Thermal Analysis of Turbocharger and Intercooler in Diesel Engine

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Abstract

Nowadays, turbocharger application of internal combustion engine has increased. Turbocharger powered by exhaust gas defined as a supercharger. Turbocharger, including the turbine compressor and the suction side of the exhaust side has two propellers.

The reason for modifying the turbocharger system into the internal combustion engine, it provides improvement of the engine's performance, fuel consumption and emissions. When turbocharger application used in engine, the suction air temperature increases in the engine and this cause the emergence of undesirable combustion conditions. To reduce this situation, application of intercooling in vehicle is used.

In this study, it is determined the thermal evaluation of thermodynamic calculations and the air temperatures of compressor outlet in accordance with the cycle principles of the present diesel engine tractor, made of Basak Tractors and Agricultural Machinery Industry and Trade Business in Turkey. In addition, excessive filled Turbo-Compressor and intercooler's main dimension and the parameters are made calculations. While the engine performance at high speed level, 2500 rev/min, the charge air outlet temperature of intercooling are reduced 370 K to 303 K. In this case, the effectiveness of inter-cooling method is determined by comparing the reduced specific fuel consumption and characteristics calculation. It has been observed that all thermodynamic calculations made according to the results of these parametric values give good results of designed the turbocharger intercooler sizes. The data obtained from the parametric calculations made for the intercooler and the turbocharger were analyzed by using the computer program. The results of this study are presented in tables and graphs.

Keywords: Intercooler, Turbocharger, Thermal analysis

1. Introduction

In current engines, one of the methods used to improve operational performance and efficiency, as is well known, a turbocharger system. In turbocharged engine has been observed that the improvement in fuel consumption and gas emissions to the environment. Turbocharged diesel engine produces 50% less NOx and CO_2 emissions compared to other engines [1],[2],[3]. The new economic and efficient use of energy resources is known to increase with the technological developments of the increasingly important. Given that oil

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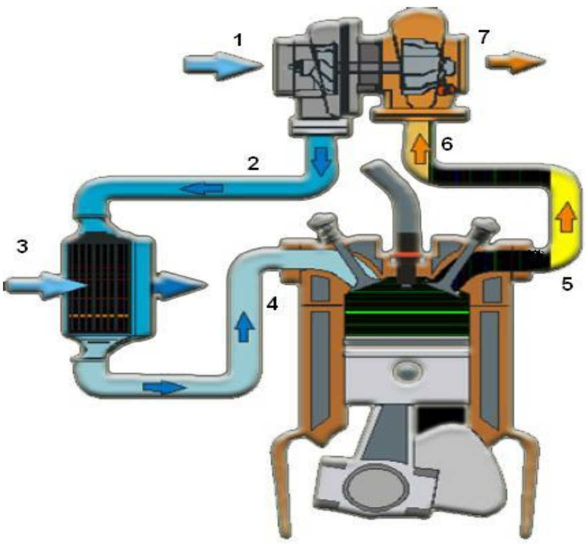
supplies quickly running out of energy resources is one of the aims of increasing the power consumption by reducing the use of vehicles with the oil field. Intended to achieve these goals, the newly modified systems has been developed. This is one of the modified turbocharger system. This system is used to get the top spot of car performance.

In this study, described as a diesel turbocharger selection appropriate to the characteristics of the engine and do a design of the intercooler to the turbocharger. These applications on both sides of the air and gas inlet intercom in many fields in the motor industry are available as flat fins. However, this is applied to the intercooler fins do this study on the air inlet side different (cold side) at louver fin surface and gas inlet side (the hot side) at flat-plate fin was used. This design is used in the study with the characteristics given below diesel engine with fixed 2500 rev/min in the intercooler turbocharger air outlet temperature was decreased to 303 K from 370 K the engine's specific fuel consumption and, consequently, the characteristic of calculations was determined by comparing the intercooler efficiency. Normally, the temperature of the charge every 10 ^{0}C reducing engine efficiency increases approximately 0.5%. Power output is increased about 3.5% in compliance for the given constant air-fuel ratio. Moreover, lowering the temperature of the piston and other components is provided to increase the engine power ratio [4]. Therefore, the intercooler air outlet temperature has been reduced. Also when looking at the calculations and graphics, it can be seen to occur in two parts of the study. First of them is selection of suitable turbocharger and the second is the design of the intercooler with charge air outlet temperature can be reduced to the temperature we want. This work is in progress, intercoolers and considering the size of the volume will occupy on the engine design is done.

2. Turbocharger Definition

Turbocharger powered by exhaust gas defined as a supercharger. It gets power from the exhaust gas pressure. Exploding a mixture of air and fuel in the combustion chamber, the mixture turns into gas and is pushed into the exhaust manifold. At this stage, the gas pressure tailpipe along a path returns the turbo propeller and a significant portion of the gas goes turbine [5].



1. Compressor inlet
2. Compressor output
3. Transition from air cooler
4. Intake valve
5. Exhaust valve
6. Turbine inlet
7. Turbine output

Figure 1. Sectional view of the turbocharger's Working System

In other words, the best way to increase the power available from an engine with turbocharger is increasing the fuel and air mixture through the cylinder of engine. This can be done in two ways: 1-increase the volume of the engine, 2-applying the turbocharger. Enhancing the volume of the engine; it is possible to increase the volume by increasing the engine air-fuel ratio. But this will get you more power, more fuel you lose (the more money you spend on fuel) means. In addition, larger and heavier of these engines and also has a negative impact because of more friction can be considered. Today, the success of the turbocharger not only from the performance perspective, it is also evaluated the reduction of fuel consumption and decreasing CO_2 emissions.

2.1. Methods of increase the efficiency with turbocharger on the engine

Basically the turbocharger increases the efficiency of the diesel engine with four-way. First, mean effective pressure and charge density and thus increases the overall efficiency of the power unit. The second one; as a result of the combination of high air, fuel ratio and mean effective pressure produce good efficiencies. Thirdly; increased air fuel ratio leads to a reduction in exhaust gas temperature. Fourth; exhaust gas energy to the turbocharger returns as previously mentioned would be wasted otherwise. Also set-up problems and losses would occur because of mechanical rotation. All these reasons, turbochargers were adopted in diesel engines for commercial vehicles and cars [4].

3. Theoretical Calculations on the Parameters

The diesel engine of tractor' specifications, made of Basak Tractors and Agricultural Machinery Industry and Trade Business in Turkey, are shown in Table 1.

Table 1. Diesel characteristic parameters

Cylinder diameter (D)	100 mm
Stroke (S)	100 mm
Number of cylinders (i)	4
Compression ratio (ε)	16.1
Number of rotation – Speed (n)	2500 d/d
Turbocharger pressure increase rate (ρ)=Pk/Po	1.8
Volumetric efficiency (η_v)	0.90
Air excess coefficient (λ)	1.7
Fuel diesel oil	50
Fuel lower heating value (Hu) kJ/kg	42437.4

4. Calculations on Turbocharger

Calculations are made by using available diesel engine's value. These calculations are theoretical cycle, real cycle, effective parameters and heat balance.

4.1 Calculations of theoretical cycle

Summary of theoretical calculations of the parameters associated with the turbocharger are given in Table 2. Equations that are used in calculations and values are shown in Table 2.

Table 2. Summary of theoretical calculations

Definitions	Equations	Value
Amount of theoretical air, mass (lo), kg-air/kg-fuel	*lo=1/0.23(8/3C+8H-O)*	14.452
Amount of theoretical air, volumetric (Lo), kmol-air/kg fuel	*Lo=1/0.208(((C/12+(H/4)-(O/32))*	0.5
The actual quantity of air (L), kg-air/kg-fuel	L = λ .lo	24.5684
Compression ratio (ε)	$M_1 = \lambda .Lo$	0.85
Total Product Quantity (M_2), kmol-combustion product/ kg-fuel	$M_2 = M_{Co_2} + M_{H_2O} + Mo_2 + M_{N_2}$	0.8815
Compressor output air pressure, (Pk), MPa	Pk = Po. π	0,18
Compressor output air temperature, (Tk), K	$Tk = To\ (Pk/Po)^{(nk-1)/nk}$	370
Fresh filling density, (r_k), kg/m³	$r_k = P_k x10^6/(R.\ Tk)$	1.7

C: Carbon, H: Hydrogen, O: Oxygen, *λ:* Air excess coefficient (1.7), CO_2: Carbon dioxide, H_2O: Water vapor, N_2: Nitrogen, Po: Normal atmospheric pressure (0.1 MPa), To: Normal atmospheric temperature, n_k: compression polytrophic base (1.65), Tr: Exhaust gas temperature (800 K), Pr: Exhaust gas pressure (0.95 MPa, Ra = Gas constant (287 kJ/kgK) [6].

4.2. Calculations of effective parameters

Calculation of effective parameters in the diesel engine and related with equations are shown in Table 3.

Table 3. Effective parameters in the diesel engine calculations

Definitions	Equations	Value
Effective pressure (Pe), MPa	$Pe = Pi - Pm$	1.0413
Effective power (Ne), kW	$Ne = P_e.V_h.i.n/30.Z$	68.1176
Effective efficiency (η_e)	$\eta_e = \eta_m \times \eta_i$	0.3939
Effective Specific Fuel Consumption (be), g/kWh	$be = 3600/(Hu.\eta_e)$	215.31
Fuel Consumption Per Hour (Gy), kg/h	$Gy = Ne.be.10^{-3}$	14.6667

4.3. Calculations of real-cycle

Thermodynamic calculations in real-cycle engine consist of intake, compression, combustion expansion and exhaust process. These calculations are given in Table 4.

Table 4. Thermodynamic calculations in real-cycle engine

Process	Definitions	Equations	Value
Suction	Exit suction pressure (Pa), MPa	$Pa = [(T_k + \Delta T).(\varepsilon - 1)P_k \eta_v + P_r T_k] / \varepsilon T_k$	0.16666
	Exit suction temperature (Ta), K	$Ta = \dfrac{Tk + \Delta t + \gamma r.Tr}{1 + \gamma r}$	393.1450
Compression	Exit compression temperature (Pc), MPa	$Pc = P_a.\varepsilon^{n_i}$	7.3374
	Exit compression temperature (Tc), K	$Tc = T_a.\varepsilon^{n_i - 1}$	1075.38
Burning	Coefficient of molecular variation of the mixture (μ)	$\mu = (\mu_o + \gamma_r) / (1 + \gamma_r)$	1.035
	The heat of combustion of the mixture (H_w), kJ/kmol	$H_w = H_u / [M_1(1 + \gamma_r)]$	48378.44
	Combustion end pressure (Pz), MPa	$Pz = \alpha.P_c$	11.061
	Constant pressure volume increase rate (ρ)	$\rho = \mu\ Tz / \alpha.Tc$	1.408
Expansion	Expansion ratio (δ)	$\delta = \varepsilon / \rho$	11.431
	The pressure of the gas at the end of the enlargement process (Pb), MPa	$Pb = P_z / \delta^n{}_2$	0.5073
	At the end of the enlargement process gas temperature ratio (Tb), K	$Tb = Tz \frac{1}{\delta_2^{n_2}}$	1155.079
Exhaust	Exhaust gas temperature (Tr^l) K	$Tr^l = T_b \sqrt[3]{p_b / p_r}$	803.87

Exhaust gas temperature: γ_r=0.0324, difference temperature: ΔT=10 K, Compression ratio: ε= 16/1, the average temperature in the combustion chamber: Tz:= 2192,24 K, α: Heat transfer rate. [6]

4.3. Calculations of heat balance

Calculations of heat balance are shown in Table 5.

Table 5. Calculations of heat balance

Definitions	Equations	Value
The total amount of heat that occurs with the burning of fuel (Qo), J/s	$Qo = Hu.Gy/3.6$	172893.5
The amount of heat that turns the effective work (Qe), J/s	$Qe = 1000 \times Ne$	68117.7
The amount of heat transferred to the cooler (Qc), J/s	$Qc = C \times i \times B1 + 2m \times nm \times 1/\lambda$	51583
The amount of heat from Exhaust gas to outside (Qr), J/s	$Qr = Gy/3.6[M_2.\ mc_p^{u} \big\|_{to}^{tr}.tr - M_1\ mc_p^{u} \big\|_{to}^{tk}.tk]$	50972.1
The amount of lost heat (Qd), J/s	$Qd = Q_o - (Qe + Qc + Qr)$	2270.7

5. The Path of in this Study

- Parametric calculations in the study; firstly, turbocharger with 2500 rev/min and 370 K were made using Matlap program. Then transfer parametric exchange values calculated by changing the temperature 370-303 K range with constant rotation speed in Excel. For Intercooler, the parametric data computed has reached the desired results using the Mathcad program.
- Specific fuel consumption and by comparing the consequent characteristic calculations determined the effectiveness of the intercooler while the best performance of the engine running at 2500 rpm and air outlet temperature of intercooler reduced 370 K to 303 K. as well as engine speed varying the number of 2500-750 rpm range, intercooler kept constant temperatures (370 K) has been found parametric values are given in tables and graphs.
- Because the turbocharger outlet gas temperature is high, intercooler is designed between intercooler and the engine to reduce the temperature of the turbocharger exhaust gas for increasing the volume of charge air.
- Contemplated Intercooler intended temperature of the gas outlet temperature 303 K is considered. So calculations are made again after intercooler gas inlet temperature reduced from 370 K to 303 K.

After calculations, obtained data are shown following figures.

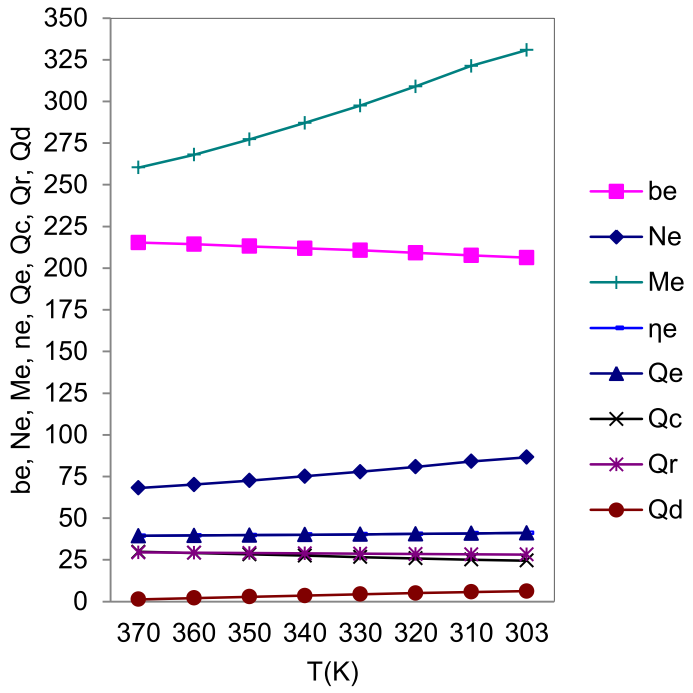


Figure 2. Specific fuel consumption, engine power, engine torque, effective efficiency and Heat balance versus intercooler outlet temperature

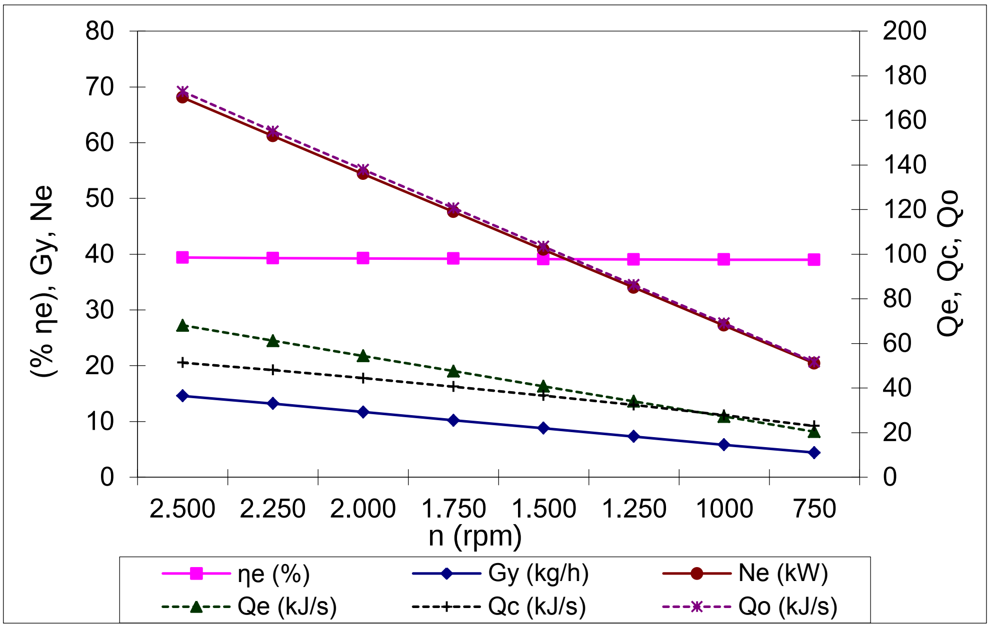


Figure 3. Parameters versus engine speed with constant temperature

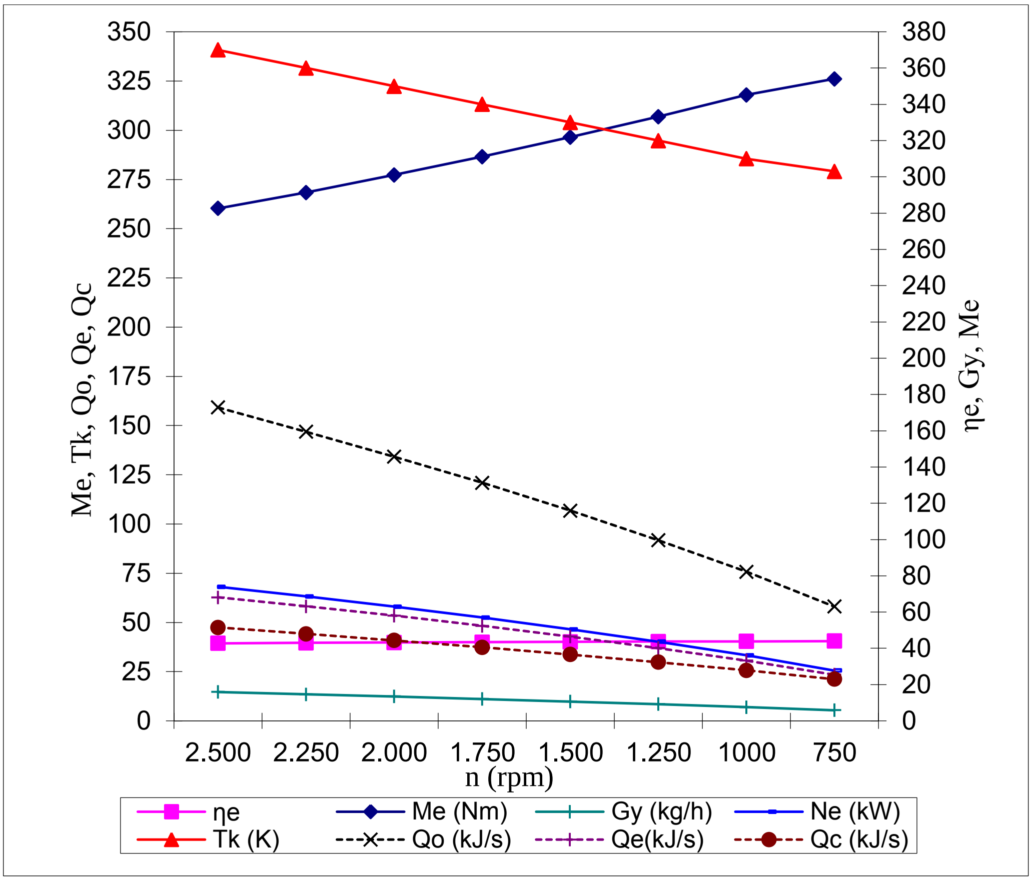


Figure 4. Parameters versus engine speed with variation temperature

6. Intercooler

Intercooler, a cooling element is used to help cool the heated air to the turbo compression results in turbocharged engines [7]. If coldest air enters in the engine, highest power gets from it. This is the reason for the large size of the intercooler always means more air molecules can send by air into the engine. Thus, by providing an increased amount of air get some benefits; the development of fuel economy, increasing the engine power, increasing engine durability and reduction of a gas emissions. The various geometric shapes of fin are used in intercooler [8]. To compare and evaluate the performance of finned surfaces, two factors must be taken into consideration. These are [9]; activity and efficiency. Intercooler valuations are taken into consideration when making design limitations are determined by the properties of the motor vehicle manufacturing companies. These are: inlet and outlet temperatures, size, airflow passing, cooling power, compressor efficiency and turbine efficiency [10]

7. Intercooler sizing and parametric calculations

Intercooler sizing and selecting the type of geometric shapes by examining the air side of the vane louvre fin surface, while the gas side straight finned surface types are selected [11]. Selected this intercooler, Basak Tractor company's engine size and magnitude are made by taking into account estimates as shown in Table 6.

Table 6. Intercooler size and values

	Intercooler Air-Side	Intercooler Gas-Side
Used surface	Louvered fin surface design, 3/8 - 6,06	Flat fin surface design, 14.77
Inlet temperature, K	293	370
Outlet temperature, K		303
Pressure, kPa	101.325	180.000
Material structure	Aluminum	Aluminum

7.1. Calculations of parametric values

Conditions given above for designing intercooler, surface flow, friction characteristics and basic heat transfer equations are given in Table 7.

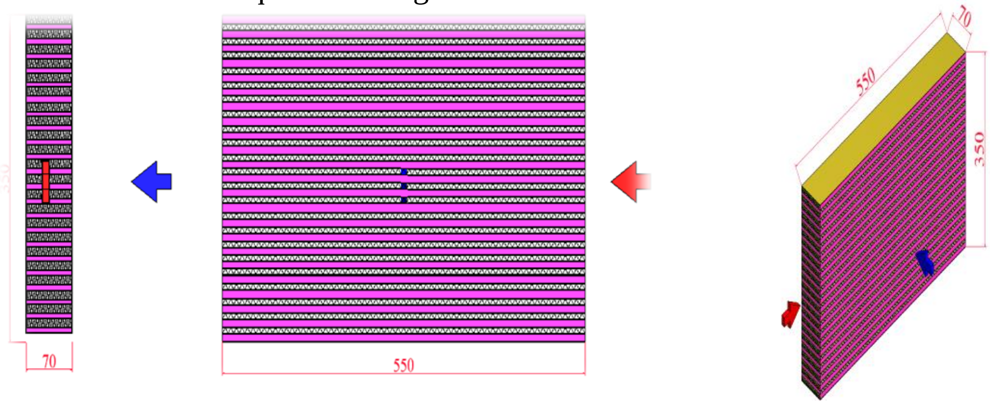


Figure 5. Designed intercooler dimensions

Table 7. Designed intercooler size, surface flow, friction characteristics and heat transfer values

Definitions		Air-side	Gas-side
Surface	Type	3/8-6.06	14.77
	Area, m^2	0.193	0.39
	Volume, m^3	0.0134	
Hydraulic diameter $4r_h$, m		4.453×10^{-3} m	2.59×10^{-3} m
Fin range δ, m		0.152×10^{-3} m	0.152×10^{-3} m
Transfer area / Volume Between Plate, (β)		840 m^2/m^3	1378 m^2/m^3
Fin area/Total area		0,64	0.844
Heat transfer area, m^2		4,68	10.15
Calculated Flow area		0,075	0.019
Calculated Fluid specification	c_p, J/kgK	1019	1021.1
	Pe, Pa	9.93×10^4	1.764×10^5
	V_{mean}, m^3/kg	0.929	0.553
Reynolds number		1.899×10^3	680.545
$St.Pr^{2/3}$		9.155×10^{-3}	7.395×10^{-3}
Friction number		0.043	0.032
Heat transfer coefficient, W/m^2K		96.012	50.447
Fin factor		0.982	0.984
Surface factor		0.989	0.986
Total heat transfer coefficient, W/m^2K		50.463	
$N_{tu,maks}$		2.302	
Heat capacity rate		0.193	
Exit temperature		360.76 K	302.24 K
Plate space b, m		6.35×10^{-3} m	8.38×10^{-3} m
Pressure drop, %		0.103	0.0819

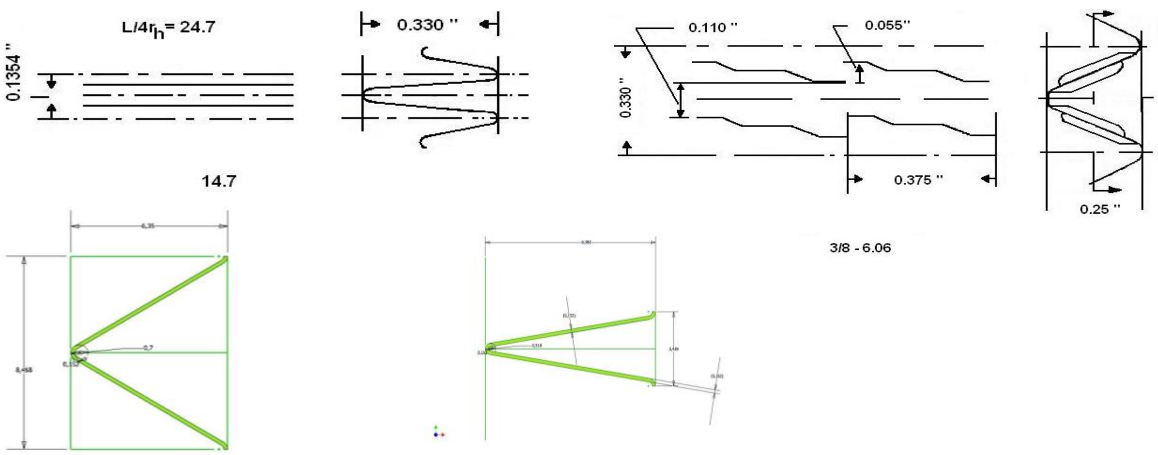


Figure 6. Designed Intercoolers the gas-side (hot side) and air-side surface fin section and sizes

8. Conclusion

In this study, to improve the performance value of the existing engine, made of Basak Tractors and Agricultural Machinery Industry-Turkey, was modified with turbocharger and intercooler system by theoretical calculations.

A 0.07x0.55x0.35 m dimension is found the size of the intercooler that is designed to achieve the intended temperatures of 302.24 K. When the cylinder air filling temperature in the engine's intake manifold reduced from 370 K to 302.24 K value at engine speed of 2500 rpm, obtained results are shown some benefits; these are specific fuel consumption decreased by 3.8%, the effective power is increased by 17.76 kW, rotation torque increases by 68 Nm, the heat rises 1.5% that is equivalent to the effective work, the heat expended for cooling a 5% decrease, the heat discharged from the exhaust has fallen 1%, the temperature 168 K decreased at end of the burning and 1% of the combustion pressure increases at end of the burning.

According to the results, selected type and size of intercooler in the modified engine with turbocharger for improving the lowering of inlet temperature of the intake manifold and engine performance is appropriate. For further improvement of the existing motor parameter values, it is recommended that Intercooler designed.

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