Additionally, Arjomandi and Xue [9] observed that VT efficiency peaked when the valve-to-tube diameter ratio was adjusted to between 0.9 and 0.98. Gao et al. [10] and Promvonge and Eiamsa-ard [11] further explored these geometric impacts, relating them to VT's cooling and heating capabilities. Liu et al. [12] conducted both numerical and experimental investigations, confirming the significant role of geometry in energy separation demonstrating the detailed interplay between design parameters and operational efficiency. Additionally, extensive comparisons of materials by Bagre et al. [13] and Chen et al. [14], illustrate the significant role of material properties like specific heat and thermal conductivity in optimizing VT efficiency.

The advancement of VT research heavily depends on the application of sophisticated experimental [15-16] and numerical methods[16-17]. These methods enable a detailed understanding of the physical and thermodynamic properties of vortex tubes, allowing for the development of more efficient and effective designs. The experimental application of the Taguchi method by Pınar et al. [18-19] to refine operational parameters under varied conditions highlights the method's utility in optimizing VT performance. Their studies adjusted inlet pressures and nozzle number (N) to fine-tune the system's efficiency. Meanwhile, Bramo and Pourmahmoud [20-21] provided detailed analyses on the effects of varying the L/D, which directly influence the thermal gradient achieved within the VT. Dutta et al. [22] compared the efficacy of different turbulence models, with the standard k-ε model proving superior in accurately predicting the temperature separation. Shamsoddini et al. [23] assessed the impact of increasing N and found a direct correlation with enhanced cooling power, a critical insight for VT design optimizations. Kumar et al.[24] applied the Taguchi method extensively to adjust several geometric parameters, which confirmed the profound impact of nozzle inlet diameter (D_{nozzle}) and system pressure on VT performance. Kırmacı carried out an experimental study to determine the effects of orifice, N, and inlet pressure on efficiency using air and oxygen as working fluids. Their results showed that an increase in the N reduced the temperature gradient between hot and cold flows [25].

The optimization of vortex tubes involves the strategic manipulation of operational and design parameters to maximize energy and exergy efficiencies. This strategic approach ensures that VTs provide maximum cooling and heating potential in various industrial scenarios, reducing energy consumption and enhancing the overall sustainability of systems. Alborn and Gordon have investigated the secondary flow following rebound [26]. Chen et al. [14,27] utilized dimensional analysis to identify optimal configurations that significantly enhance VT performance. Their work achieved substantial improvements over traditional setups. Shaji et al. [28] applied the Re-Normalization Group k-ε model to further refine the VT dimensions, successfully boosting energy separation efficiency. This approach demonstrates the potential of computational fluid dynamics in optimizing VTs. Xue and Arjomandi [29] investigated the effect of vortex angles on VT efficiency, uncovering that cooling efficiency varies inconsistently with vortex angle adjustments under different pressure settings. Additionally, Wang and Suen [30] compared the thermal behavior of air and refrigerants within VTs, revealing that air, due to higher velocities and shear stresses, exhibits more pronounced cooling and heating effects than refrigerants. This is a crucial factor in VT application across different industrial scenarios. Prabakaran et al. used Response Surface Methodology to optimize nozzle and orifice geometries along with inlet pressure parameters, showing a high degree of model accuracy within a 95% confidence interval, underscoring the effectiveness of their optimization [31].

Despite numerous studies in the literature examining the performance of the VT, research specifically focusing on the application of the ANOVA approach and regression analyses within the VT is quite limited. This study has achieved the optimal Cooling Coefficient of Performance ($COP_{cooling}$) for a counter-flow VT using the Taguchi approach, employing an L_{25} orthogonal array derived from four factors: Conical Valve Angle (α), N, the cold flow exit diameter ($D_{cold\ exit}$), and D_{nozzle}, each with five different levels. Additionally, the effect value of these four factors has been determined through the ANOVA. Furthermore, an empirical equation for the VT was obtained through regression analysis. Finally, a confirmation test was applied to the results obtained.

2. MATERIALS AND METHODS (MATERYAL VE METOD)

2.1. Geometry and Validation (Geometri ve Doğrulama)

In this study, the geometric parameters of the vortex tube were meticulously designed for performance optimization using the commercial design software CATIA V5. The dimensions for all designs—diameter (12 mm), tube length (240 mm), and wall thickness (10 mm)—were consistently set to facilitate direct comparisons and systematic optimization. Figure 2 illustrates the isometric geometry of the optimized vortex tube and highlights the parameters used for optimization.

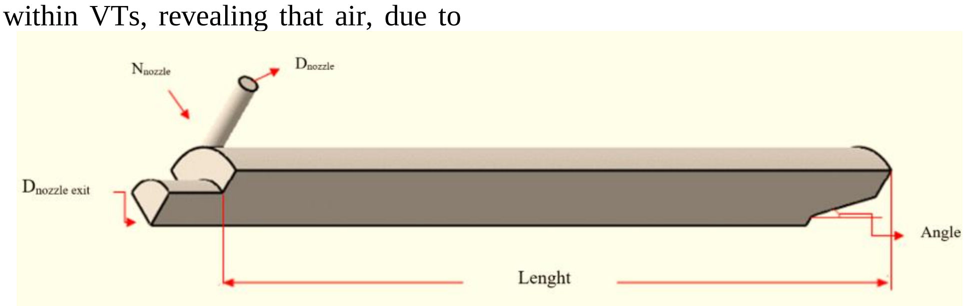

Figure 2. Geometric representation of the optimized VT (Optimizasyonu yapılmış VT’nin geometrik temsili)

Furthermore, for validation purposes, this study adopted the air-filled VT dimensions from Behara et al. [32], which provided comprehensive and clearly measured data. These dimensions included nozzle number (N), vortex diameter, and the length-to-diameter ratio (L/D), set respectively at 6 mm, 12 mm, and 20 mm. The boundary conditions for the inlet were set as follows: flow rate of 0.00921 kg/s, 300 K temperature, and 0.5422 MPa pressure, with a cold mass fraction (μ) of 0.22, as displayed in Table 1. While Behara et al. [32] achieved a ΔT of 21.6°, this study obtained a slightly higher ΔT of 21.72°, indicating an error rate of 3.1%, which is within the acceptable range in the literature standards and was used for validation.

Table 1. Boundary Conditions (Sınır Koşulları)

m_{inlet}	T_{inlet}	P_{inlet}	ξ
0.00921 kg/s,	300 K	0.5422 MPa	0,22

2.2. Mesh Independence (Ağ Bağımsızlığı)

Given the presence of 25 different geometries in the L_{25} orthogonal array, each geometry has a distinct mesh structure, making it challenging to discuss independence from a single mesh. However, the mesh counts have been specified considering the balance between geometric structures and mesh quality (Element Quality, Skewness, Orthogonal Quality, and y^+). Therefore, as illustrated in Figure 3, geometry case 7 within the L_{25} series has been designated as the reference geometry to conduct a mesh independence study on this case. To achieve a reasonable mesh structure for case 7, solutions at different mesh counts have been analyzed, as shown in Figure 4. Since the error rate at 1 202 813 meshes is below 1%, this mesh count has been determined as the reasonable mesh.

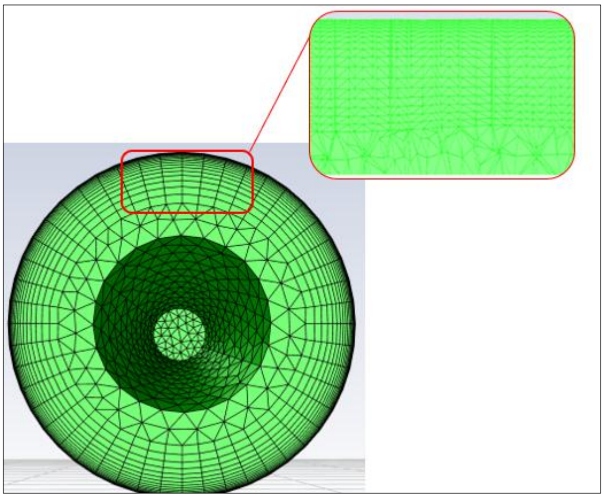

Figure 3. Mesh detail (Mesh Ayrıntısı)

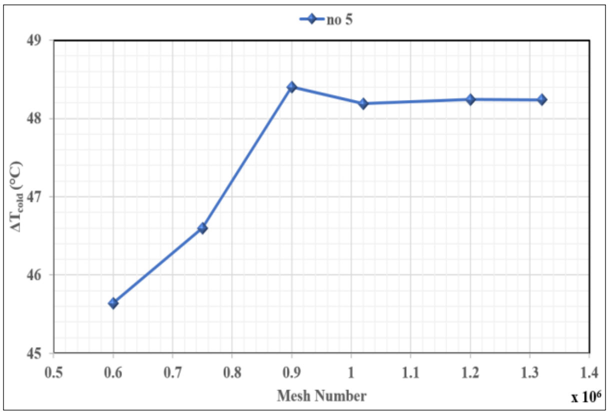

Figure 4. Grid Independence (Mesh Bağımsızlığı)

Table 2. Mesh Quality (Mesh Bağımsızlığı)

Element Quality	Skewness	Orthogonal Quality
0,8546	0,2253	0,772

In addition, there is variability in cell sizes regionally, and tetrahedral mesh has been used across all geometries with the same quality targets (element quality and y^+) aimed. Furthermore, Table 2 presents the average quality values for the 25 cases. The element and orthogonal quality values are considered reasonable, being close to 1, and skewness values are preferable when near 0. While refining the mesh on the tube surface, attention must be paid to the mesh cells within the boundary layers around critical areas of the case. y^+ is a dimensionless parameter used to assess the frictional effects of the fluid near the wall within the boundary layer. It is calculated using friction velocity (u), the distance to the wall (y), and the fluid's local kinematic viscosity (ν), as shown in Eq. 1 [33,34]. To achieve a y^+ of less than 5 in critical areas, 16 layers of inflation have been set across the entire VT surface. Although the y^+ is primarily related to the first mesh cell's thickness, the use of 16 inflation layers is intended not only to control y^+ but also to improve resolution across the entire boundary layer. This approach helps in capturing the complex behavior of the flow within the boundary layer more accurately.

$$y^+ = \frac{u*y}{v} \tag{1}$$

2.3. Governing equations and Turbulence model (Korunum Denklemleri ve Türbülans Modelleri)

This study utilized the ANSYS Fluent CFD commercial program to perform numerical modeling of VTs. In the vortex tube, the flow is considered as compressible, turbulent, and exhibits significant rotational effects. It is modeled as a three-dimensional, steady-state flow using the standard k-epsilon turbulence model based on the finite volume method. Bramo et al. [20] demonstrated that the k-epsilon model is suitable for capturing the turbulence effects within the vortex tube's computational domain. The fundamental governing equations include the conservation of mass, momentum, and energy, which are structured as follows: The mass conservation equation, also known as the continuity equation, is expressed as follows: [35–37].

$$\frac{\partial p}{\partial t} + \nabla(\rho\vec{v}) = S_m \quad (2)$$

$$\frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}\right) - \frac{\partial}{\partial x_j}\overline{\rho u'_i u'_j}\right] \quad (3)$$

$$\frac{\partial}{\partial x_j}\left[u_i\rho(h + \frac{1}{2}u_i u_j)\right] = \frac{\partial}{\partial x_j},\ k_{eff} = K + \frac{c_p \mu_t}{Pr_t} \quad (4)$$

The turbulent kinetic energy (k) and its dissipation rate (ε) are calculated using the equations below [38,39]:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial_k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M \quad (5)$$

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_j}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial_\varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - \rho C_{2\varepsilon}\frac{\varepsilon^2}{k} \quad (6)$$

In the given equations, G_k refers to the generation of turbulence kinetic energy caused by mean velocity gradients, G_b denotes the generation of turbulence kinetic energy due to buoyancy effects, and Y_M represents the contribution from fluctuating dilatation in compressible turbulence to the dissipation rate. The constants $C_{1\varepsilon}$ and $C_{2\varepsilon}$, along with the turbulent Prandtl numbers for k and ε, denoted as σ_k and σ_ε, are also included. The turbulent (or eddy) viscosity, μ_t, is calculated using the following relationship:

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \quad (7)$$

2.4. Performance Parameters (Performans Parametreleri)

Key parameters contribute to determining the performance of a VT. Three temperature differences are calculated based on the inlet temperature (T_i), the cold exit fluid temperature (T_c), and the hot exit fluid temperature (T_h).

$$\Delta T_c = T_i - T_c \quad (8)$$

$$\Delta T_h = T_h - T_i \quad (9)$$

$$\Delta T_T = T_h - T_c \quad (10)$$

In the equations, the terms ΔT_c, ΔT_h, and ΔT_T represent the heating effect, cooling effect, and total effect, respectively [8]. μ, defined as the ratio of the mass flow rate of the cold exit ($\dot{m}_c$) to the mass flow rate at the inlet ($\dot{m}_{in}$), is a crucial metric as it directly impacts the performance of the VT [40].

$$\mu = \frac{\dot{m}_c}{\dot{m}_{in}} \quad (11)$$

The working fluid at a hot and a cold outlet can also be used to heat and cool the VT. The VT's heating and cooling capacity can be expressed as follows:

$$\dot{Q}_H = \dot{m}_h\, C_p(T_h - T_{in}) \quad (12)$$

$$\dot{Q}_C = \dot{m}_c\, C_p(T_{in} - T_c) \quad (13)$$

Calculation of coefficient of performance is given below [41]:

$$COP = \frac{Q_C}{W} = \frac{\mu_C C_p \Delta T_c}{\frac{\gamma}{\gamma-1}RT_i\left[\left(\frac{P_i}{P_a}\right)^{(\gamma-1)/\gamma} - 1\right]} \quad (14)$$

Q_c represents the degree of cooling and W the work input ratio, C_p is the specific heat at constant pressure, and R is the specific gas constant.

2.5. Taguchi Method (Taguchi Metot)

The Taguchi method is an experimental design methodology developed to determine optimal results among extensive parameter settings. Introduced by Taguchi, this method enables engineers and researchers to maximize performance, durability, and quality while minimizing the costs associated with extensive experimentation [42,43]. Notably, the Taguchi method has demonstrated its efficacy even in single-response situations, where a multitude of studies attest to its effectiveness [44]. Particularly when applied to vortex tube (VT) optimization, this method yields high success rates; studies based on the Taguchi method for VT optimization often report confidence interval values and absolute percent change (R^2) values exceeding 95% [45,46]. This substantiates why the method is favored in VT studies and underscores its effectiveness in determining VT design parameters. The application steps of the Taguchi design parameters are illustrated in Figure 5.

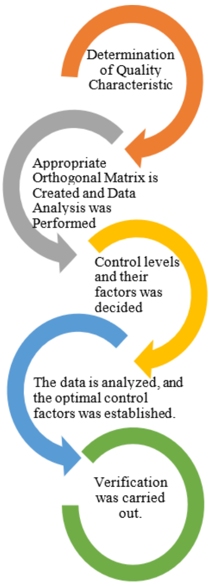

Figure 5. Steps of the Taguchi design parameters
(Taguchi tasarım parametrelerinin adımları)

The design parameter steps help determine the effect of control factors in the VT. Based on the Taguchi approach, the control factors and parameters to be used in the numerical design are shown in Table 3. Although there are many parameters that can affect the performance of a VT, the four determined control factors - α, N, $D_{cold\ exit}$, and D_{nozzle} - have been selected due to their significant impact on the cold exit temperature of the VT. The selection of each factor is critical, as previous studies and preliminary simulations have shown that these factors play key roles in optimizing VT performance. Specifically, α affects the flow dynamics within the VT, influencing energy separation efficiency and consequently the temperature difference between the hot and cold ends. This parameter plays a central role in the thermal separation process, and even minor adjustments can lead to significant changes in temperature separation [47–49]. N increases the amount of air flowing through the system, thereby increasing the total volume of air involved in energy conversion processes, which enhances the VT's cooling capacity [18,19,44].

D_{cold} determines how efficiently the cooled air is expelled from the VT, affecting the system's pressure balance and the temperature distribution within the tube [50,51]. D_{nozzle} controls the volume and initial speed of air entering the system, directly affecting the VT's thermal separation performance [52,53]. These four control factors, selected for the L_{25} orthogonal array consisting of four columns and 25 cases, are shown in Table 4. Orthogonal arrays are matrices created to determine which factor level combinations will be used in each case for analysis; the cases represent the levels of the factors in the study, while the columns represent the factors, i.e., the independent variables.

Control Factor		Levels				
		1	**2**	**3**	**4**	**5**
A	Conical Valve Angle (α)	15°	30°	45°	60°	75°
B	Cold diameter ($D_{cold\ outlet}$), (mm	5	6	7	8	9
C	Nozzle number (N)	4	5	6	7	8
D	Nozzle diameter (D_{nozzle}), (mm	1	1.25	1.5	1.75	2

In the Taguchi method, the Signal-to-Noise (S/N) ratio is used to achieve the desired quality characteristic. The approach also incorporates a metric called the S/N ratio, which measures the robustness of the design against noise factors — variables that cause deviations from the desired performance but are difficult or costly to control in real-world conditions. The S/N ratio varies depending on each characteristic value, which is why it is used as a measurable criterion instead of standard deviation. There are three types of S/N characteristics: "Nominal is the better," "the Smaller the better," and "the Larger is better" [42,54,55]. In this study, due to the desire for high $COP_{cooling}$, the "Larger is better" characteristic has been used, and the equation for this characteristic is provided below.

$$\frac{S}{N} = -10log\ \frac{1}{n}\ (\sum_{i=1}^{n}\frac{1}{y_i^2}) \quad (15)$$

In the given equation, 'n' represents the number of observations, and 'y' indicates the observed data. The unit of the S/N ratio is decibels. For the "Larger is Better" characteristic, an increase in the S/N ratio implies that higher performance is achieved with the obtained result.

Table 4. L_{25} Orthogonal Array (L_{25} Orthogonal Array)

Run	A	B	C	D
1	1	1	1	1

2	1	2	2	2
3	1	3	3	3
4	1	4	4	4
5	1	5	5	5
6	2	1	2	3
7	2	2	3	4
8	2	3	4	5
9	2	4	5	1
10	2	5	1	2
11	3	1	3	5
12	3	2	4	1
13	3	3	5	2
14	3	4	1	3
15	3	5	2	4
16	4	1	4	2
17	4	2	5	3
18	4	3	1	4
19	4	4	2	5
20	4	5	3	1
21	5	1	5	4
22	5	2	1	5
23	5	3	2	1
24	5	4	3	2
25	5	5	4	3

3. RESULT AND DISCUSSION (SONUÇLAR VE TARTIŞMA)

3.1. Analysis of Taguchi Approach (Taguchi Yaklaşımının Analizi)

Based on the Taguchi approach, 25 different three-dimensional case designs were numerically analyzed. The $COP_{cooling}$ values obtained from the numerical analyses and the S/N ratio values derived from Eq. 15 are shown in Table 5. Among the 25 design cases, the most efficient S/N ratio and $COP_{cooling}$ values were observed in case 1, with values of 33.5161 and 0.073062468, respectively, while the lowest results were obtained in case 21, with values of 30.5260 and 0.01485463. There was a difference of 0.89 times in $COP_{cooling}$ between case 1 and case 21.

3.2. Determination of optimum VT geometry parameter (Optimum VT Geometri Parametresinin Belirlenmesi)

Due to the ideal condition being a high $COP_{cooling}$ in this study, the "larger is better" equation has used in Figure 6 to determine the S/N ratio. According to Eq.15, the peak level value of factors in the S/N graph produces the most optimal result. Therefore, when examining the means (S/N) ratio values shown in Figure 6, A2B1C1D1 represents the best levels for each factor. However, A2B1C1D1 (optimal case), as defined by the factor levels in Table 5, is not included in the L_{25} orthogonal design. Consequently, a model designated as case 26 with the design factor levels of A2B1C1D1, as shown in Table 6, was created and numerically analyzed in terms of cooling load performance. According to the results obtained, the $COP_{cooling}$ in case 26 conducted with the A2B1C1D1 was 0.07454, which is higher than the values found in the 25 cases analyzed. Moreover, at 0.07454, the optimal case's $COP_{cooling}$ ratio is 1.98% higher than case 1's $COP_{cooling}$ of 0.073062468. This indicates the effectiveness of the Taguchi approach in optimizing VT geometries based on $COP_{cooling}$. Table 7 presents the design factors and corresponding levels for A3B3C3D3, derived from the average factor values.

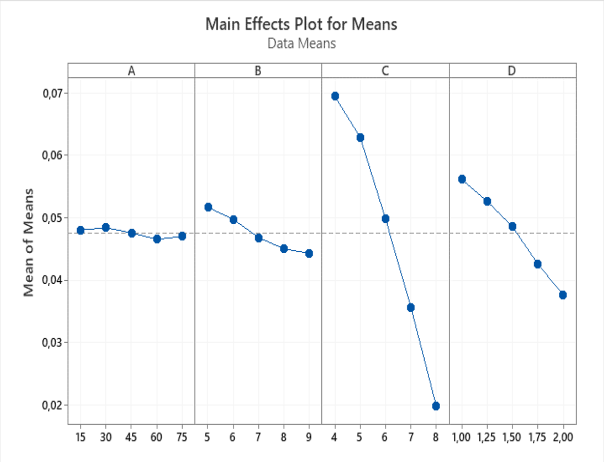

Figure 6. Mean S/N ratio graph for cooling Effect (Soğutma etkisi için ortalama S/N oranı grafiği)

The correlation among the four control factors was determined through regression analysis. Using Minitab 20, a regression analysis was conducted, resulting in an empirical equation that includes the four control factors, as seen in Eq. 16. In the equation, all four factors are included as independent variables, while $COP_{cooling}$ is the dependent variable.

$$COP_{cooling}=0.16369+0.000038*\alpha-0.001778*N-0.011803*D_{cold\ outlet}-0.01811*D_{nozzle} \quad (16)$$

As shown in Table 8, the actual cooling load obtained from numerical analyses using optimal VT geometries is compared with the predicted cooling effects derived from the empirical equation Eq. 16.

Table 5. Temperature Difference Results and S/N Ratio Values for the L_{25} Orthogonal Array (L25 Ortogonal Dizisi için Sıcaklık Farkı Sonuçları ve S/N Oranı Değerler)

Run	**A**	**B**	**C**	**D**	**$COP_{cooling}$**	**S/N Ratio**
1	1	1	1	1	0,0730625	-22,7261
2	1	2	2	2	0,0651542	-23,7212
3	1	3	3	3	0,0450014	-26,9355
4	1	4	4	4	0,0244801	-32,2237
5	1	5	5	5	0,0154116	-35,3335
6	2	1	2	3	0,0618173	-24,1778
7	2	2	3	4	0,0421680	-27,5003
8	2	3	4	5	0,0216177	-33,3038
9	2	4	5	1	0,0223182	-33,0268
10	2	5	1	2	0,0654596	-23,6805
11	3	1	3	4	0,0401680	-27,9224
12	3	2	4	1	0,0412621	-27,6890
13	3	3	5	2	0,0187804	-34,5259
14	3	4	1	3	0,0613986	-24,2368
15	3	5	2	4	0,0476042	-26,4471
16	4	1	4	2	0,0389068	-28,1995
17	4	2	5	3	0,0166284	-35,5830
18	4	3	1	4	0,0571261	-24,8633
19	4	4	2	5	0,0438807	-27,1545
20	4	5	3	1	0,0480513	-26,3659
21	5	1	5	4	0,0148546	-36,5628
22	5	2	1	5	0,0540166	-25,3495
23	5	3	2	1	0,0640328	-23,8720
24	5	4	3	2	0,0451160	-26,9134
25	5	5	4	3	0,0295073	-30,6014

Table 6. Optimal Levels of Factors According to Obtained S/N Ratios (Elde Edilen S/N Oranlarına Göre Faktörlerin Optimum Seviyeleri)

Factor	Conical Valve Angle (α)	$D_{cold\ outlet}$	Nozzle number	D_{Nozzle}
Optimal Model (Run 26 (A2B1C1D1)	30°	5 mm	4 Nozzle	1 mm

Table 7. Factors and Their Levels for the A3B3C3D3 Design (A3B3C3D3 Tasarımı İçin Faktörler ve Seviyeleri)

Factor	Conical Valve Angle (α)	$D_{cold\ outlet}$	Nozzle number	D_{Nozzle}
Average (initial) Model (A3B3C3D3)	45°	7 mm	6 Nozzle	1,5 mm

A significant difference of 40.3% is observed between the study designated as case 26 with A2B1C1D1 and the initial case designated as A3B3C3D3. This demonstrates clear evidence that Taguchi optimization has improved the $COP_{cooling}$ of the VT by 40.3% compared to the average values obtained without such optimization. Case 26 exhibits approximately 2% higher performance than case 1, which is the highest case in orthogonal array, which holds the highest value prior to optimization. The improvement in S/N ratio from the initial operating parameters to the level of optimal operating parameters was 9.669 dB.

Table 8. Factor Levels for the Optimized Model (Optimize Edilmiş Model İçin Faktör Seviyeleri)

	Initial parameters	Optimal parameters	
		Prediction	Numerical
Level	A3B3C3D3	A2B1C1D1	A2B1C1D1
$COP_{cooling}$	0,0445	0,0746571	0,07454
S/N ratio (dB)	-32.221	-20,8929	-22,5522
Improvement of S/N ratio	9.669 dB		
Prediction error (dB)	1.6593		

3.3. Analysis of Variance (ANOVA) (Varyans Analizi (ANOVA))

In the VT, determining the most effective control factor on $COP_{cooling}$ is conducted using analysis of variance (ANOVA). ANOVA was performed to assess the relative importance of the design parameters and their interactions in affecting the performance characteristics. This step is crucial for understanding which factors most significantly impact the outcome and should therefore be the focus of optimization efforts [56]. The ranking of control factors affecting the cooling effect in the VT was determined using ANOVA, which is utilized to decide the impact levels of design parameters. The impact degrees of the control factors given in Table 3 were examined in ANOVA applications with the percent contribution ratio (PCR). The PCR is formulated as seen in Eq. 17 [57] and the findings obtained are expressed in Table 9.

$$\%PCR = \frac{(SS_A-(V_e)(v_A))}{SS_T} * 100 \tag{17}$$

The F-Test and P-value indicate the confidence levels of the control factors [58]. Upon reviewing Table 9, the N, identified as factor C, affects the $COP_{cooling}$ as the most significant parameter with 78.82%, while the D_{nozzle}, with 10.54%, is the second most important parameter; the D_{cold} exit, at 1.85%, is identified as the third important parameter. The parameter A, the α, has the lowest effect among the four factors, with 0.64%. Additionally, the error rate obtained from the ANOVA results is 8.15%, which is considered acceptable in the literature.

Table 9. Results of ANOVA and PCR (ANOVA ve PCR Sonuçları)

Source	DF	Seq SS	Adj MS	F	P	%PCR
A	4	13.45	3.361	1.47	0.297	0.64
B	4	21.6	5.400	2.36	0.14	1.85
C	4	540.04	135.011	59.03	0	**78.82**
D	4	80.13	20.032	8.76	0.005	10.54
Residual Error	8	18.3	2.287			91.85
Total	24	673.51				

3.4. Confirmation Test (Doğrulama Testi)

For the confirmation test in the VT, the numerically obtained ΔT_c data were divided into two parts: training data and testing data. A total of 19 values were used for training in the regression analysis, while 6 values were designated for testing, resulting in 25 different case trials. The predicted values of ΔT_c for both testing and training data were obtained by the empirical Eq. 17 formulated through regression analysis. The comparison of predicted and numerical results for both training and testing data is illustrated in Figure 7. The predicted results from both training and testing data closely match the numerical outcomes. Furthermore, the R^2 for the cooling effect in the testing data is 0.9802 in the regression analysis (RA), indicating a strong agreement between numerical and predicted values. The R^2 value being close to 1 supports the reliability of the findings, while similar results have also been obtained in the study conducted by Sarıoğlu et al.[59] which is another expression showing the alignment. RA proves to be a highly useful and reliable method for examining the difference in cooling effect and for VT geometry optimizations. Additionally, the ΔT_c obtained from RA and the ΔT_c values obtained from numerical analysis are shown in Figure 8.

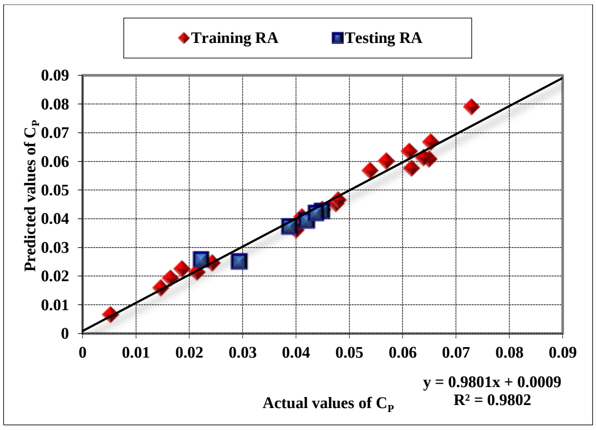

Figure 7. Comparison of regression results with numerical results for the ΔT_C (ΔT_C için regresyon sonuçlarının sayısal sonuçlarla karşılaştırılması)

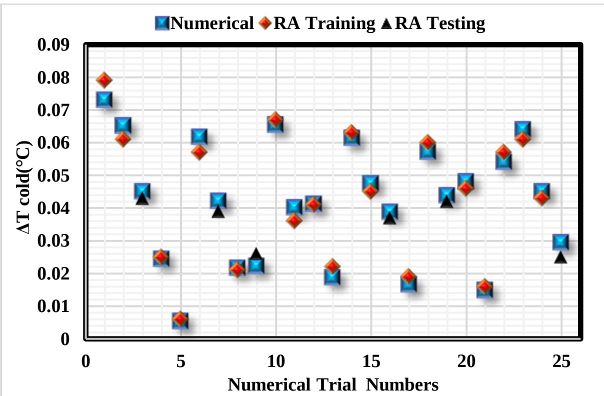

Figure 8. Comparison of numerical and predicted ΔT_C (Sayısal ve tahmini ΔT_C değerlerinin karşılaştırılması)

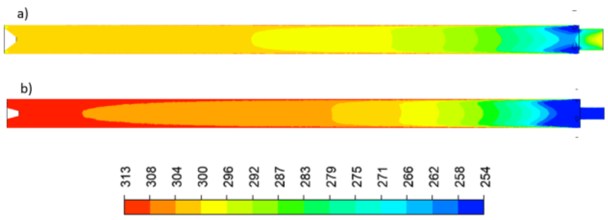

Figure 9. Comparison of temperature distribution in the longitudinal cross sections of a) Run 21 and b) Run 26 (Boyuna kesitlerde sıcaklık dağılımının karşılaştırılması: a) Çalışma 21 ve b) Çalışma 26)

In Figure 9, the total temperature fields in the longitudinal cross-sections of VTs case 26 and case 21 are displayed. The reason for selecting case 21 and case 26 is that they have the lowest and highest $COP_{cooling}$, respectively, among all the orthogonal arrays. This selection aims to clearly illustrate the difference between the two cases. When examining the general temperature distributions of the cases, high temperature distributions are observed near the tube's wall and in the area where the hot exit is located, while low temperature distributions are found in the center of the tube and in the cold exit area, indicating a behavior similar to that observed in previous VT studies. The maximum temperature reached in the hot exit area is 304.52 K for case 21, whereas for case 26, this value is determined to be 312.71 K. Moreover, in the cold exit area near the conical valve, a lower temperature distribution (≤ 258 K) is much more pronounced in case 26 compared to the other case. The sharp difference between the hot and cold areas in case 26 indicates a high energy exchange, providing as evidence that case 26 generates a higher $COP_{cooling}$ compared to other cases.

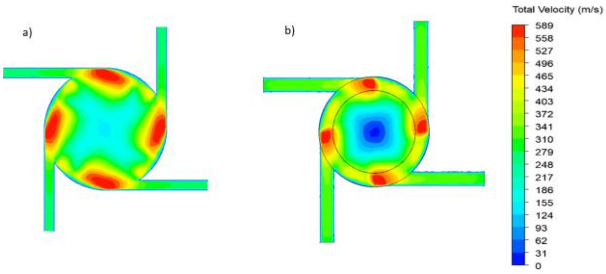

Figure 10. Comparison of the velocities in the inlet region of a) Run 21 and b) the Run 26. (Giriş bölgesindeki hızların karşılaştırılması: a) Çalışma 21 ve b) Çalışma 26)

The total velocity distributions in the cross-sectional areas of case 21 and case 26 are displayed in Figure 10. In case 21, a low-velocity region (≤120 m/s) forms in the center of the tube, while in case 26, the velocity in the same region drops to a minimum of 150 m/s. The presence of low velocity distribution in the center of the VT leads to a decrease in the fluid's temperature by the time it reaches the cold exit area. The results of this study successfully demonstrate the performance improvements achieved through the application of the Taguchi method for VT optimization. The study reveals that design parameters such as the N and D_{nozzle} have a significant impact on VT performance. Increasing the nozzle number enhances the VT's cooling capacity by maximizing energy separation, while optimizing the nozzle diameter increases the air flow speed and kinetic energy within the system, thereby improving cooling performance. These findings are consistent with those reported by Alsaghir et al. [44], emphasizing the sensitivity of VT performance to nozzle parameters. Conversely, reducing the number of nozzles negatively affects VT performance, a finding that aligns with the results presented by Pinar et al. [18,19]. The outcomes of this study validate the effectiveness of the Taguchi method in optimizing VT design parameters aligning with similar studies in the literature using Taguchi and other advanced optimization techniques.

4. CONCLUSIONS (SONUÇLAR)

This study has successfully applied the Taguchi method to optimize the design parameters of a VT, significantly enhancing its performance based on a thorough analysis of the temperature difference and the $COP_{cooling}$. The RNG k-ε turbulence model was employed, and all 25 cases were conducted under the same boundary conditions. The key findings from the study include:

- **High Level of Predictive Accuracy:** The regression analysis showed an R^2 of 0.9802, indicating a very high level of accuracy in predicting the performance of VTs based on the optimized parameters. This underscores the reliability of the empirical equation derived from the regression analysis for forecasting cooling effects in VTs.

- **Significant Improvement in Performance:** The optimized case (case 26) demonstrated a remarkable 40.3% improvement in $COP_{cooling}$ compared to the initial case, showcasing the effectiveness of the optimization process. The optimal case's parameters, featuring the best levels for factors A, B, C, and D, were 30º for the α, 4 nozzles, a $D_{cold\ exit}$ of 5mm, and a D_{nozzle} of 1mm, designated as A3B1C1D1. Case 26 demonstrates an approximate 2% increase in performance compared to case 1, which was the top-performing case within the orthogonal array before optimization.

- **Notable Difference in Cooling Load Performance:** A significant difference in $COP_{cooling}$, specifically 0.89 times, between the best and worst-performing cases. This highlights the potential for performance variance in VT operations and underscores the importance of meticulous design optimization.

- **Impact of Design Parameters on Performance:** Upon reviewing Table 9, it was evident that the N had the most significant impact on the $COP_{cooling}$, contributing to 78.82% of the performance variation. The D_{nozzle} was the second most impactful at 10.54%, followed by the $D_{cold\ exit}$ at 1.85%. Interestingly, the parameter with the least effect was the α, contributing only 0.64%.

- **Compatibility and Applicability of the Taguchi Method:** The findings from this study clearly illustrate the Taguchi method's suitability and applicability in optimizing VT designs. The method not only simplified the optimization process but also provided a structured approach to identifying the most influential design parameters for improving performance.

This study fills a significant gap in the research on VT optimization, demonstrating the effectiveness and applicability of the Taguchi method in optimizing the parameters affecting the performance of the VT. The Taguchi method has proven to be an effective tool in identifying the interactions between parameters and their effects on outcomes. The results highlight that this methodology is not only applicable in engineering and thermal system design but also in developing solutions that contribute to energy savings. The careful adjustment of VT parameters offers significant efficiency gains in industrial cooling, electronic cooling, and various process cooling applications.

DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission. (Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.)

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Himmet Erdi TANÜRÜN*:** He conducted the numerical analyses, interpreted the results, and wrote the manuscript. (Sayısal analizleri gerçekleştirdi, sonuçları yorumladı ve makaleyi yazdı.)

Adem ACIR: He processed the data, interpreted the results, and reviewed the manuscript. (Diğer yazar verileri işledi, sonuçları yorumladı ve makaleyi gözden geçirdi.)

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study. (Bu çalışmada herhangi bir çıkar çatışması yoktur)

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