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Experimental Comparison of Air Cooler Designs in a Heavy-duty Diesel Engine

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Abstract

This study aims to increase the system efficiency by changing the design of heat exchangers used as intercoolers in locomotive engines. For this purpose, computational fluid dynamics analysis was performed for each of 12 different intercoolers. Since the position and outer dimensions of the intercooler on an engine cannot be changed, the new designs had the same dimensions as the outer dimensions of the existing intercooler. The designs made by changing the tube distances and shapes were compared with the existing intercooler in terms of temperature and pressure differences. As a result of the comparisons, the optimum design was determined and then a prototype was manufactured. The existing intercooler and the newly designed intercooler were mounted on an engine and tested separately in the engine test unit. In the test program carried out at maximum speed in test engines, it was determined that the air cooler outlet temperature was 7 °C lower in the test engine to which the designed air cooler was connected, as compared to the test engine to which the existing air cooler was connected. The effective efficiency of the test engine to which Design 4 and Design 8 were connected were found as 31.62% and 33.74%, respectively.

Keywords: Diesel engine, Intercooler, Computational fluid dynamics analysis

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1. Introduction

One of the most important goals in research and development studies of internal combustion engines is to increase efficiency and power by reducing the heat losses of the engine. This can be achieved with an overfill system. With overfilled diesel engines, it is possible to improve the engine performance by placing an intercooler between the engine intake manifold and the turbo. At the same filling pressure as the filling air being cooled, the average effective pressure increases with increasing amount of air. In addition, as the temperature decreases, the heat loss decreases and the engine efficiency increases. As the temperature decreases, the workload of the cooling system of the engine is reduced [1]. Diesel engine filling air is cooled by means of heat exchangers, which increases the performance of the intercooling process. Selecting or designing the most suitable intercooler for the overfill system is one of the methods for improvement, especially for locomotive diesel engines. Many types of heat exchangers have been designed and put into use to improve the performance of heat exchangers. Finned and tube heat exchangers are one of the most widely used types of heat exchangers in many engineering applications such as automotive radiators, oil and air cooling in vehicles.

In the literature, there are many experimental and numerical studies conducted using different fin types and fin spacing as well as the different number of pipes and pipe alignment in finned and circular tube heat exchangers [2, 3]. In recent years, Computational Fluid Dynamics (CFD), which is a method of numerical analysis of fluid problems in the analysis of heat exchangers, has become widespread among researchers, as it offers a good solution to reduce the number of experiments and to analyze challenging and costly productions. The advantage of elliptic tube heat exchangers is not only their resulting low pressure drop but also high heat transfer rate per unit volume Today, finned elliptical tube heat exchangers are often used instead of finned circular tube heat exchangers due to the smaller pressure drop. Matos et al. simulated the effect of tube ellipticity on the air-side heat transfer of a finned elliptical tube heat exchanger and found that the maximum relative heat transfer gain was 13% for tubes with a tube ellipticity ratio of 0.65 [4]. Tao et al, who conducted numerical research on wavy fin elliptical tube heat exchangers found a 30% increase in heat transfer and a 10% decrease in the friction factor compared to circular tubes [5]. Han et al. in their study; The fluid flow and heat transfer properties of finned tube heat exchangers were numerically investigated for different elliptical and circular tubes. They worked on three different pipes and two different fins (wavy fin, louvered fin). They said that, the results reveal that using the oval fin-tube can not only reduce the flow resistance but also improve the heat transfer capacity of the heat exchangers which effectively improved the fin efficiency. They also stated that as comparing with the big circle-tube louver fin, the heat transfer rate of oval-tube fin is increased by 1.5–4.9%, while the pressure drop loss is decreased by 22.0–31.8%.[6]. Sun et al. performed numerical simulations to investigate the overall thermal performance of elliptical and circular tube fin heat exchangers. They reported a 3.6-6.7% increase in the performance when using elliptical pipes [7]. Tahseen et al. stated that, in the heat exchanger applications of circular and elliptical cylinders, if the distance between the pipes in both applications is the same, the heat transfer can be increased by up to 30% with the same rate of pressure drop in the elliptical cylinder application [8]. The heat transfer properties of circular and elliptical pipes with straight arrays for different Reynolds numbers were investigated by Park et al. [9]. As a result, it was stated that elliptical pipes had a lower friction factor, but the Nusselt number value was 9.3% higher for circular pipes and the heat exchanger designed with elliptical pipes was better in terms of compactness. Lotfi et al. analyzed the thermal and hydraulic characteristics of straight wave finned and elliptical tube heat exchangers using 3D CFD analysis and concluded that the straight wave fin and elliptical tube heat exchangers increased the heat transfer performance [10]. Yogesh et al. analyzed the friction and heat transfer characteristics of a finned tube heat exchanger with elliptical pipes of different diameter (0.6-0.8) ratios and the horizontal alignment of these pipes using the k-turbulence model [11]. Colburn factor, friction factor, and thermal-hydraulic efficiency changes with different angles were evaluated. Lotfi et al. studied the thermo-hydraulic performance of a straight finned and elliptical tube heat exchanger [12]. They were investigated numerically using a three-dimensional computational fluid dynamics analysis to explore the effects of the geometric shape of the pipe rows on heat transfer and flow properties. The effects of elliptical ratio, pipe angle, and fin space on heat transfer were investigated by Wang et al. using CFD analysis [13]. They increased their elliptical ratios by 0.4 to 1.0 by an interval of 0.1, while they changed the pipe angles between 0 ° - 90 °. They stated that the inclined elliptical finned tube heat exchanger with a pipe elliptical ratio of 0.6 and a pipe angle of 30 ° had the best heat exchange performance and air flow characteristics.

In this study, 12 different intercoolers designed as an alternative to the cross-flow, straight-finned circular tube heat exchanger currently used to increase system efficiency in a heavy-duty diesel engine (16-cylinder diesel locomotive engine) were analyzed by computational fluid dynamics simulation. Since the position and outer dimensions of the heat exchangers used as intercoolers in the locomotive diesel engine cannot be changed, the new designs had the same dimensions as the outer dimensions of the existing intercooler. In this study, CFD analyzes were performed based on the designs in which the distances of finned, elliptical, and vertical pipes were changed with a flat finned circular tube heat exchanger, and the pressure and temperature changes were compared. According to the analysis results, the optimum design was determined and a prototype was manufactured. Finally, both the existing intercooler on the diesel engine, and the prototype intercooler were experimentally tested and compared.

2. Experimental Method

2.1 CFD Analysis of Intercooler Designs

The establishment of a model suitable for the geometry studied is the first step of the CFD analysis. Thereafter, a solution mesh is created for the volume in the geometry in order to realize the solution. The mesh quality of this structure is important as the quality of the resulting mesh structure affects the results of the CFD analysis. In the study, the orthogonality quality, known as the angle between the vectors of the cell inner surfaces and the normal surface vectors, which is one of the parameters showing the mesh quality, was in the range of 0.20 - 0.69, the geometric structure of the cells was in the mesh structure and the skewness value was 0.50-0.80. According to these values, firstly the turbulence model and then independence were determined.

When selecting the turbulence model, the turbulence models were compared using the experimental data of the existing intercooler (Design 4) on the locomotive engine, and the model yielding the closest results to the experimental results was selected and used in the subsequent analyzes.

In the turbulence model study, the flow rate was taken as 1.8 kg/s and the temperature as 438 K. The results were analyzed separately for 5 different turbulence models and the results were compared with each other. The Realizable k-ε model, which yielded the closest results to the data from the current intercooler and had the lowest pressure difference, was selected as the most suitable model, and analyzes were made using this model in subsequent designs.

One of the steps to prove the accuracy of the model is to show that the model is independent of the mesh. Even if the number of elements of the model is different, the solutions give similar results to each other, which is called the independence from the digital mesh. Optimization must be made between the processing time and the number of elements for the solution to be within an acceptable limit. In the study, 5 different numerical models were used in the independence study of the mesh. Since the temperature did not show a significant increase after 146849 element number and there was not much difference between temperature changes, the most suitable element number was determined as 146869 according to the mesh structures formed, the number of elements and the obtained temperatures. In all analyzed designs, the cell surface area was taken as 0.00027 mm^2.

In air cooler design studies, two-dimensional solutions were made using ANSYS Fluent 15.0, a commercial software in the field of CFD, and the k-ϵ realizable model was chosen as the turbulence model. The 2-dimensional main calculation area and geometric parameters of the intercooler studied are given in Fig. 1. Different design dimensions of the analyzed intercoolers are given in Table 1.

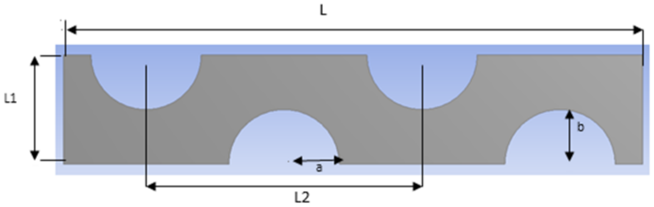

Fig. 1. Main calculation area and geometric parameters of the Intercooler [14]

Table 1. Different intercooler design sizes [14]

Group no	Design no	L (mm)	L1 (mm)	L2 (mm)	b/a
1	Design 1	52.5	7.5	12.5	1
	Design 2	52.5	7.5	12.5	0.8
	Design 3	52.5	7.5	12.5	0.6
2	Design 4	52.5	10	12.5	1
	Design 5	52.5	10	12.5	0.8
	Design 6	52.5	10	12.5	0.6
3	Design 7	52.5	12.5	12.5	1
	Design 8	52.5	12.5	12.5	0.8
	Design 9	52.5	12.5	12.5	0.6
4	Design 10	52.5	15	12.5	1
	Design 11	52.5	15	12.5	0.8
	Design 12	52.5	15	12.5	0.6

Calculations were made by taking the air inlet temperature of 438 K, mass flow rate of 1.8 kg/s, and air inlet velocity of 10 m/s. The pipes and fins of the heat exchanger are made of copper material, and the thermophysical properties of the copper material are taken as constant.

2.3. Intercoolers on Diesel Engine Tests

The existing (Design 2) and newly designed (Design 8) intercooler were mounted on the diesel engine, whose geometric and basic characteristics are given in Table 2, and they were tested separately in the engine test unit.

Table 2. Geometric properties and basic characteristics of the test engine. [14]

Cycle	4-stroke, single acting
Number of cylinders	16
Cylinder's type	90° V form
Cylinder diameter	185 mm
Piston stroke length	210 mm
Course volume (for each cylinder)	0.0056 mm^3
Combustion chamber volume (for each cylinder)	0.00045 mm^3
Compression ratio	13,5/1

During the test, the engine test unit can detect low-high temperature water inlets, oil inlet-outlet temperatures, intake-exhaust temperatures, intake air, cooler inlet-outlet pressure, power, speed, load and fuel values. In addition, the engine test unit was equipped with a computer, all intermediate circuit hardware and software, whereby these measurements could be viewed and printed and records were stored.

During the engine test, there were many temperature gauges (14 PT100, 26 K type) and pressure sensors (16 units) placed in different points on the system to measure temperature and pressure values. The connection equipment of the engine test unit is shown in Fig. 2.

Fig. 2. Engine test unit and equipment [14]

In the engine test unit, there was a cooling system connected to the engine test unit to provide the necessary brake water to the turbine in the braking unit and also to cool the water, oil and air systems of the tested diesel engine.

The engine, which was connected to the test stand, was connected with the control desk by lifting after all connections were made. After the lubrication, the engine test was initiated by starting the engine with the air starter motor.

By setting the idle to be 640 ± 5 rpm, the engine was run. After the no-load program was applied for 2 hours and 10 minutes, the preloading program was applied for 4 hours. Later on, the running-in program was applied for 2 hours and 10 minutes and the engine and control desk connections were made to get the cylinder and turbine exhaust temperatures, and then the oil, water and fuel were checked for the final loading and the engine was started. Finally, the final loading program was applied for 2 hours and 10 minutes.

Fig. 3 shows the intercoolers and intercooler connections mounted on the diesel engine. Fig. 4 shows the connection of the test engine in the test unit and Fig. 5 shows the temperature measurement points on the intercooler.

Fig. 3. Diesel engine intercooler connections [14]

Fig. 4. Test engine connected in test unit [14]

Fig. 5. Temperature measuring points on the intercooler [14]

3. Results and Discussion

3.1. CFD Analysis Results

12 different designs with different geometric parameters were analyzed. First, the designs were divided into 4 separate groups, and then all the designs were compared with the graphs. The first group consisted of Design 1-3, the second group of Design 4-6, the third group of Design 7-9, and finally the fourth group of Design 10-12. The vertical distance between the pipe centers of the four groups was changed. Within each group, the vertical distance between the pipe centers was kept constant and the changes on three different pipe shapes were examined for a total of 12 different designs. In the designs, the effect of the change between the vertical pipe centers and the pipe shape on the total pressure drop and temperature change was investigated.

The highest inlet temperature of the air, which was the fluid to be cooled, to the cooler was taken as 438 K. The flow rate of the air was determined as 1.8 kg/s. Water was used as the refrigerant and the inlet temperature of the water was determined as 313 K.

The pressure contours for Design 1-12 at inlet temperature of 438 K and intercooler speed of 10 m/s are given in Fig. 6.

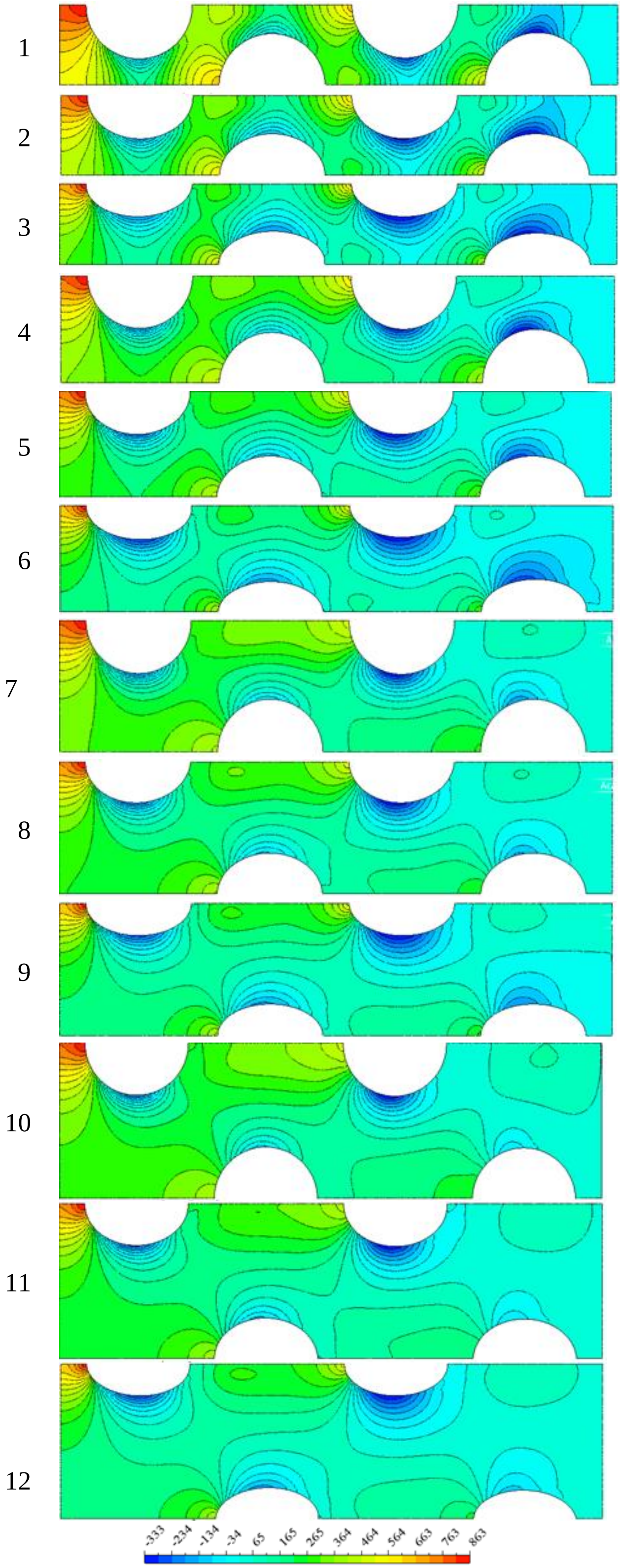

Fig. 6. Pressure contours (Pa) (1-12 stand for Design 1- Design 12, respectively) [14]

When the 1st group design, in which the vertical distance between the pipes was taken as L1 = 7.5mm, was examined, it was determined that the ΔP value of Design 2 was 43.39% lower than Design 1, and the ΔP value of Design 3 was 39.96% lower than Design 2 and 66.02% lower than Design 1.

When the 2nd group design, in which the vertical distance between the pipes was taken as L1 = 10mm, was examined, it was determined that the ΔP value of Design 5 was 33.43% lower than Design 4, and the ΔP value of Design 6 was 28.14% lower than Design 5 and 52.16% lower than Design 4.

When the 3rd group design, in which the vertical distance between the pipes was taken as L1 = 12.5mm, was examined, it was determined that the ΔP value of Design 8 was 36.98% lower than Design 7, and the ΔP value of Design 9 was 26.82% lower than Design 8 and 53.88% lower than Design 7.

When the 4th group design, in which the vertical distance between the pipes was taken as L1 = 15mm, was examined, it was determined that the ΔP value of Design 11 was 22.48% lower than Design 10, and the ΔP value of Design 12 was 37.16% lower than Design 11 and 51.28% lower than Design 10. In all four groups, it was observed that as the ellipticity of the pipes increased, the ΔP value decreased, which is in parallel with the literature [15-17].

In Fig. 7, the temperature contours of Design 1-12 are shown for air inlet temperature of 438 K and speed of 10 m/s.

When the temperature change in the 1st group (Design 1-3) was evaluated, it was determined that the temperature change in Designs 1, 2 and 3 was 4.44%, 4.11% and 3.73%, respectively.

When the temperature change in the 2nd group (Design 4-6) was evaluated, it was determined that the temperature change in Designs 4, 5 and 6 was 3.64%, 3.25% and 3.07%, respectively.

When the temperature change of the 3rd group (Design 7-9) was evaluated, it was determined that the temperature change in Designs 7, 8 and 9 was 3.74%, 3.47% and 2.97%, respectively.

When the temperature change in the 4th group (Design 10-12) was evaluated, it was determined that the temperature change in Designs 10, 11 and 12 was 3.26%, 3.16% and 2.43%, respectively.

The temperature change (ΔT) and pressure change (ΔP) graph for the 12 designs is shown in Fig.8 When Fig. 8 is examined, it is seen that the pressure changes in Design 3, Design 6, Design 8 and Design 9, and Design12 are close. When Design 4 and Design 8 are compared, it is seen that they are identical in terms of temperature changes, but when evaluated in terms of pressure loss, Design 8 is the most suitable design. The comparisons revealed that the optimum design is Design 8. Tahseen et al., in their study on the heat exchanger applications of circular and elliptical cylinders, stated that in pipes with the same distance, heat transfer can be increased by up to 30% with the same pressure loss using elliptical cylinders [8]. Erek et al., stated that as the ellipticity ratio of finned pipes increases, the heat transfer increases and the pressure drop decreases [17].

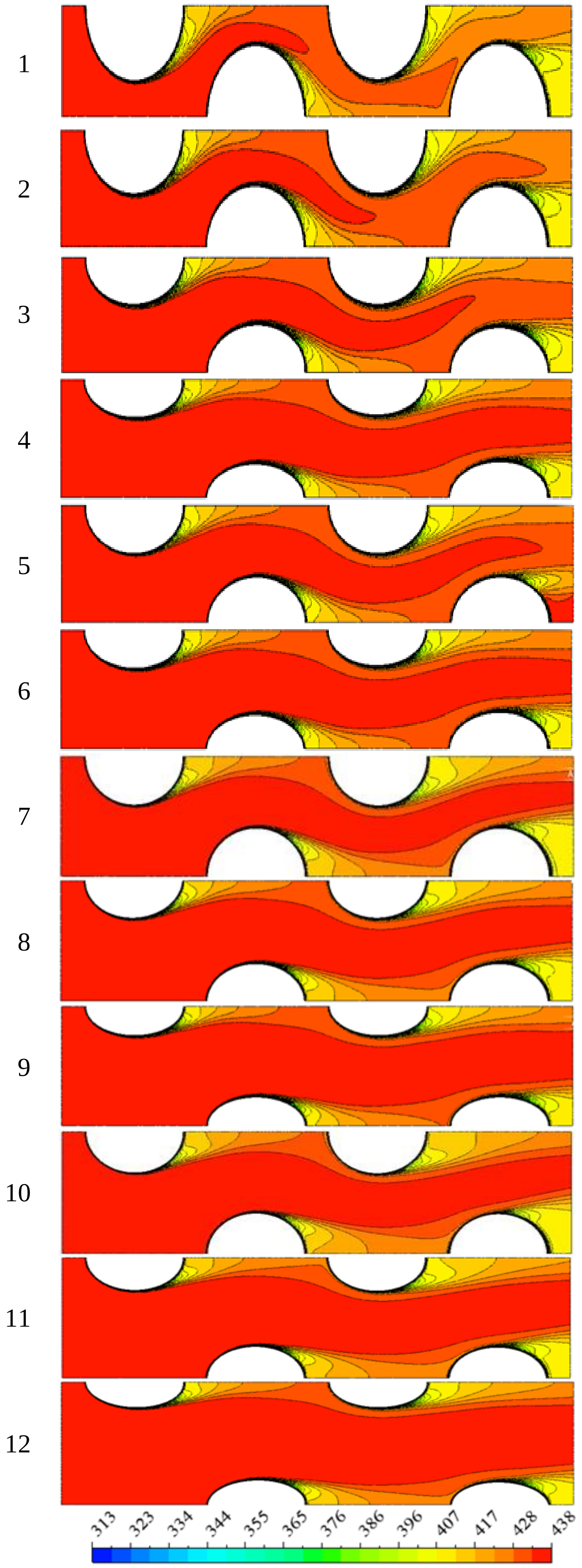

Fig. 7. Temperature change contours (K)
(1-12 respectively Design 1- Design 12) [14]

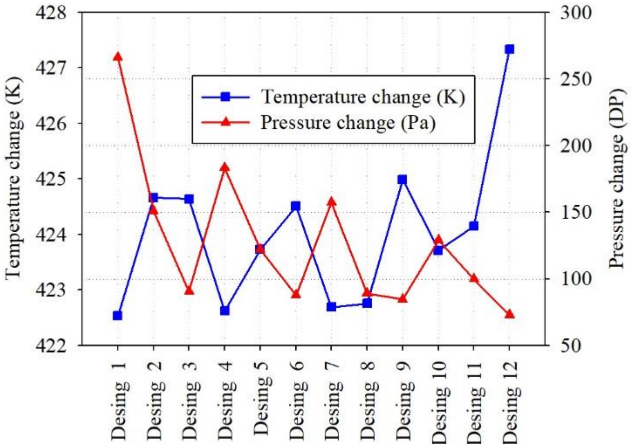

Fig. 8. The temperature and pressure changes of designs [14]

The prototype intercoolers are shown in Fig. 9. The intercoolers were finned tube heat exchangers with a cross-flow, confined tube array. The pipes and plates of the prototype intercooler were made of SF Cu F25 material, and the ellipticity value in the pipes was taken as 0.8 and the blade thickness as 0.16 mm.

Fig. 9. Prototype intercoolers [14]

Figure 10 shows the change in air cooler inlet temperature as a result of the tests at 1500 rpm and under different loads of the Design 4 and Design 8 intercoolers. Since the system feeding air to the intercooler in the test engine was not changed, it is seen that the inlet temperature of the air to the intercooler is the same in both designs as shown in Figure 10.

Fig. 10 Air cooler inlet temperature variation of Design 4 and Design 8 [14]

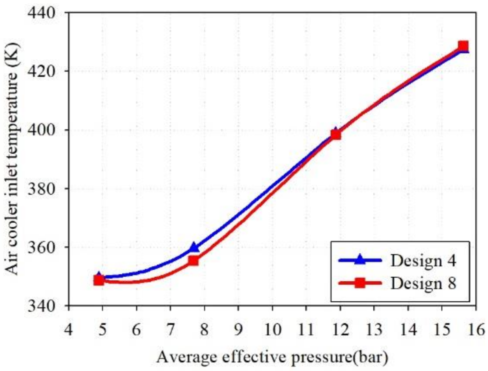

Figure 11 shows the change of the air cooler outlet temperature of Design 4 and Design 8 at 1500 rpm under different loads. Comparing the air cooler temperature at the test engine, Design 8 was found to be 7 °C lower than Design 4.

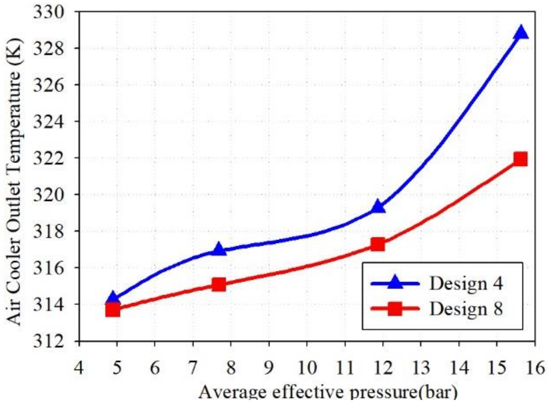

Fig. 11. Air cooler outlet temperature of designs [14]

In Figure 12, the effective efficiency was obtained lower in the test engine in which Design 4 was mounted with a high air cooler outlet temperature. It was observed that the effective efficiency was higher in the test engine in which Design 8 was mounted with a low air cooler outlet temperature.

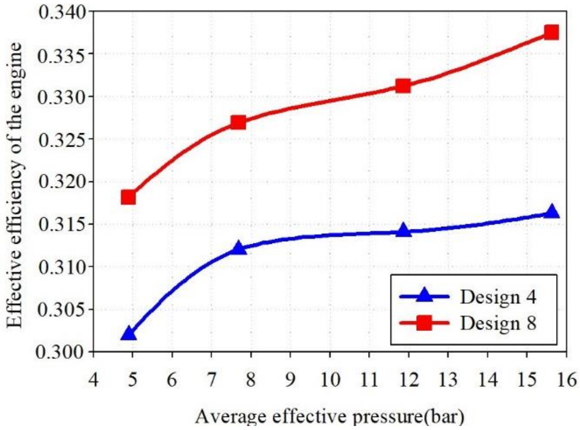

Fig. 12. Effective efficiency of designs for different average effective pressure values [14]

3. Conclusions

This study was conducted to improve the existing intercooler performance values used in diesel locomotive engines;

When the data obtained in the test program at the maximum speed of the test engines were evaluated, it was determined that the air cooler outlet temperature was 7 ℃ lower in the test engine where the Design 8 air cooler was mounted, as compared to the test engine on which the Design 4 air cooler was mounted. The effective efficiency was found to be 31.62% for the engine on which Design 4 was mounted and 33.74% for the engine on which Design 8 was mounted. This intercooler that was designed to improve the parametric values of the existing engine, is recommended.

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Şule Apaydın: Conceptualization, Supervision,
Ramazan Köse: Conceptualization, Formal analysis

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