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Enhancing Combi Boiler Efficiency through Waste Heat Recovery Using a Copper-Finned Counter-Flow Heat Exchanger

Bakır Kanatçıklı Ters Akışlı Isı Değiştirici Kullanılarak Atık Isının Geri Kazanımı Yoluyla Kombi Kazan Verimliliğinin Artırılması

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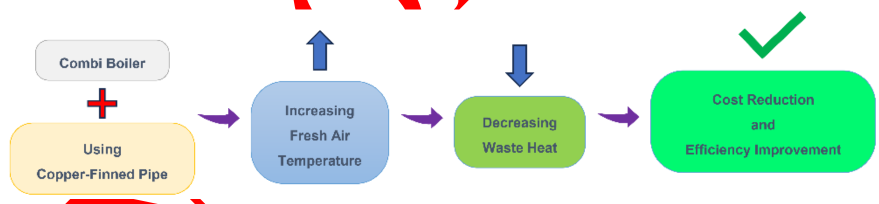
Highlights

- *Copper fins efficiency: The use of copper fins increased heat recovery efficiency from 9.3% to 14.8%.*
- *Air preheating impact: The fresh air temperature entering the combustion chamber rose from 13 K to 26 K.*
- *Numerical validation: Experimental and numerical results showed deviations of 4.77% for the Nusselt number and 5.36% for the friction factor.*
- *Thermal performance: The thermo-hydraulic performance parameter was calculated as 0.62, providing a reference value for optimal design.*

Graphical Abstract



Abstract

Natural gas-fired combi boilers are widely used to meet domestic hot water and space heating demands. Waste heat recovery is important for improving energy efficiency and reducing environmental impacts. In this study, a double-pipe heat exchanger utilizing copper's high thermal conductivity and the large surface area provided by finned structures was experimentally and numerically investigated. Preheating the fresh air supplied to the combustion chamber decreases the fuel required for water heating. Heat transfer between the incoming fresh air and outgoing flue gases was enhanced by incorporating copper fins into the pipe assembly. Experimental results obtained from straight and copper-finned pipe configurations were compared with numerical predictions. The results showed that the flue gas outlet temperature decreased by approximately 6%. Heat recovery efficiency increased from 9.3% to 14.8% with the use of copper fins, while the inlet air temperature increased from 13 K to 26 K. Numerical and experimental results agreed well, with differences of 4.77% and 5.36% for the Nusselt number and friction factor, respectively. The enhanced heat transfer provided by copper fins resulted in a 3.98% increase in the Nusselt number.

Özet

Doğal gazla çalışan kombiler, konutların sıcak su ve ısınma ihtiyaçlarını karşılamak amacıyla yaygın olarak kullanılmaktadır. Atık ısı geri kazanımı, enerji verimliliğinin artırılması ve çevresel etkilerin azaltılması açısından önemli bir role sahiptir. Bu çalışmada, bakırın yüksek ısıl iletkenliği ve kanatçıklı yapıların sağladığı geniş yüzey alanı avantajlarından yararlanılarak geliştirilen çift borulu bir ısı değiştiricisi deneysel ve sayısal olarak incelenmiştir. Yanma odasına giren taze havanın önceden ısıtılması, suyun ısıtılması için gerekli yakıt miktarını azaltmaktadır. Bu amaçla, gelen taze hava ile dışarı atılan baca gazı arasındaki ısı transferi, boru sistemine bakır kanatçıklar eklenerek iyileştirilmiştir. Düz boru ve bakır kanatçıklı boru tasarımlarından elde edilen deneysel sonuçlar sayısal sonuçlarla karşılaştırılmıştır. Sonuçlar, baca gazı çıkış sıcaklığının yaklaşık %6 oranında azaldığını göstermiştir. Bakır kanatçık kullanımıyla ısı geri kazanım verimi %9,3'ten %14,8'e yükselmiş, kombi giriş havasındaki sıcaklık artışı ise 13 K'den 26 K'ye çıkmıştır. Sayısal ve deneysel sonuçlar arasında Nusselt sayısı ve sürtünme katsayısı açısından sırasıyla %4,77 ve %5,36 fark bulunmuştur. Bakır kanatçıkların sağladığı iyileştirilmiş ısı transferi sonucunda Nusselt sayısında %3,98 artış elde edilmiştir.

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1. INTRODUCTION

Heating needs of buildings constitute an important part of global energy consumption [1]. In order to meet this increasing energy needs every year, various energy sources are used [2]. The fact that energy resources are limited and the need for energy consumption is constantly increasing, increasing the efficiency in energy use becomes more important. In countries with insufficient energy resources, residential heat needs can be provided with environmentally friendly natural gas. Heating of the living environments and daily use water in the houses was provided by the combi boiler in which natural gas is used as fuel. Combi boiler was a heat exchanger used to heat the daily domestic water and central heating water of the heat released by the burning of natural gas. Various studies were carried out to increase efficiency on combi boilers for energy saving [3, 4].

One of the methods applied to reduce energy costs in meeting space heating and hot water needs was the use of solar energy and combi boiler systems. In the study of Jens et al., the integration of solar energy and combi boiler system was investigated [5]. In this simulation study, in which different integration situations were evaluated, it was seen that solar heat did not have a negative effect on boiler efficiency. In another study, the efficiency of the solar energy system increased due to the heating of the colder space heating circuit instead of the hot water in a buffer boiler with solar collectors [6].

Studies to increase boiler operating efficiency focus on the improvement of the heat transfer in the combustion chamber and the recovery of the heat thrown out with the burned air and exhaust gas. A new type of heat exchanger has been proposed for the heating of cold water in a study for the recovery of heat loss by flue gas [7]. By reducing the flue gas pipe diameters, the boiler efficiency has been improved by increasing the heat transfer surface area. In addition, the size of the heat exchanger has been reduced.

A numerical study has been carried out on the development of a new geometry to increase the performance of the plates used in the plate heat exchanger for use in a condensing boiler [8]. The efficiency of the heat exchanger, in which zig-zag geometric plates were used, has increased.

In a system where biomass was burned as an energy source, waste energy has been tried to recover by using flue gas enthalpy [9]. A heat pump with a gas compressor and cooler was added to the system. The heat in the flue gas with the heat pump was used to heat the cold water. While operating costs have increased by 2% to 13%, CO2 gas emissions have also decreased.

In the study of Balci et al. in 2019, preheating was done using flue gas before the domestic water entered the heat exchanger [10]. In the study, in which a boiler with a condensing system was used, transitive analyzes were carried out to reveal the effects of the condensation mass, phase change temperature and flow rate of the domestic water. It has been determined that the designed system increases the efficiency of the combi boiler and the domestic water is heated in a much shorter time.

The thermodynamic efficiency of waste heat recovery condensing boilers (EGR-CWR-WHRCB) was calculated using thermodynamic analysis and compared with other boilers. In the proposed system, both condensate water and fresh air temperature were increased with exhaust gas. According to the thermodynamic analysis of this proposed method, the boiler efficiency has improved significantly [11].

In order to increase efficiency in the condensing heat exchanger, the dehumidification of the fresh air by heating and the recovery of the waste heat in the exhaust gas were mathematically modeled. In this study by Wang et al., it was seen that the boiler efficiency could be improved up to 3% [12].

Fins are used on the convection surfaces to improve heat transfer [13]. Despite the disadvantages such as friction and pressure drop, fins enhance heat transfer by increasing the transition surface [14]. In many studies, fin geometry and fin layout have been tried to be optimized [15, 16]. Turbulators are preferred to improve the heat transfer between the pipe and the fluid in internal flows [17]. Molecules in laminar flow collide with the turbulator surfaces, resulting in turbulent flow [18]. Heat transfer between molecules with high temperature difference is accelerated by forcing fluid molecules to displace with turbulators [19]. Many experimental and numerical studies on turbulator geometry have shown that turbulators significantly increase efficiency in heat exchangers [20, 21]. The combined use of turbulator and fins further improves heat transfer [22].

In hermetic combi boilers, the exhaust gas is discharged from the house, and the fresh air was taken from the outside thanks to the nested pipe pair. Some of the waste heat carried by the flue gas was transferred to the fresh air entering the combi boiler, thus both reducing the humidity of the incoming air and increasing its temperature. Various research was also carried out to increase the heat transfer between the fluids passing through the nested pair of pipes. According to a study conducted in 2021, the efficiency of heat transfer between the two fluids improved by approximately 38% with the use of helical fins in the nested tube pair [23]. Maakoul et al. investigated the effect of different fin types on heat transfer on the nested tube pair [24]. The analysis results show that the use of helical fins significantly increases the heat transfer rate, but also increases the pressure drop.

In this study, it was aimed to recover the waste heat from flue gas in a combi boiler. In the experimental study, the heat transfer between the pipe pair was improved. Copper fins are added to the system to preheat fresh air using flue gas enthalpy. By increasing the inlet temperature of the fresh air, higher temperature was achieved in the combustion chamber. Also, experimental work has simulated numerically with the CFD approach. The numerical analysis was conducted in ANSYS Fluent steady-state case.

2. MATERIAL AND METHOD

2.1 Experimental Setup

Hermetic combi boiler with fan was Demir Döküm brand C 275 F model in the experiments carried out in the counter flow chimney. It is domestic type and was operated with natural gas in the experiments (Table 1).

Table 1: Technical specifications of combi boiler

Specification	**Value**
Fuel type	Natural gas
Rated thermal power	275 kW (Kcal./min)
Rated thermal load	328 kW (Kcal./min)
Gas inlet pressure (Natural gas)	200 mBar (mmSS)
Gas consumption (Natural gas)	2.43 m3/h
Minimum water pressure	0.1 bar (mSS)
Water flow range	2.7-11 l/min

Temperature measurements were made at five important points in the heat flow. T1 and T3 in region 1 and T2 and T4 in region 2 were aligned on the vertical axis (Figure 1). Care has been taken to avoid contact between thermocouples and aluminum pipes, as air temperatures will cause incorrect measurement in case of contact with the aluminum pipe.

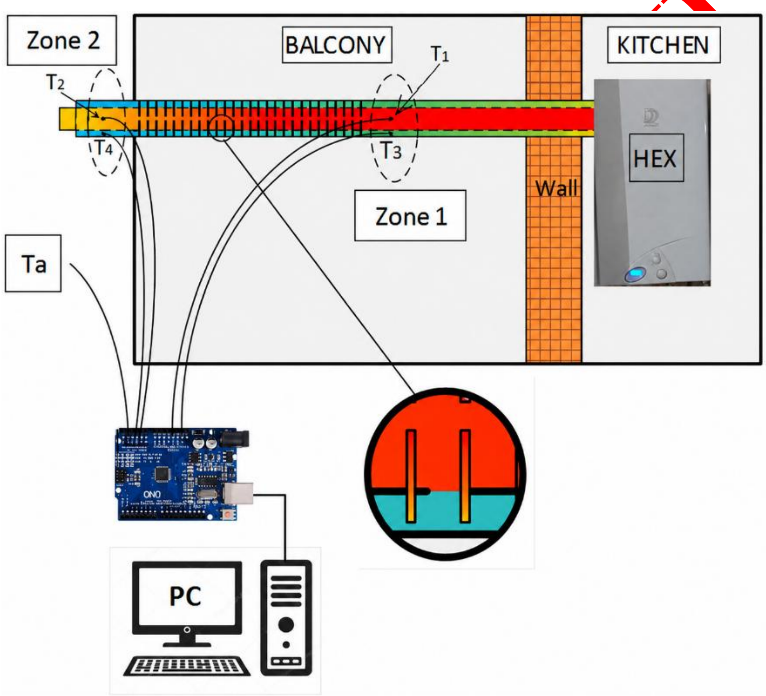

Figure 1: The experimental setup.

4 mm diameter copper pins were inserted into the regular hexagonal diagonal points of the 60 mm diameter aluminum inner tube (Figure 2). It was fixed with tabs for safety purposes so that the pins do not gouging. Pins and pipe insertion were of great sensitivity. Contact surface roughness, which is the first of this sensitivity, has been ignored. Secondly, since the gas passage between the inner and outer pipes will cause a significant measurement error, careful assembly has been made by paying attention to their tightness.

Arduino (UNO) was an electronic board with microcontroller. Atmel brand Atmega 328 / P series microcontrollers were used in Arduino board. The microcontroller, which did not require an external programmer, makes the ready-made hardware easier to control thanks to its open-source software infrastructure.

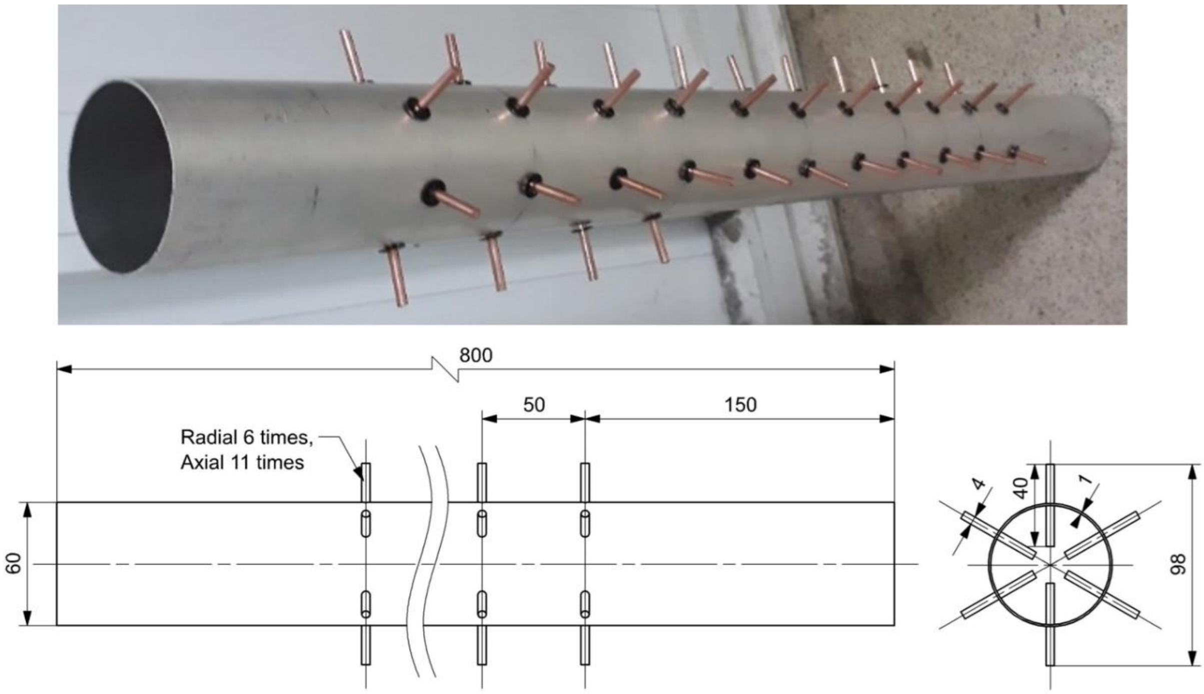

Figure 2: The copper finned inner pipe and dimensions.

Arduino UNO has 16Mhz processor, 2 Kb RAM and 32 Kb program memory used in system design. It can be powered from the connected computer via the USB socket. Temperature measurements were measured with a K-type thermocouple at five points in total. Thermocouples operate with an accuracy of 0.25 °C and a measuring range of -20 °C to 800 °C. The MAX6675 was able to convert the thermocouple's signal to a voltage compatible with the input channels of the ADC.

The Nusselt number was a significant parameter that can contribute to the heat transfer rate in heat exchanger. The friction factor was considered via pressure drop, also the Nusselt number, friction factor, Nusselt enhancement ratio (NER), friction factor enhancement ratio (FFER) and thermo hydraulic performance parameter (THPP) are calculated by Equation 1-5 [26,28].

$$Nu = h\frac{D}{k} \tag{1}$$

$$f = \frac{(\Delta P/L)D}{2\rho v^2} \tag{2}$$

$$NER = \frac{Nu_{fin}}{Nu_{pt}} \tag{3}$$

$$FFER = \frac{f_{fin}}{f_{pt}} \tag{4}$$

$$THPP = \frac{NER}{(FFER)^{\frac{1}{3}}} \tag{5}$$

2.2 Numerical Analysis

Numerical analysis was needed to solve engineering problems where there were equations that cannot be solved analytically by formulas. The experimental work was also simulated numerically with the CFD approach. Also, numerical results of Nusselt number and friction factor for the smooth pipe were computed and validated with equations of Dittus-Boelter and Blasius as given Equation 6-7 [25].

$$Nu = 0.024\, Re^{0.8}\, Pr^{0.4} \tag{6}$$

$$f = 0.085\, Re^{-0.25} \tag{7}$$

Grid independency test is a very important parameter in numerical analysis, also the accuracy of the analysis depends on the mesh structure (Figure 3). Table 2 shows the independence test for the grid. 5 different cell numbers were tested to validate the model. When the number of elements increased from 465738 to 587877, the variation in Nusselt number is 0.58%. Based on the grid independency test 519808 elements are used for numerical analysis (Table 2).

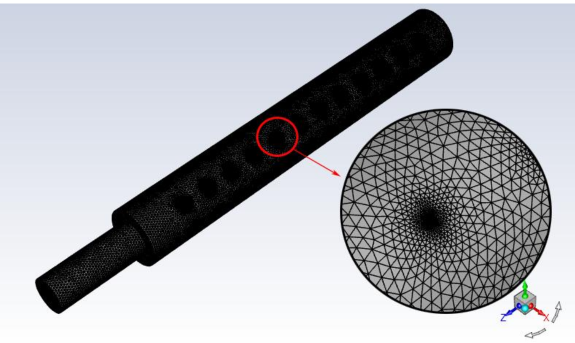

Figure 3: The mesh structure of the numerical.

Table 2: Grid independency test

Element Number	Nusselt Number	Relative Error
465738	42.207	-
489599	41.934	0.65%
519808	**42.827**	2.13%
551690	43.076	**0.58%**
587877	42.732	0.80%

The finite volume methods are used for the model solution of the governing continuity, energy and momentum equations as given Equation 8-12. The Coupled algorithm was used in the equation solutions. Second order upwind discretization schemes are forced on all the equations in the analysis. The convergence criteria of 10-3 for the residuals of all equations were selected, 10-6 for the residuals only for the energy equation. Selection and validation of the turbulent model are significant to forecast the enhancement of the heat transfer coefficient for geometry in numerical analysis. in this study, RNG k-Ɛ model is used for turbulent flow in the heat exchanger. RNG k-ε model, which is the most used in literature and has been experimentally proven, has been chosen [26-28].

$$\frac{\partial}{\partial_{x_i}}(\rho u_i) = 0 \tag{8}$$

$$\frac{\partial}{\partial_{x_i}}(\rho u_i u_j) = -\frac{\partial p}{\partial_{x_i}} + \frac{\partial}{\partial_{x_j}}\left[\mu\left(\frac{\partial_{u_i}}{\partial_{x_j}} + \frac{\partial_{u_j}}{\partial_{x_i}}\right)\right] + \frac{\partial}{\partial x_j}(-\rho \acute{u}_i \acute{u}_j) \tag{9}$$

$$\frac{\partial}{\partial_{x_i}}(\rho u_i T) = -\frac{\partial}{\partial_{x_i}}\left((\tau + \tau_t)\frac{\partial T}{\partial_{x_j}}\right) \tag{10}$$

where τ and τt are molecular thermal diffusivity and turbulent thermal diffusivity, respectively, expressed as;

$$\tau = \frac{\mu}{Pr} \tag{11}$$

$$\tau_t = \frac{\mu_t}{Pr_t} \tag{12}$$

2.3 Uncertainty Analysis

The validity of an experimental setup depends on the accuracy of the experimental setup. Data obtained from experiments were obtained using appropriate equipment. Uncertainty analysis is one of the most important indicators of the accuracy of experimental studies. The accuracy of measurements during experiments depends on errors, one of the most important parameters. Even if the devices used to obtain experimental data are of the highest quality, there is uncertainty in the experimental data due to errors such as the device connection method, test planning, the type of measuring devices, and the attention of the experimenter. Analysis of this uncertainty is a calculable method. Eq. (13) is used in calculating total uncertainty [29, 30].

Experimental data were obtained by measuring with a suitable measuring device. The precision levels of the experimental setup are important for the experimental data to be considered valid.

Uncertainty analysis is a common method used in planning experimental studies. The accuracy of experimental data can be significantly affected by measurement errors. Therefore, even if the measuring devices used in the experiments are sensitive enough, uncertainty analysis should be performed due to errors caused by device selection, environment, data reading, test conditions, observation, test plan, measurement accuracy, connection probe type or port of the measuring device, etc. (W_S) is used to calculate total uncertainty.

$$W_S = \left[\left(\frac{\partial S}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial S}{\partial x_2} w_2 \right)^2 + \ldots\ldots\ldots\ldots + \left(\frac{\partial S}{\partial x_n} w_n \right)^2 \right]^{1/2} \qquad (13)$$

The parameter S, representing the target quantity to be measured, is influenced by a set of independent variables $x1, x2, x3, \ldots, xn$. The associated uncertainty for each independent variable is denoted as $w1, w2, w3, \ldots, wn$, while the cumulative uncertainty in the measurement of S is expressed as W_S. The technical specifications, measurement accuracies, and overall uncertainty values of the instruments employed in the experimental setup are presented in Table 3. As evidenced by the data, the uncertainty levels of the experimental results remain within acceptable limits, thereby validating the reliability of the measurements conducted.

Table 3: Technical specifications of the measurement equipment

Measurement device	Measuring range	Precision	Total Uncertainty
Thermometer	0–120 °C	± 0.1 °C	± 0.075 °C
Thermocouple	0-1200 °C	± 0.1 °C	± %0.15 °C
Anemometer (Air velocity)	0–20 m/s	±0.01 m/s	± %0.011 m/s

3. RESULTS AND DISCUSSION

Before each experiment, data was taken after the flue gas temperature reached the ambient temperature so that the system would reach equilibrium. Thus, possible errors are fixed. Experiments were carried out in the active combi system. For this reason, the air inlet velocity is constant and is 1 $m.s^{-1}$. The air inlet temperature is 273.15 K. The numerical study performed was confirmed by both experimental results and correlations in the literature. After the procedure, there was a deviation of 3% with the Dittus-Boelter correlation and 4.77% with the experimental data for Nusselt number. This deviation is 7.5% in the Blasius correlation and 5.36% in the experimental results for the friction factor. Nusselt enhancement ratio (NER), friction factor enhancement ratio (FFER) and thermo hydraulic performance parameter (THPP) are calculated by Equation 2-6. Comparison results are given in Table 4 and Table 5.

Table 4: Enhancement rate values

	NER	FFER	THPP
Numerical	1.041	4.591	0.62
Experimental	1.048	4.513	0.63
Deviation	0.6%	1.2%	1.7%

Table 5: Comparison of the results

	Numerical		**Experimental**	
	Straight tube	**Copper finned**	**Straight tube**	**Copper finned**
Nu	12.12	12.63	12.73	13.34
f	0.0103	0.047	0.0113	0.051
Tin (inner tube, T1), K	433.15	433.15	433.15	433.15
Tout (inner tube, T2), K	392.81	369.21	390.65	371.65
Tin (outer tube, T4), K	273.15	273.15	273.15	273.15
Tout (outer tube, T3), K	286.19	299.06	285.65	301.15

In the normal system, the inlet air temperature increases around 13 K. In the system where copper finned is applied, this increase is around 26 K. These values are very important for the efficiency of the system, the average temperature changes in the inner and outer tube are given in Figure 4 and Figure 5.

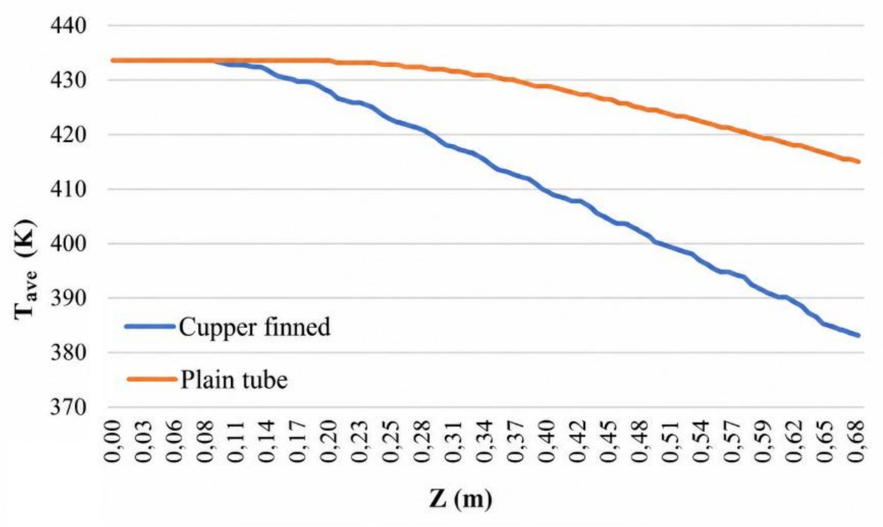

Figure 4: Average temperature of inner tube.

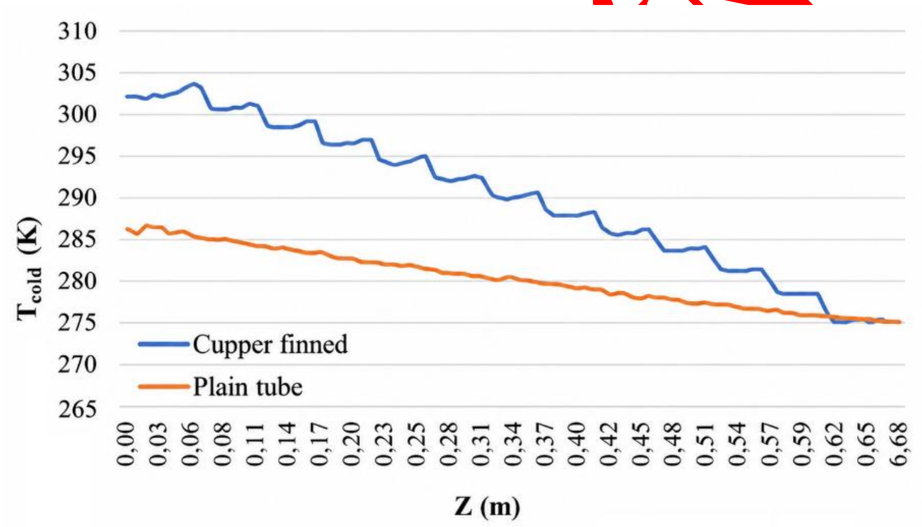

Figure 5: Average temperature of outer tube.

In addition, with the application of copper finned, the temperature of the air discharged to the outside was lowered by another 24 K, resulting in heat gain. Temperature distributions are given Figure 6 and Figure 7. When the figures are examined, it can be observed that the air inlet temperature increased with the addition of copper fin. Also, turbulence due to copper fin can be observed in the air inlet temperature profile.

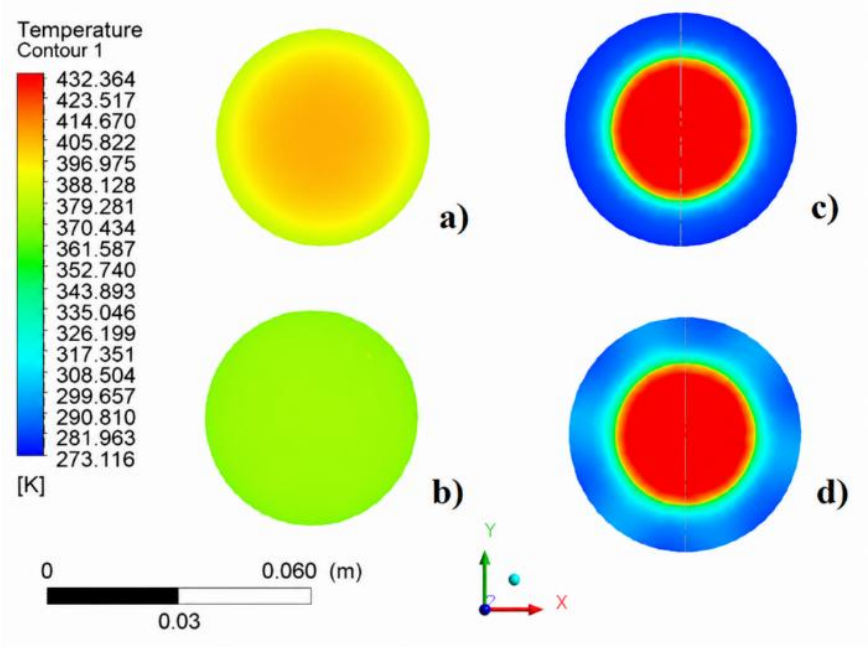

Figure 6: Temperature distributions. (a: straight tube outlet, b: copper finned outlet, c: straight tube inlet, d: copper finned inlet)

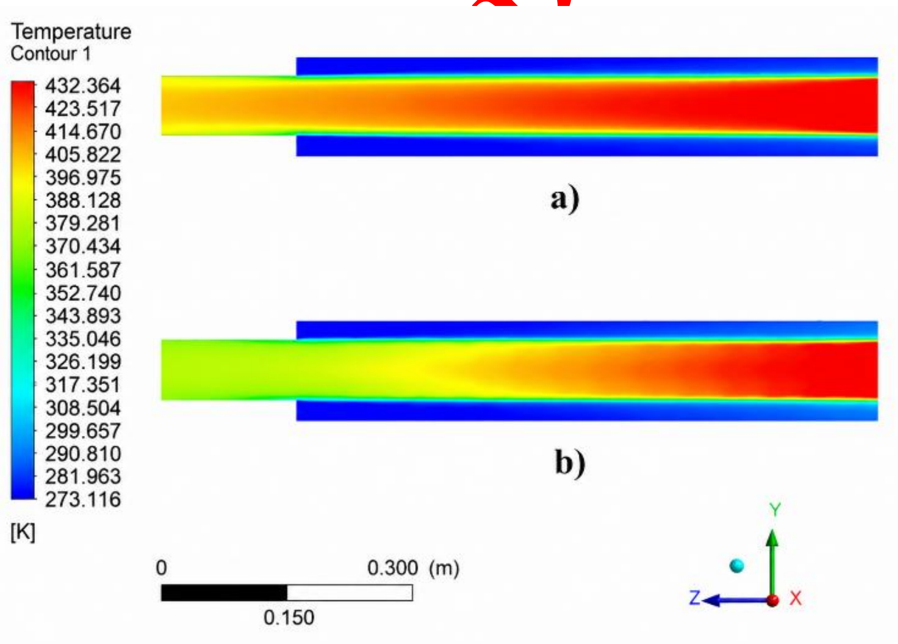

Figure 7. Temperature distributions. (a: straight tube, b: copper finned)

As the fluid encounters the copper finned, a decrease in velocity and a decrease in pressure occur. If the pressure drop is higher than normal, it causes additional pumping costs. The pressure distribution in the straight tube and the copper finned tube is shown in Figure 8 and Figure 9. When the figures were examined, pressure losses caused by the fins were revealed. this is expected. However, this type of fins applied to increase heat transfer should be designed considering the pressure drop. The THPP value reveals exactly the result of these two situations.

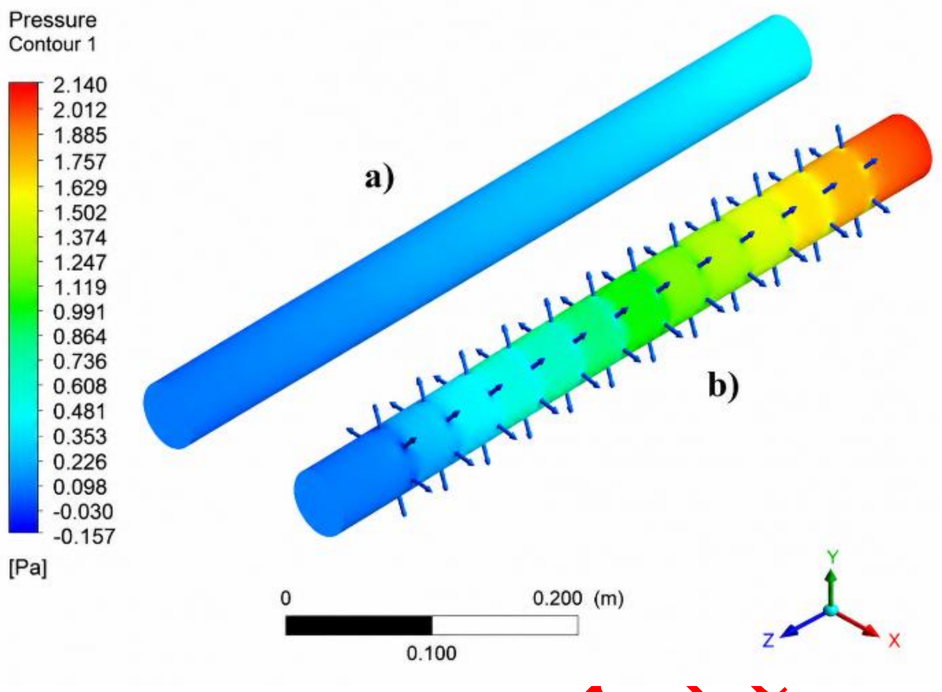

Figure 8: Pressure distributions. (a: straight tube, b: copper finned)

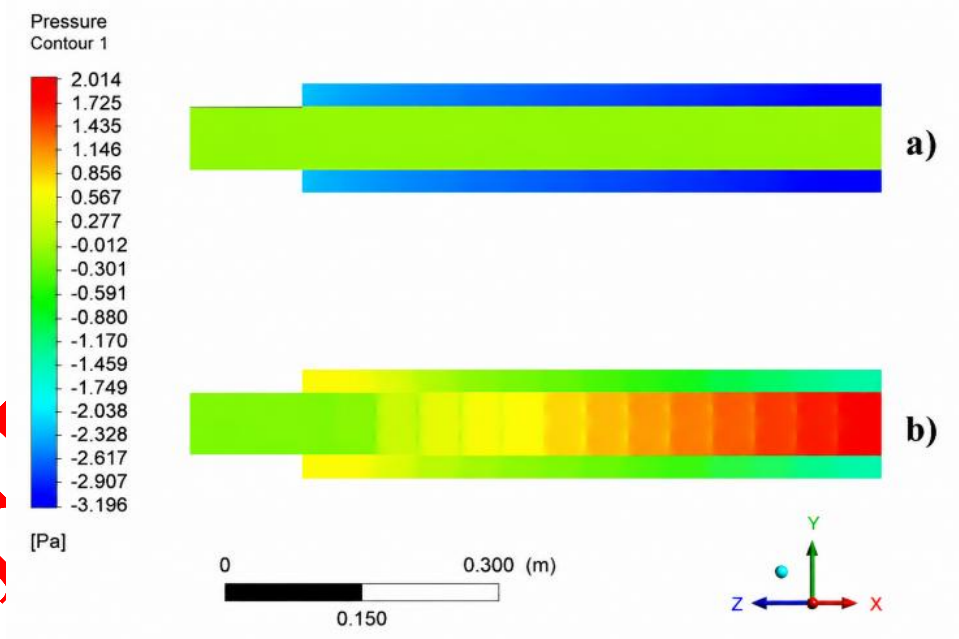

Figure 9: Pressure distributions. (a: straight tube, b: copper finned)

Non-slip boundary conditions are applied on all surfaces of the walls for the nested counter flow pipe pair, and velocity distributions are given in Figure 10.

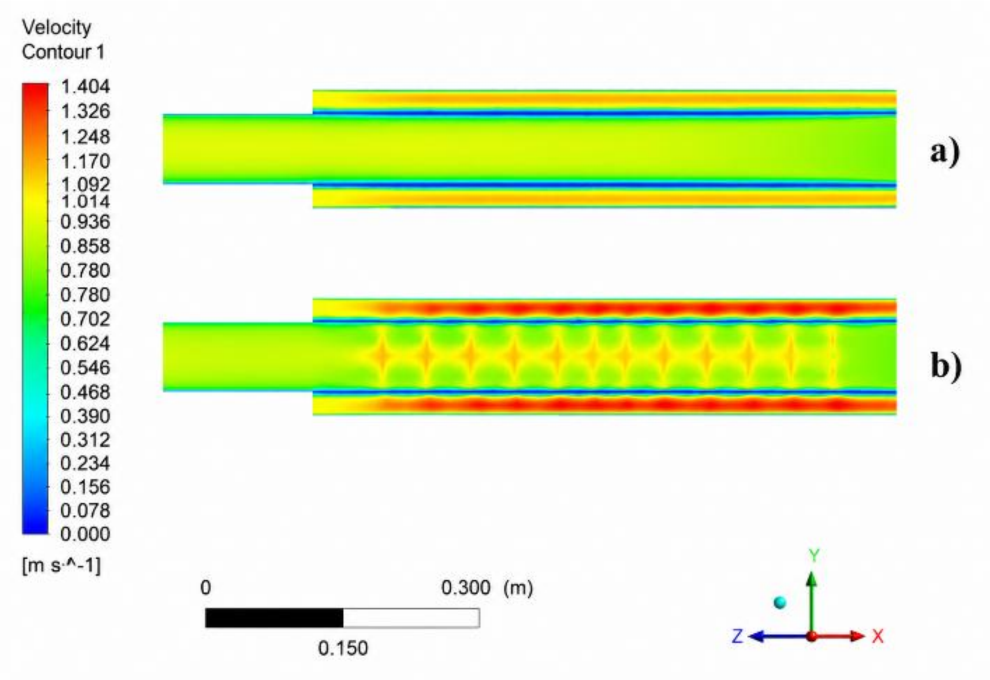

Figure 10: Velocity distributions. (a: straight tube, b: copper finned)

As shown in the velocity contours, vortices form around the copper fins. Such eddies help disrupt the boundary layer, and the fluid mixing results in improved thermal behavior and reduction in environmental temperature gradients.

The extent of heat transfer enhancement achieved in the present study was also compared with the fin and turbulator based enhancement techniques reported in the literature for similar double-pipe or nested-tube heat exchanger configurations. The same is summarized in Table 6.

Table 6: Comparison of heat transfer enhancement with the literature

Study	Enhancement Method	Reported Result
Present study	Copper fins in nested tube pair (combi boiler)	Nu +3.98%; heat recovery efficiency 9.3% → 14.8%; THPP = 0.62
Sivalakshmi et al. [23]	Helical fins in double pipe HX	~38% increase in heat transfer rate
El Maakoul et al. [24]	Helical fins, air-to-water double pipe HX	Significant heat transfer increase, but also a notable rise in pressure drop
Sheikholeslami and Ganji [17]	Perforated turbulators in double pipe HX	Notable enhancement in heat transfer coefficient with a pressure drop penalty
Hebenstreit et al. [9]	Heat pump-assisted flue gas heat recovery (biomass boiler)	Operating cost increased by 2–13%; CO2 emissions decreased

The enhancement of heat transfer obtained with the copper fins in the present study (3.98% increase in Nusselt number, THPP = 0.62) is more moderate than the enhancement levels reported for helical fin configurations in double-pipe heat exchangers, where increases up to approximately 38% were obtained [23, 24], as shown in Table 6. However, the helical fin and perforated turbulator studies also reported a much higher pressure drop penalty [17, 24]. In contrast, the present copper-finned configuration presents a better tradeoff between heat transfer enhancement and pumping power requirement as observed in the THPP value calculated above unity. The passive heat recovery offered by the copper-finned approach studied here has no additional energy input. On the other hand, heat-pump-assisted flue gas recovery systems improve the efficiency at an additional operating cost [9]. These comparisons show that the relatively more aggressive fin or turbulator geometries may provide higher raw heat transfer enhancement, but the copper-finned nested-tube configuration can be considered as an easier and inexpensive retrofitting solution and hydraulically more attractive for waste heat recovery in domestic combi boilers.

4. CONCLUSIONS

To increase the combi boiler operating efficiency, the heat transfer is increased by adding copper fins between the pipe pair. This experimental study was also validated numerically with the CFD approach. With the increase in the air inlet temperature of the combustion chamber, the operating efficiency of the boiler has also increased. The numerical study was validated experimentally with a difference of 4.77% and 5.36% in terms of Nusselt number and Friction factor, respectively. A heat transfer increase of 3.98% was obtained in the Nusselt number due to the use of copper fins. While the exhaust air temperature (T2) in the hermetic combi boiler system decreased around 40 K, the temperature difference was around 64 K via the copper fins application. Thus, the heat gain increased from 9.3% to 14.8%. The air inlet temperature difference of the combi boiler increased from 13 K to 26 K. The surface was increased with copper finned and the thermo-hydraulic performance parameter based on the constant pumping power requirement was adopted for the optimization of the flow parameters and this value was calculated as 0.62. Research has been done that will be a reference for future studies and heat transfer can be increased with different surface enhancement processes.

Despite these results, there are some limitations to this study that should be considered. The numerical analysis was carried out under steady-state conditions, and the transient thermal response of the system during start-up and shutdown of the combi boiler was not investigated. The experiments and simulations were performed for a single air inlet velocity (1 m/s) and a single combi boiler model (Demir Döküm C 275 F); therefore, the generalizability of the results to other flow rates, boiler capacities and geometries requires further verification. The contact resistance between the copper pins and the aluminum inner tube was neglected in both the experimental and numerical analyses, which may introduce a minor deviation from the actual thermal performance. In addition, only the RNG k-ε turbulence model was employed in the CFD simulations, without a comparative sensitivity analysis against other turbulence models. Long-term effects such as corrosion, fouling and degradation of the copper fins under continuous operating conditions were not evaluated and remain an important direction for future work.

Although economic analysis was beyond the scope of the present study, future work will include a detailed economic evaluation of the proposed copper finned-tube design for waste heat recovery in domestic boilers. This will allow assessment of the cost-effectiveness and practical applicability of the system.

Nomenclature

Nu	Average Nusselt number
Nufin	Average Nusselt number copper finned tube
Nupt	Average Nusselt number straight tube
Re	Reynolds number
h	Convective heat transfer coefficient
k	Thermal conductivity
f	Friction factor
ΔP	The pressure drop
ρ	Density
ϑ	Velocity
D	Hydraulic diameter
L	Tube length
Pr	Prandtl Number
Tin	Inlet temperature of tube
Tout	Outlet temperature of tube
NER	Nusselt enhancement ratio
FFER	Friction factor enhancement ratio
THPP	Thermo hydraulic performance parameter
T1	2. zone exhaust gas temperature, K
T2	1. zone exhaust gas temperature, K
T3	2. zone exhaust gas temperature, K
T4	1. zone exhaust gas temperature, K
Ta	Ambient temperature, K

DISCLOSURE STATEMENT

We hereby declare that there is no conflict of interest about this article.

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AUTHOR CONTRIBUTIONS

Faruk KILIÇ: Conceptual design, Investigation, Methodology, Experimental work, Project administration.

Abdulkadir KOÇER: Analysis, Visualization, Conceptual design, Investigation, Methodology, Data curation.

Mustafa GÖKTAŞ: Conceptual design, Investigation, Methodology, Writing, Editing.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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