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# Numerical simulation to evaluate the influence of geometric parameters on the physical behavior of heat exchangers

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**Abstract.** In the present investigation, a methodology was developed by means of numerical simulation for the evaluation of the influence of the geometric parameters of the heat exchangers used in thermoelectric generation devices. The validation of the proposed methodology was carried out through experimental tests on a diesel engine test bench under four load conditions (2 Nm, 4 Nm, 6 Nm, and 8 Nm) and a constant speed of 3600 rpm. The results obtained show that the methodology proposed by means of the numerical simulation presents a high concordance with the behavior described experimentally. The deviation between the simulation predictions and the experimental results was less than 4%. Additionally, it was evidenced that the change in the geometry of the heat exchanger has a considerable impact on the parameters of heat flow and surface temperature. It was shown that a 50% reduction in fin distance causes an increase of 2% and 2.4% in the previous parameters. Through geometric modifications, the electrical power generated increased by 7.9%. In general, the methodology developed through numerical simulation allows the analysis of the physical, thermal, and hydraulic phenomena present in heat exchangers focused on use in thermoelectric devices.

## 1. Introduction

The reduction of fossil fuel reserves, global warming, and environmental pollution have increased interest in developing and implementing more efficient technologies to reduce fuel consumption and polluting emissions. In particular, in internal combustion engines (ICE), only a third of the fuel's energy is transformed into useful work, while the rest is lost through cooling systems, lubrication, and exhaust gases [1–3]. To reduce these losses and reduce fuel consumption, different energy conversion systems have been considered, including turbomachines [4], thermodynamic cycles [5], and thermoelectric generators (TEG) [6]. These systems make it possible to recover part of the waste heat from the exhaust gases and transform it into useful work, often electricity, which can be used to power electronic and auxiliary components of the engine.

Generating electricity with thermoelectric devices represents a promising approach to increase efficiency in internal combustion engines [7,8]. In the presence of a temperature gradient, thermoelectric generators transform heat into electricity through the Seebeck effect [9]. TEGs include a heat exchanger, thermoelectric modules (TEM), and a refrigeration system. Among the advantages of these systems are their long useful life, high reliability, zero emissions, lightweight and scalable system, the absence of moving parts, and their compact volume [10]. Due to their characteristics, applications of TEGs are currently being developed for electronics, space systems, remote sensors, power plants, geothermal systems, and solar thermoelectric systems [11]. In particular, TEGs represent a promising alternative to improve the efficiency of internal combustion engines [12].



Different investigations have focused on improving the heat transfer between the exhaust gases and the surface of the thermoelectric modules through different designs of heat exchangers (HE). Marvao, *et al.* [13] compared the power output of a TEG using three different rectangular fin heat exchanger designs. Borcuch, *et al.* [14] point out the importance of the geometric design of the heat exchanger for the energy conversion efficiency of the TEG. Currently, despite the research carried out, the efficiency of energy recovery in TEG devices.

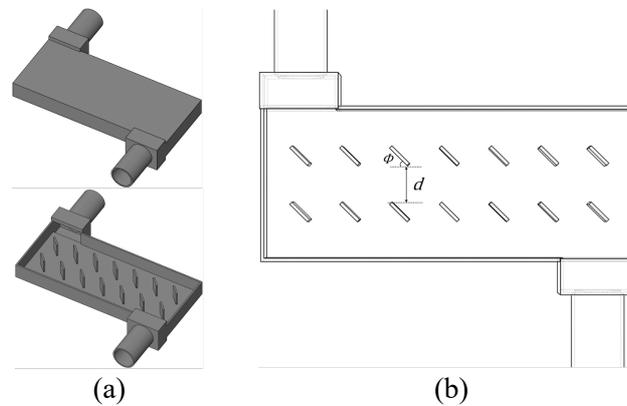
Due to the above, the present research aims to develop a methodology through numerical simulation to analyze the influence of the geometric parameters of an exchanger on the thermal and hydraulic phenomena present in this type of device. The analysis involves the evaluation of heat fluxes, temperature, pressure drop, and energy power of the heat exchanger. In this way, it seeks to improve the energy recovery potential in thermoelectric generation systems.

## 2. Methodology

This section describes the methodology used for the present investigation, which presents the configuration of the numerical simulations and the experimental procedure carried out to guarantee the reliability of the results predicted by the simulation.

### 2.1. Numerical simulation

For the development of the numerical simulations, the SolidWorks commercial software was used to construct the geometry of the heat exchanger (see Figure 1). The analysis of the influence of the internal geometry of the HE is carried out through changes in the parameters of fin distance ( $d$ ) and fin tilt angle ( $\phi$ ). The minimum and maximum values of the  $d$  and  $\phi$  parameters are based on manufacturing limitations and the available space inside the HE.



**Figure 1.** (a) heat exchanger geometry to be evaluated; (b) parameters for the optimization process.

The numerical simulations were carried out using the open-source software OpenFOAM applying the finite volume method [15]. The gas flow through the HE is considered a steady-state. The established convergence criterion was  $10^{-5}$  for turbulence kinetic energy and turbulence dissipation rate and  $10^{-6}$  for energy. The realizable  $k - \epsilon$  model was selected to solve the Reynolds-averaged Navier-Stokes equations. The equations for dissipation rate ( $\epsilon$ ) and turbulence kinetic energy ( $k$ ) of the realizable model  $k - \epsilon$  are shown in Equations (1) and Equation (2) [16].

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \frac{\partial k}{\partial x_j} \left( \mu + \frac{\mu_t}{\sigma_k} \right) \right] + G_k + G_b - \rho \epsilon - Y_m + S_k, \quad (1)$$

$$\frac{\partial(\rho \epsilon)}{\partial t} + \frac{\partial(\rho \epsilon u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \frac{\partial \epsilon}{\partial x_j} \left( \mu + \frac{\mu_t}{\sigma_\epsilon} \right) \right] + \rho C_1 S \epsilon - \rho C_2 \frac{\epsilon^2}{k + \sqrt{\nu \epsilon}} + C_{1\epsilon} \frac{\epsilon}{k} C_{3\epsilon} G_b + S_\epsilon, \quad (2)$$

where  $k$  is the turbulent kinetic energy,  $\varepsilon$  is the turbulence dissipation rate,  $S_k$  is the strain rate for  $k$ ,  $S_\varepsilon$  is the strain rate for  $\varepsilon$ ,  $G_k$  is the generation of turbulence kinetic energy due to mean velocity gradients,  $G_b$  is the generation of turbulence kinetic energy due to buoyancy,  $Y_m$  is the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate,  $\sigma_k$  is the Prandtl number for  $k$ ,  $\sigma_\varepsilon$  is the Prandtl number for  $\varepsilon$ ,  $\mu_t$  is the turbulent viscosity,  $\mu$  is the dynamic viscosity,  $C_2 = 1.9$  and  $C_{1\varepsilon} = 1.44$  are model constants,  $\rho$  is the density,  $C_1$  is the function of the time scale ratio of the turbulence to the mean strain,  $\nu$  is the kinematics viscosity,  $u_j$  is the mean axial velocity component,  $x_j$  is the axial axis,  $t$  is the time and  $C_{3\varepsilon}$  is the hyperbolic tangent function of the velocity components.

The building material copper HE was established. The properties of the gas flow are considered equivalent to those of air [17]. Since the properties of air change in relation to temperature, Equation (3) was used to determine the density, specific heat, viscosity, and thermal conductivity of air. Table 1 shows the polynomial constants used in the different properties.

$$y = a + b \cdot T + c \cdot T^2 + d \cdot T^3. \quad (3)$$

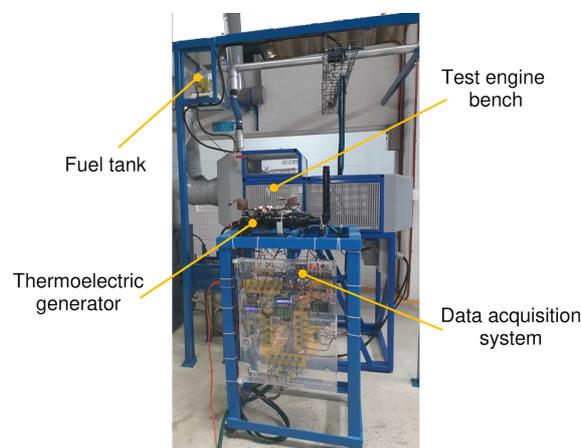
**Table 1.** Properties of air as a function of temperature [17].

Characteristics	Unit	Value			
		a	b	c	d
Density	kg/m <sup>3</sup>	$2.504 \times 10^0$	$-5.958 \times 10^{-3}$	$5.579 \times 10^{-6}$	$-1.772 \times 10^{-9}$
Specific heat	J/kgK	$1.016 \times 10^3$	$-1.512 \times 10^{-1}$	$4.545 \times 10^{-4}$	$-1.785 \times 10^{-7}$
Viscosity	kg/ms	$1.325 \times 10^{-6}$	$6.740 \times 10^{-8}$	$-3.749 \times 10^{-11}$	$1.110 \times 10^{-14}$
Thermal conductivity	W/mK	$-3.182 \times 10^{-3}$	$1.186 \times 10^{-4}$	$-7.706 \times 10^{-8}$	$2.939 \times 10^{-11}$

Additionally, a natural convection heat transfer coefficient of 20 W/m<sup>2</sup>K is established on the outer walls of the heat exchanger, with an ambient temperature of 27 °C; a temperature and mass flow are defined at the HE inlet, and pressure equal to atmospheric pressure is considered at the HE outlet. For the computational domain, a hexahedral mesh was used. In order to guarantee the precision of the simulation results, a mesh independence analysis was carried out, which was achieved with a number of nodes of  $6.5 \times 10^6$ .

## 2.2. Experimental procedure

To validate the predictions obtained through numerical simulations, experimental tests were carried out on a test bench, which is described in Figure 2. This Figure shows the components used for the development of the experimental tests, which consist of the test bench engine, the thermoelectric generator, and the data acquisition system.



**Figure 2.** Experimental test bench.

The bench is made up of a single-cylinder diesel engine, 4 strokes, naturally aspirated, and direct injection. Using a data acquisition system, the temperatures and pressures in the HE were measured and recorded. K-type sensors were used for temperature, and pressure transducers (PSA-CO1) were used in the case of pressure. The heat exchanger is installed in the exhaust system of the engine. The experimental tests were carried out at a constant speed of 3600 rpm and four load conditions (2 Nm, 4 Nm, 6 Nm, and 8 Nm).

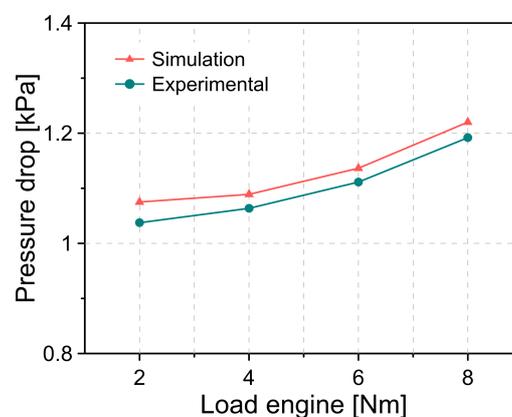
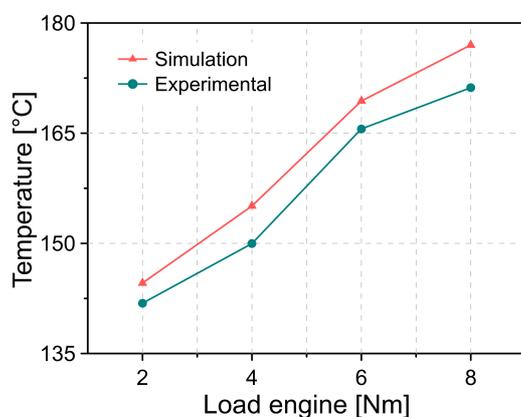
### 3. Results

This section describes the results and discussions obtained in this research; the analysis carried out includes the evaluation of the predictive capacity of the numerical simulations and the influence of the geometric in the thermal characteristics and electrical potential of the heat exchangers.

#### 3.1. Comparative analysis between numerical simulation and experimental results

To guarantee the reliability of the results obtained through the numerical simulation, a comparison is made with the data obtained through the experimental tests. The mean surface temperature and HE pressure drop are compared under the four load conditions of the engine for the analysis. The results obtained are shown in Figure 3 and Figure 4.

The results of Figure 3 and Figure 4 show that the numerical simulation predictions are in agreement with what was reported experimentally. In general, the trends and magnitudes of the HE temperature and pressure parameters are similar to the experimental results. However, the simulation results show a higher level in the HE parameters, which may be associated with the irregularities present during engine operation and other sources of heat losses not considered in the numerical simulation. Despite the above, the average deviation was 2.8% and 2.7% for the mean surface temperature and pressure drop, respectively.



**Figure 3.** Mean surface temperature for HE. **Figure 4.** Pressure drop for HE.

#### 3.2. Influence of geometric parameters

To analyze the influence of the geometric parameters of the HE, three conditions are defined for the fin distance (10 mm, 15 mm, and 20 mm) and the fin tilt angle (15°, 30°, and 45°). The results obtained are described below. The heat flux transferred towards the external walls and the average surface temperature of HE for the different geometric modifications is indicated in Figure 5 and Figure 6.

The results described in Figure 5 show that the increase in the angle of inclination and the fin distance decreases heat flow to the outer walls of the HE. This behavior is attributed to the greater ease for the engine exhaust gas flows to pass through the interior of the HE as a consequence of the less restriction in its internal structure. It was evidenced that an increase of 15° in the angle of inclination of the fin and an increase of 5 mm in the distance of the fin causes a reduction of 0.7% and 1.2% in the heat flux of the HE.

Figure 6 shows that the mean surface temperature has a behavior similar to the results described in Figure 5, which is a consequence of the close relationship between these two parameters. In the case of a 20 mm fin distance, a temperature of 173 °C, 172 °C, and 169 °C was obtained for a fin inclination angle of 15°, 30°, and 45°, respectively.

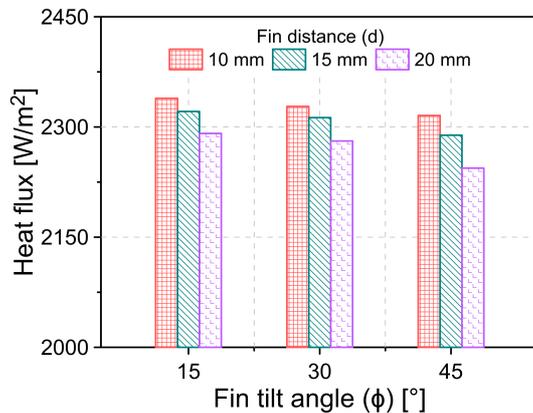


Figure 5. Heat flux for different geometries.

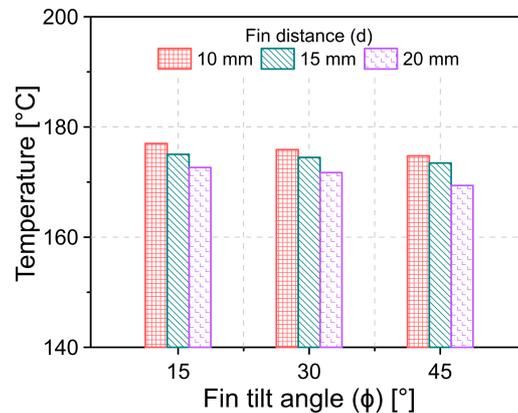


Figure 6. Mean surface temperature for different geometries.

Figure 7 describes the HE pressure drop for the different geometric modifications. The results show that the highest pressure drop occurs for a fin distance of 10 mm, 6.9%, and 14.2% greater than a distance of 15 mm and 20 mm, respectively. This increase in pressure drop is associated with the greater restriction of the flow of exhaust gases in the HE, facilitating the formation of turbulent zones inside the HE. The previous behavior is demonstrated in the results described in Figure 8, which indicates that the turbulence kinetic energy tends to increase with the decrease of the fin distance.

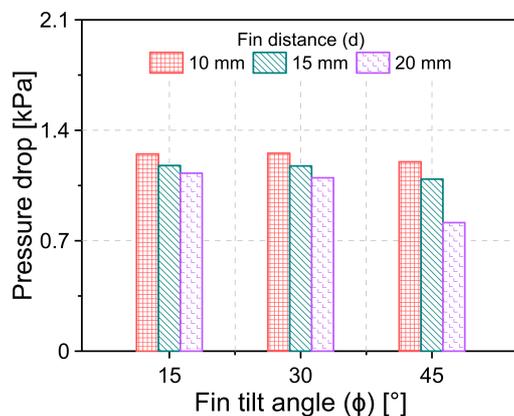


Figure 7. Pressure drop for different geometries.

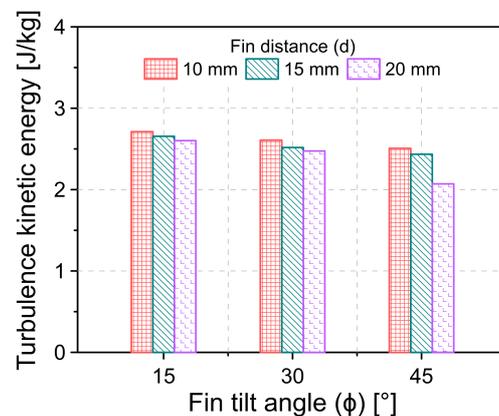
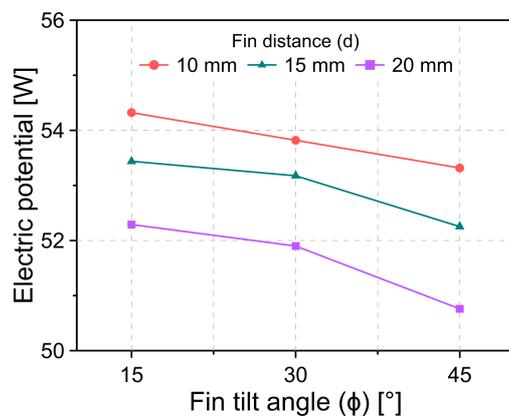
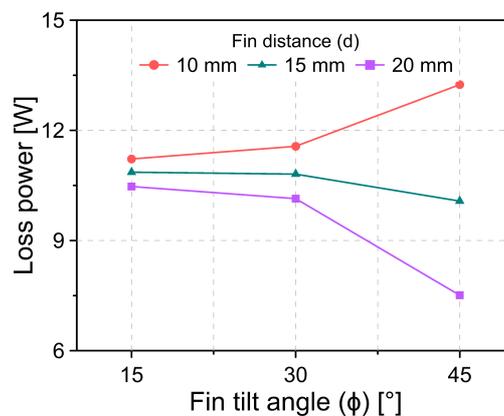


Figure 8. Turbulence kinetic energy for different geometries.

From the surface temperature obtained through the simulation and the characteristic curves of the thermoelectric modules, the electric potential for the different geometric modifications of the HE is determined. The results obtained are shown in Figure 9. It was evidenced that the highest powers are obtained for a fin distance of 10 mm. This is attributed to the highest average surface temperatures, as indicated in Figure 6. The highest electric potential was 54.3 W, obtained with a 10 mm fin distance and a 15° fin tilt angle. However, for this geometric modification, the greatest power loss is obtained, as shown in Figure 10. This result is a consequence of the greater pressure drop, as indicated in Figure 7.



**Figure 9.** Electric potential for different geometries.



**Figure 10.** Loss power for different geometries.

#### 4. Conclusions

In this research, a methodology is proposed through numerical simulation to analyze the influence of the geometric parameters of the heat exchangers used in the construction of thermoelectric devices. To ensure the reliability of the numerical predictions, experimental tests were carried out on a stationary diesel engine under different load conditions (2 Nm, 4 Nm, 6 Nm, and 8 Nm) and at a constant speed of 3600 rpm.

The results obtained show that the methodology proposed by means of numerical simulation presents a high concordance with the behavior described experimentally. The maximum relative error in the predictions of the numerical simulations was 3.4% and 3.6% for the average surface temperature and the pressure drop of the heat exchanger. The analysis by means of numerical simulation allowed to quickly evaluate the influence of geometric modifications in the heat exchanger. In the particular case of the present investigation, it was demonstrated that the change in the distance of the fin and the angle of inclination of the fin have a considerable impact on the heat flux towards the heat exchanger walls and the surface temperature. In general, a 50% reduction in fin distance causes a 2% and 2.4% increase in heat flow and heat exchanger temperature. In the case of a 33% reduction in the tilt angle of the fin, an increase of 1.41% and 1.1% was evidenced in the previous heat exchanger parameters.

The change in thermal conditions directly impacts the electrical potential of the heat exchanger when used in thermoelectric generation devices. It was shown that through geometric modifications, the electrical power generated increased by 7.9%. In general, the methodology developed through numerical simulation allows the analysis of the physical, thermal, and hydraulic phenomena present in heat exchangers focused on use in thermoelectric devices. In this way, it is possible to improve the energy potential of heat exchangers, which implies greater energy recovery in thermoelectric generation systems.

#### References

- [1] Shen Z-G, Tian L-L, Liu X 2019 Automotive exhaust thermoelectric generators: current status, challenges and future prospects *Energy Conversion and Management* **195** 1138
- [2] Ramírez R, Gutiérrez A S, Cabello Eras J J, Hernández B, Duarte Forero J 2020 Data supporting the evaluation of the energy recovery potential of thermoelectric generators in diesel engines *Data in Brief* **28** 105075
- [3] Orozco W, Acuña N, Duarte Forero J 2019 Characterization of emissions in low displacement diesel engines using biodiesel and energy recovery system *International Review of Mechanical Engineering (IREME)* **13(7)** 420
- [4] Kim T Y, Kwak J, Kim B 2018 Energy harvesting performance of hexagonal shaped thermoelectric generator for passenger vehicle applications: an experimental approach *Energy Conversion and Management* **160** 14

- [5] Saidur R, Rezaei M, Muzammil W K, Hassan M H, Paria S, Hasanuzzaman M 2012 Technologies to recover exhaust heat from internal combustion engines *Renewable and Sustainable Energy Reviews* **16(8)** 5649
- [6] Muralidhar N, Himabindu M, Ravikrishna R V 2018 Modeling of a hybrid electric heavy duty vehicle to assess energy recovery using a thermoelectric generator *Energy* **148** 1046
- [7] He M, Wang E, Zhang Y, Zhang W, Zhang F, Zhao C 2020 Performance analysis of a multilayer thermoelectric generator for exhaust heat recovery of a heavy-duty diesel engine *Applied Energy* **274** 115298
- [8] Duarte Forero J, López Taborda L, Bula Silvera A 2019 Characterization of the performance of centrifugal pumps powered by a diesel engine in dredging applications *International Review of Mechanical Engineering (IREME)* **13(1)** 11
- [9] Ando Junior O H, Maran A L O, Henao N C 2018 A review of the development and applications of thermoelectric microgenerators for energy harvesting *Renewable and Sustainable Energy Reviews* **91** 376
- [10] Cheng K, Qin J, Jiang Y, Zhang S, Bao W 2018 Performance comparison of single-and multi-stage onboard thermoelectric generators and stage number optimization at a large temperature difference *Applied Thermal Engineering* **141** 456
- [11] Negash A A, Choi Y, Kim T Y 2021 Experimental investigation of optimal location of flow straightener from the aspects of power output and pressure drop characteristics of a thermoelectric generator *Energy* **219** 119565
- [12] Ramírez R, Sagastume Gutiérrez A, Cabello J J, Valencia K, Hernández B, Duarte J 2019 Evaluation of the energy recovery potential of thermoelectric generators in diesel engines *Journal of Cleaner Production* **241** 118412
- [13] Marvão A, Coelho P J, Rodrigues H C 2019 Optimization of a thermoelectric generator for heavy-duty vehicles *Energy Conversion and Management* **179** 178
- [14] Borcuch M, Musiał M, Gumuła S, Sztekler K, Wojciechowski K 2017 Analysis of the fins geometry of a hot-side heat exchanger on the performance parameters of a thermoelectric generation system *Applied Thermal Engineering* **127** 1355
- [15] Greenshields C J 2015 *OpenFOAM The Open Source CFD Toolbox Programmer's Guide Version 3.0.1* (London: The OpenFOAM Foundation Ltd)
- [16] Lien F-S, Yee E 2004 Numerical modelling of the turbulent flow developing within and over a 3-d building array, part I: a high-resolution Reynolds-averaged Navier—Stokes approach *Boundary-Layer Meteorology* **112(3)** 427
- [17] Hatami M, Jafaryar M, Ganji D D, Gorji-Bandpy M 2014 Optimization of finned-tube heat exchangers for diesel exhaust waste heat recovery using CFD and CCD techniques *International Communications in Heat and Mass Transfer* **57** 254