Artvin Çoruh Üniversitesi
Mühendislik ve Fen Bilimleri Dergisi
Cilt:2 No:2, 2024 (100-110)

Artvin Coruh University
Journal of Engineering and Sciences
Vol:2 No:2, 2024 (100-110)

Araştırma Makalesi / Research Article

Design and Performance Optimization of Double-Pipe Type Heat Exchangers Based on CFD and Economic Analyses-A Numerical Study

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Received/Geliş Tarihi: 01.10.2024 **Accepted/Kabul Tarihi:** 30.11.2024

Abstract: In this study, Double-Pipe Type Heat Exchangers design and performance optimization were examined. Dimensionless parameters were suggested for the heat exchanger design and the experimental design was made using these parameters through response surface methodology. Numerical models were created using the obtained design of experiments parameters and the models were solved using computational fluid dynamics software. Quadratic models have been proposed to estimate the outlet temperature and pressure drop values of Double-Pipe Type Heat Exchangers using various design parameters. The effect of each dimensionless design parameter on outlet temperature and pressure drop was evaluated and an optimum design for maximum heat transfer with minimum pressure loss is presented.

Keywords: Computational fluid Dynamics, Double pipe, Heat exchanger, Response-surface optimization, Statistical optimization

Çift Borulu Tip Eşanjörlerin Tasarım ve Performans Optimizasyonu CFD ve Ekonomik Analizlere Dayalı Sayısal Bir Çalışma

Özet: Bu çalışmada çift boru tip ısı eşanjörü tasarımı için boyutsuz parametreler önerilmiş ve bu parametreler kullanılarak yanıt yüzeyi metodolojisi ile deneysel tasarım yapılmıştır. Elde edilen deney tasarım parametreleri kullanılarak sayısal modeller oluşturulmuş ve modeller Hesaplamalı akışkanlar dinamiği yazılımı kullanılarak çözülmüştür. Çeşitli tasarım parametreleri kullanılarak Çift Borulu Tip Isı Değiştiricilerin çıkış sıcaklığı ve basınç düşüşü değerlerini tahmin etmek için kuadratik modeller önerilmiştir. Her bir boyutsuz tasarım parametresinin çıkış sıcaklığı ve basınç düşüşü üzerindeki etkisi değerlendirilmiş ve minimum basınç kaybı ile maksimum ısı transferi için optimum bir tasarım sunulmuştur.

Anahtar Kelimeler: Hesaplamalı akışkanlar dinamiği, Çift boru, Isı eşanjörü, Tepki yüzeyi optimizasyonu, İstatistiksel optimizasyon

1. Introduction

Energy saving is of great importance today due to the increasing energy need and limited energy resources. In particular, a production bakery that produces snacks can efficiently use 35% of the energy it consumes (Mukherjee et al., 2019). It may be possible to achieve energy efficiency by replacing existing machines with new machines with lower energy consumption or by using heat exchangers in existing machines. The first suggestion presented, purchasing new machinery with lower energy consumption, means high investment costs. By incorporating a heat exchanger into existing machines, it is possible to have much lower investment costs or to recover a large portion of the unused and wasted energy (Cengel and Ghajar, 2015).

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It is known that there are many types of heat exchangers and these types are classified in many different ways (Cengel and Ghajar, 2015; Omidi et al., 2017). The performance of heat exchangers is measured by heat transfer efficiency. The performance of heat exchangers depends on the exchanger design, fluid properties and operating conditions. Heat transfer improvement methods are divided into three main groups: active method, passive method and combined method. Briefly, the active method aims to increase the heat transfer rate by using an external force (piston pumps, flow- disturbing magnetic, etc.) (Omidi et al., 2017). Briefly, the passive method aims to increase the heat transfer rate by using different geometric designs or flow-disturbing geometries (different flow surfaces, geometric turbulators, different material types, different nanofluids, etc.). In short, the combined method aims to increase the heat transfer rate by using both active and passive methods together (Omidi et al., 2017). Recent studies on heat exchangers seem to focus on increasing heat transfer efficiency and economic comparisons (Du et al., 2022; Ya et al., 2015). In this context, the easiest to apply heat exchangers are the intertwined tubes or also known as double tubes (Omidi et al., 2017). Double-pipe heat exchangers are used in the food industry, oil industry, chemical industry and gas industries. In double-pipe heat exchangers, cold and hot fluids generally transfer heat by moving parallel to each other, in the same direction or in opposite directions (Ya et al., 2015).

Söylemez (2004) made optimization based on both experimental and numerical results, depending on the geometry and dimensions of some double-pipe heat exchangers available on the market. It has determined the optimization goal to achieve maximum waste heat recovery in the most economical way with the most suitable pipe diameters and lengths. The dimensions obtained as a result of optimization were checked by comparing some data in the catalogs of heat exchanger manufacturers. As a result, it has been reported that the optimization formulation found will be more useful for double-pipe heat exchanger designers and manufacturers (Söylemez, 2004). Sunu et al. (2016.) changed the volumetric flow rate of cold and hot water in order to see the effect of the corrugations on the temperature in the rectangular corrugated double-pipe heat exchanger. They found that the corrugated heat exchanger reduced the temperature difference between cold water and hot water by 37.9% compared to the corrugated one. At the same time, they stated that the grooves improve the inner tube thermal surface and reduce the overall weight of the heat exchanger (Sunu et al., 2016). Venkatesh et al. (2023.) aimed to make an efficient heat exchanger with increased thermal efficiency by collecting the data used in optimization studies on double-pipe counter-flow heat exchangers. They used the Taguchi method to find the parameter that most affects the thermal efficiency of the heat exchanger. They stated that using a genetic algorithm in the optimization phase will give the most efficient results (Venkatesh et al., 2023). Taghilou et al. (2014) planned to minimize entropy formation in heat exchangers of different lengths by using Brent's optimization algorithm in a double-pipe cylindrical fin heat exchanger. They calculated the optimum Reynolds Number that provides the least entropy formation. Based on these, they calculated the optimum length for each heat exchanger. As a result, they stated that by reducing the Reynolds Number, the number of cylindrical vanes used was also reduced, which allowed the pump power to decrease (Taghilou et al., 2014). Moloodpoor et al. (2021) in their study, an interactive search algorithm was integrated with the developed fly-back method for thermo-economic optimization of the double-pipe heat exchanger and they used the compound ISA-IFB method. The main goal was to achieve cost minimization without reducing the thermal performance of the double-pipe heat exchanger too much. The results obtained using the ISA-IFB method were compared with the results obtained by the selected methods given in the literature. They found that the proposed ISA-IFB method provides a numerical approach for solving both constrained and unconstrained optimization problems. They stated that this method can start from a random point in the search space, regardless of the initial conditions of the process. Therefore, they stated that it would not require the user to have any prior knowledge about the optimization workflow (Moloodpoor et al., 2021).

In his study, Sridharan (2022) utilized gray relational analysis (GRA) to optimize the output parameters of a counterflow double-pipe heat exchanger, specifically the cold water outlet temperature (t2), hot water outlet temperature (T2), and efficiency (ε). Through both experimental work and GRA analysis, the optimal input parameters for the heat exchanger were determined, along with the corresponding performance values (Sridharan, 2022). Dalkılıç et al. (2021) investigated the impact of various geometric modifications and the use of different nanofluids on the heat transfer, cost reduction, and extended service life of double-pipe heat exchangers, both with and without plates. Their findings revealed that nanofluids with high thermal conductivity and low- cost particles yielded the lowest total costs. For instance, mixtures containing graphene or carbon nanotubes (CNTs) as nanoparticles demonstrated the best heat transfer properties while remaining cost-effective. Conversely, Ti and TiO_2 nanoparticles showed the worst performance due to their lower thermal conductivity and higher costs. The study also compared plated and plateless designs, finding that the plated design exhibited slightly higher contamination and a lower cleaning factor. In the plateless design, the cleanliness factor did not significantly affect the overall costs. However, in the plated design, contamination led to increased costs across all categories. The authors pointed out that fouling, which increases both pressure drop and cost, negatively impacts heat transfer. Furthermore, they observed that the plated design, which had fewer pipes, resulted in lower pressure compared to the plateless design. Based on these findings, they concluded that the plated designs were more cost-effective (Dalkılıç et al., 2021).

Esfandyari et al. (2023) conducted an optimization study on a double-pipe heat exchanger using Artificial Neural Networks (ANNs), Adaptive Neuro-Fuzzy Inference System (ANFIS), and Particle Swarm Optimization (PSO) methods to optimize the heat transfer rate, Nusselt number, and number of transfer units (NTU). They validated their results by comparing them with experimental data and concluded that the ANN-PSO model slightly outperformed the ANFIS-PSO model (Esfandyari et al., 2023). Dastmalchi et al. (2017) performed an optimization study on a double-pipe heat exchanger with three micro-finned tubes, each having different inner diameters and Reynolds numbers. They proposed new correlations for determining the optimum micro-fin height and helix angle, which are dependent on the inner tube diameters and Reynolds number. The PSO algorithm was used to optimize the micro-finned tubes under turbulent fluid flow conditions, aiming to maximize heat transfer while minimizing pressure drop. Their findings showed that the optimum micro-fin height increased with an increase in the Reynolds number. However, they observed an opposite trend for the optimum helix angle (Dastmalchi et al., 2017).

Han et al. (2015) aimed to achieve an optimal geometric design for double-pipe heat exchangers with internal corrugated pipes through a multi-objective optimization approach using Response Surface Methodology (RSM). They integrated a three-dimensional heat transfer and flow model and applied various optimization models. The results from each model were compared by evaluating their respective accuracy percentages (Han et al., 2015). Colaço et al. (2022) focused on determining the efficiency parameters of double-pipe heat exchangers and sought to achieve an optimal geometric design with minimal pressure losses and improved heat transfer efficiency, represented by the thermal performance index (TPI), as well as energy savings. The team employed a multi-objective non-dominated sorting genetic algorithm (NSGA-RL) to maximize both the TPI and Nusselt number while minimizing the Fanning friction factor. Their findings showed that in a split-pipe double-pipe heat exchanger, the Nusselt number increased by approximately 7.93-8.25 times, while the friction factor increased by 6.5-9.75 times compared to a straight-tube heat exchanger. Based on these results, they concluded that heat transfer was significantly enhanced (Colaço et al., 2022). Zamani et al. (2023) conducted a study on a double-pipe heat exchanger using phase change materials (PCMs) for energy storage. The analysis was carried out using Ansys Fluent CFD software. Their optimization process utilized a genetic algorithm to maximize the energy stored or minimize the exergy destruction within the heat exchanger. The system used 70°C hot water as the working fluid. Following the optimization, they observed that the hot water returned at a temperature of 8°C. The results indicated that the stored energy was a function of adiabatic time and reached a peak of 25.312 J during an adiabatic time interval of 2150 seconds (over 1 hour) (Zamani et al., 2023).

Kumar et al. (2018) used a passive technique to examine the effect of thermal parameters on the improvement of heat transfer in a double-pipe heat exchanger. The input parameters were bandwidth, band gap and mass flow rate, and the output variables were Nusselt number (Nu) and pressure difference (ΔP). They accepted. The effects of input parameters, Nu (increasing the Nusselt number) and ΔP (decreasing the pressure difference) were investigated by ANOVA analysis, and Response Surface methodology (RSM) was used to provide optimum conditions. They found that for Nu, the mass flow rate was the main factor affecting the bandgap, and similarly, for ΔP, the mass flow rate and the bandwidth were the main factor affecting the bandgap. As a result of RSM, they found that the combination of a mass flow rate of 0.037 kg/s, a band gap of 20 mm and a band width of 3.8 mm gave optimum values of Nu 48.4 and ΔP 895.2 Pa (Kumar et al., 2018). Kola et al. (2021) used the Response Surface Method in their study to maximize the heat transfer of cut twisted tapes of varying cross-sections placed in a double-pipe heat exchanger and to find optimum values to minimize the friction factor. The input parameters were taken as mass flow rate, cutting radius and cutting angle, and the effect of the parameters on the response variables was analyzed using ANOVA. The results showed optimum values giving higher HTC and less friction factor at mass flow rate of 0.05 kg/s, cutting radius of 5.464 mm and cutting angle of 45° (Kola et al., 2021). Arjmandi et al. (2020) numerically examined the effect of band-shaped twisted vortex generators and nanofluid (Al2O3-H2O) placed in a double-pipe heat exchanger on the thermal performance of the exchanger. They used the response surface method (RSM) to optimize the vortex generator geometry and twisted band turbulator geometry to provide the maximum Nusselt number and minimum friction factor. It has been observed that parameters such as the number of vortex generators (decreasing the number of blades) and the angle of the vortex generator increase Re and, as a result, increase the heat transfer efficiency. They also stated that the vortex generators positively affected the pitch ratio, Nusselt number and friction factor, resulting in five times more efficiency compared to the original version. They found the optimum result that provides the most effective thermal efficiency by applying the optimum vortex generator geometry and the spacing ratio of the vortex generator (Pi/l = 0.18, 0.5235 (rad) angle and Re = 20000) (Arimandi et al., 2020).

Majidi et al. (2018) experimentally studied the overall heat transfer coefficient (OHTC) of air in a double-pipe heat exchanger. To enhance the heat transfer rate, they attached a copper wire to the outer surface of the inner tube. In addition, they proposed a novel method to calculate the heat transfer coefficients for both the inner tube and the annular section of double-pipe helical heat exchangers. This method combines two previously established approaches with subsequent modifications, such as replacing the hydraulic diameter with the equivalent diameter. The study also examined the influence of both the hot and cold mass flow rates on the OHTC, along with the impact of the fin installed in the annular section on the heat transfer coefficient. The results demonstrated the effectiveness of the proposed correlation, showing an increase in OHTC due to the presence of the fin inside the annulus. A comparison of the theoretical results from the proposed correlation with the experimental data revealed a closer match between the two. Additionally, the study found that increasing one of the flow velocities—while maintaining constant inlet temperatures—led to a rise in the Reynolds number and a corresponding increase in the OHTC. The effects of both the mass flow velocities (hot and cold) and the temperature on the OHTC were also discussed. Finally, the analysis of the soldered wire fin revealed that its presence significantly improved the heat transfer coefficient of the annular section, leading to a higher overall heat transfer rate (Majidi et al., 2018).

El Maakoul et al. (2020) used numerical simulations to evaluate the thermo-fluid performance of double-pipe heat exchangers equipped with split longitudinal fins. The performance of configurations featuring split longitudinal fins is compared with that of traditional longitudinal fins, focusing on heat transfer capacity, pressure drop, and overall efficiency. Additionally, the impact of the fin split interval and mass flow rate on the thermo-fluid performance is examined. They found that for the same mass flow rate and pumping power, the heat transfer rate with split longitudinal fins is higher than that of conventional longitudinal fins, ranging from 31% to 48% higher. In general, the thermo-fluid performance of double-pipe heat exchangers improves with the use of split longitudinal fins, as the increase in pressure loss is compensated by the enhanced heat transfer efficiency (Maakoul et al., 2020). Poongavanam et al. (2021) conducted an analytical study on the pressure loss and thermal performance of a double-pipe heat exchanger with shot peening. The thermal performance improvement of the proposed design was 1.19 times greater than that of the previous model (Poongavanam et al., 2021). Ishaq et al. (2021) carried out a study to evaluate the thermal performance efficiency of a double-pipe heat exchanger (DPHX) with diamond-shaped fins in the annular region. Their proposed design was examined with the aim of optimizing thermal efficiency and enhancing energy conservation (Ishaq et al., 2021). Ashraf et al. (2024) conducted an innovative design featuring extended arrow fins optimized for high-performance heat transfer in a double-pipe heat exchanger. These arrow fins are integrated into a trapezoidal fin structure to reduce material usage, weight, and cost, while enhancing the energy efficiency of the double-pipe heat exchangers. The results are analyzed in terms of the friction factor (fRe), Nusselt number, and j-factor. The findings suggest that specific geometric configurations of arrow fins lead to a significant increase in the Nusselt number. For instance, an 80% fin height is recommended when the number of arrow fins ranges from 6 to 24, and a 20% fin height is suggested for 30 arrow fins, particularly when the radii ratio is small Ashraf et al. (2024).

Zhang et al. (2023) introduced novel double-pipe heat exchangers featuring different serpentine channel designs to induce chaotic advection. The hydrothermal performance of these proposed configurations is numerically analyzed under laminar flow conditions. Compared to the conventional double-pipe heat exchanger, the suggested designs show a significant improvement in heat transfer, except for the twisted in-phase and twisted out-of-phase configurations. The performance evaluation criterion and the compactness factor are used as the key metrics to compare the performance of these geometries across different Reynolds numbers. Among the designs, the enhanced C-shaped double-pipe heat exchanger outperforms the others in both performance evaluation and compactness. At a Reynolds number of 500, the performance evaluation criterion and compactness factor of the enhanced C-shaped design are 1.3–197% and 22.3–736% higher than those of the other configurations, respectively (Zhang et al., 2023).

Gandjalikhan Nassab et al. (2023) emphasized the significant role of combining the radiant gas effect with circumferential ribs in the inner tube of a double-pipe heat exchanger to improve thermal performance by recovering waste heat for air heating. They proposed that a notable performance enhancement could be achieved by increasing the heat transfer rate from the hot exhaust gas to the cold air flow, utilizing the radiative properties of the gases. This concept was demonstrated and validated through the numerical solution of the radiative transfer equation, integrated with a set of energy, momentum, and continuity conservation equations under steady- state conditions. The turbulent forced convection was modeled using the widely recognized k-ε model to calculate turbulent stress and heat flow. All calculations were carried out using COMSOL Multiphysics software, considering a broad range of gas radiation properties in double-pipe heat exchangers with and without ribs. The numerical results indicated that the contributions of the ribs and the gas radiation effect to improving the heat exchanger's efficiency were 21% and 45%, respectively.

Additionally, when ribs were added to the heat exchanger configuration, pressure drops of 1.76 Pa and 0.71 Pa were observed for the gas and air flows, respectively (Gandjalikhan Nassab et al., 2023). In this study, the effects of pipe diameter ratio and diameter/length ratio on heat exchanger performance in a double-pipe heat exchanger system were numerically examined. The analyzes were modeled with CFD software using incompressible air. Using the obtained results, the parameters that yield the most heat change in the constant flow condition were statistically determined and optimized. The accuracy of the regression model was questioned by re-analysis on the optimized geometry. This study will provide insights for future research on the design of heat exhangers with optimal length and diameter.

2. Materyal ve Metot

2.1. Çalışma Alanı

In this study, CFD analyzes were applied on the counterflow heat exchanger geometry shown schematically in Figure 1. In the analyses, the diameter of the inner pipe was assumed to be a constant 400 mm. The diameter of the outer tube and the length of the tubes were determined according to the response surface test methodology. The created geometry was solved as a steady state in the Solidworks Flow Simulation program and the results were evaluated statistically.

For parametric analyses, inner diameter (Di), outer diameter (Do) and pipe length (L) are varied so that L/Do obtain as seen in Table 1.

Table 1. Design of experiments parameters in accordance with response surface method (Di= 400 mm, Inlet temperature= 30 °C)

	Min	Max
L (mm)	1208	2792
Do (mm)	602	998
L/Do	1.304904	4.316832
Do/Di	1.505	2.495
Total number of runs= 100		

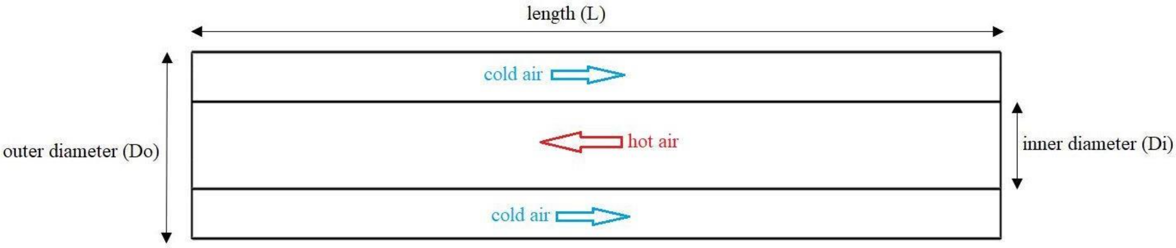

Figure 1. Topology of proposed heat exchanger and dimensions

In CFD analyses, a regression model was created by determining heat transfer efficiency and pressure loss values in heat exchangers with different geometric dimensions under constant flow rate. On the obtained model, the parameters where the lowest pressure loss and the highest heat transfer occurred for cold air flow were determined by the response surface optimization method.

The material of all designs created was determined as AISI 304 stainless steel. The mechanical properties of AISI 304 stainless steel are given as density 8000 kg/m^3, heat conduction coefficient 16

W/m.K and specific heat 500 J/kg.K (Kola et al., 2021). In SolidWorks Flow Simulation CFD software, two designs were analyzed as internal flow analysis by having the same geometric structure (except for their internal designs) and the same initial conditions were determined. The material of all solids was determined as AISI 304 and the initial temperature of all solids was entered as 20.05 °C and the initial static pressure was entered as 101325.00 Pa. The fluid was determined as air and the initial temperature of the fluid was entered as 30 °C. Air at 185 °C is defined as the second fluid that will heat the inlet air. Allowing heat conduction in solids, the flow type was chosen exclusively laminar. The heat transfer coefficient was chosen as the external wall thermal condition, and the air heat transfer coefficient was determined as 17 $W/m^2.K$ as the external effect fluid and the external effect air temperature was determined as 28 °C. In the analysis, the software was asked to automatically determine the flow type by selecting flow characteristics, turbulence and laminar for hot and cold air flow**.** Turbulence parameters were entered as turbulence intensity 2% and turbulence length 0.00072 m. Analyzes were solved using Navier-Stokes equations as steady state (Arimandi et al., 2020). The turbulence conservation law of homogeneous fluids followed by laminar, turbulent and transitional flows is given in the k-ε turbulence model with damping function realized by Lam-Bremhorst (Majidi et al., 2018). The constants in $k - \varepsilon$ model are chosen as $C_{\mu} = 0.009$, $C_{s1} = 1.44$, $C_{s2} = 1.92$, and empirical constant in Turbulence model are chosen as $\sigma_k = 1$, $\sigma_s = 1.3$, $\sigma_B = 0.9$ and $C_B = 1$, for $P_B > 0$ and $C_B = 0\ for\ P_B < 0$ respectively.

3. Results and Discussions

Figures 2-3 show the variation of average outlet temperature of the cold air versus dimensionless parameters L/Do and Do/Di. As seen in these figures outlet temperature increases with increasing L/Do ratio while it decreases with increasing Do/Di ratio. The increase of L/Do ratio enables the fluid for heat transfer for longer durations. On the other hand, increasing Do/Di ratio, causes the ratio of the part of the fluid in contact with the heat transfer surface to decrease.

Figures 4-5 show the variation of pressure loss of the cold air versus dimensionless parameters L/Do and Do/Di. As seen in these figures, pressure loss increases with increasing L/Do ratio as expected. The pressure loss shows considerable variation with increasing Do/Di ratio. It is concluded that the increased turbulence has result in this variation.

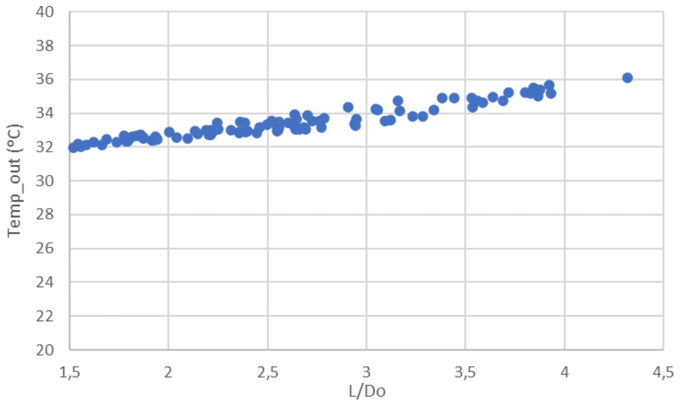

Figure 2. Variation of outlet temperature of the cold air versus L/D_o ratio (Inlet temperature=30 °C, D_i=400 mm)

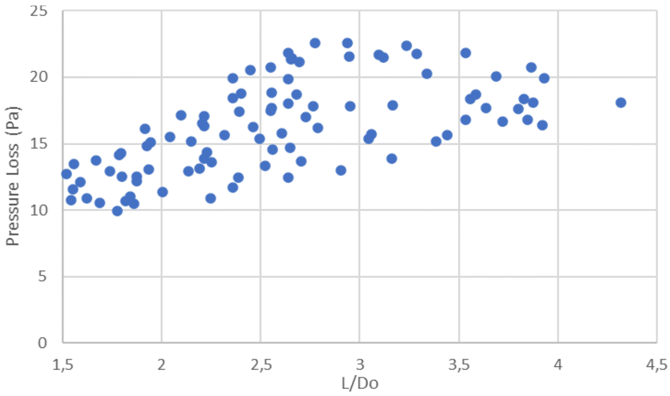

Figure 3. Variation of outlet temperature of the cold air versus Do/Di ratio (Inlet temperature=30°C, Di=400 mm)

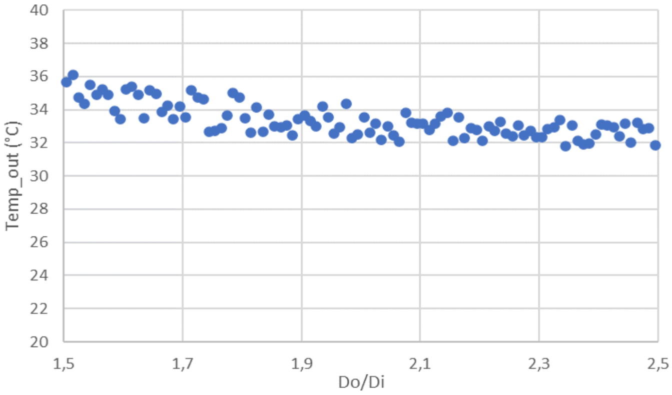

Figure 4. Variation of pressure loss of the cold air versus L/D$_o$ ratio (Inlet temperature=30 °C, D$_i$=400 mm)

For further evaluations, quadratic models were proposed for both outlet temperatures and pressure loss as follows ;

$$T_{out} = A.P_1 + B.P_2 + C.P^2 + D.P^2 + E.P_1.P_2 \quad (1)$$

1→2

$$\Delta P = A.P_1 + B.P_2 + C.P^2 + D.P^2 + E.P_1.P_2 \quad (2)$$

1→2

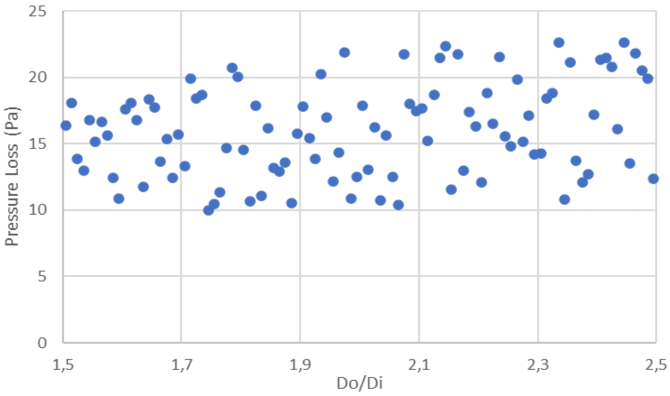

Figure 5. Variation of pressure loss of the cold air versus Do/Di ratio (Inlet temperature=30°C, Di=400 mm)

Where P1 and P2 are L/Do and Do/Di respectively. The curve fitting coefficients are presented in Table 2. As can be seen in Table 2, the correlation coefficient is satisfactory for both models. According to the results obtained, the parameters P1 and P2 have approximately similar effects in the outlet temperature prediction model. However, it is seen that the cross interaction of the parameters has a negative effect on the outlet temperature. On the other hand, in the pressure drop model, the P1 parameter acts in the direction of decrease, while the parameter P2 acts in the direction of increase. It has also been concluded that cross interactions are much more effective in this model.

Table 2. Curve fitting parameters for proposed models

	Outlet Temperature Model	Pressure loss Model
A=	14.307	-1.854
B=	15.049	1.0757
C=	-1.079	-0.0748
D=	-1.580	-0.2650
E=	-3.853	4.0462
R2=	0.8579	0.999

A heat exchanger should provide the lowest pressure loss and maximum heat transfer. In this study, when evaluating the performance of the heat exchanger, both the amount of heat transfer and the pressure loss were considered to be of equal importance and the parameters where the greatest heat transfer and the lowest pressure loss occurred were determined. According to this, L/D_o= 2.773 and D_o/D_i=2.445 yields the most heat transfer with minimum pressure loss. By using these parameters, the outlet temperature and pressure loss is estimated with error of 0.536 °C and 0.16 Pa. This result shows that the accuracy and reliability of proposed models are satisfactory.

5. Conclusions

This study presents a design optimization approach for Double-Pipe Type Heat Exchangers. For this aim, dimensionless parameters were proposed and determined in accordance with response surface methodology. Subsequently, CAD models were solved by using CFD.

The obtained results showed that outlet temperatures of the cold air increase with increasing L/D_o ratio while it decreases with increasing D_o/D_i ratio. It is also showed that pressure loss of the cold air increases with increasing L/D_o ratio as expected.

It is concluded that proposed quadratic models for estimation of outlet temperatures and pressure losses are satisfactory. It is also concluded that the parameters P1 and P2 have approximately similar effects in the outlet temperature prediction model while the cross interaction of the parameters has a negative effect on the outlet temperature. It was observed that the P1 parameter acts in the direction of decrease, while the parameter P2 acts in the direction of increase in the pressure drop model. It has also been concluded that cross interactions are much more effective in this model.

It is concluded that proposed models estimates the maximum temperatures with minimum pressure loss to be obtained where L/D_o= 2.773 and D_o/D_i=2.445 with a minimum error. So, it is concluded that the proposed models are successful for further estimations and designs.

Acknowledgement

The authors would like to thank Tüfekçioğulları Machinery R&D Center and The Scientific and Technological Research Council of Türkiye under grant number 1501-3221347 for their support in the implementation part of the project.

Conflict of Interest Statement

There is no conflict of interest between the authors.

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