Experimental Investigation of Thermal Balance and Valve Cover Heat Transfer in a Small Internal Combustion Engine

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Abstract

Heat transfer in internal combustion engines is one of the most significant topics. Heat transfer may take place through thermal conduction and thermal convection in spark ignition engines. In this study, valve cover heat transfer and thermal balance of an air-cooled engine are investigated experimentally. The thermal balance analysis is a useful method to determine energy distribution and efficiency of internal combustion engines. In order to carry out experiments, a single cylinder, air-cooled, four-stroke gasoline engine is applied. The engine is installed on proper chassis and equipped with measuring instruments. Temperature of different points of valve cover and exhaust gases is measured with the assistance of K-type thermocouples. These experiments are conducted in various engine speeds. Regarding to the first law of thermodynamics, thermal balance is investigated and it is specified that about one-third of total fuel energy will be converted to effective power. It is also evaluated that for increasing brake power, fuel consumption will increase and it is impossible to prevent upward trends of wasted energies. In addition, it is resulted that, there is a reduction heat transfer to brake power ratio by increasing engine speed. Furthermore, it is found that, at higher engine speed, lower percentage of energy in form of heat transfer will be lost.

Keywords: *Small Internal Combustion Engine, Heat Transfer, Thermal Balance, Brake Thermal Efficiency*

1. Introduction

In internal combustion engines, heat transfer affects engine performance, efficiency and emissions. For a given mass of fuel within the cylinder, higher heat transfer to the combustion chamber walls will lower the average combustion gas temperature and pressure, and reduce the work per cycle transferred to the piston. The specific power and efficiency are affected by the magnitude of engine heat transfer. Heat transfer could be done through thermal conduction, thermal convection and thermal radiation [1]. Major part of fuel energy is lost due to heat transfer to surroundings and exhaust. About 35% of the total chemical energy that enters an engine in the fuel is converted to useful crankshaft work, and about 30 percent of the fuel energy is carried away from the engine in the exhaust flow in the form of enthalpy and chemical energy. This leaves about one-third of the total energy that must be dissipated to the surroundings by some mode of heat transfer [2]. Regarding to the high temperature in combustion chamber, heat should be transferred well. Materials in the engine cannot tolerate this kind of temperature and would quickly fail if proper heat transfer did not occur. Regarding to importance of thermal behavior of rocker arms and valve springs and fatigue cracks, valve cover heat transfer should be taken account. On the other hand, it is desirable to operate an engine as hot as possible to maximize thermal efficiency. As an engine is studied, according to mentioned points, heat transfer and thermal balance analysis are of significant importance.

Heat transfer through thermal conduction per unit of time and area in a steady state could be calculated by Fourier's law [3]. Heat will be transferred to cylinder head, cylinder walls and piston via conduction [4]. Additionally, heat will be transferred through piston ring and cylinder block. Between gases in the cylinder and cylinder heat transfer will take place by forced convection. Generally, in an air-cooled internal combustion engine, dissipated heat is transferred to the wall by convection, and then conducted through the wall and finally convected to the air.

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Alkidas [5] measured the instantaneous heat flux in the cylinder head of a four-stroke, 820CC engine and realized that this heat flux could be affected by factors such as engine velocity, air to fuel ratio and volumetric efficiency. Shayler et al. [6] used two methods for calculating instantaneous heat flux in combustion chamber. In first method, they used first thermodynamic law to estimate heat flux and in the second method they used Eichelberg model which lead to more precise results. Also, Franco and Martorano [7] worked on two-stroke, 125CC spark ignition engine, and they realized that about 50 percent of fuel energy is wasted as thermal energy. Chen et al. [8] studied about small scale internal combustion engines. In order to improve the accuracy of predicted heat transfer rate for different engines, a modified heat transfer model using Stanton number based on two engines was proposed in their study. It was found that the proposed model has prediction results closer to the measured data than the previous models at the most engine operation conditions. Javan et al. [9] investigated the temperature of spark plug in a bi-fuel, 4 cylinder engine experimentally. K-type and J-type thermocouples are used for measuring temperatures in their study. They also studied the effect of temperature on electrode erosion. In this research, temperature of spark plug was measured in different operation conditions with two types of fuels. Gasoline and CNG were used in these experiments. Their results show that, temperature of center electrode is lower than ground electrode. Generally, they studied to demonstrate spark plug erosion in different conditions. Abedin et al. [10] examined energy balance of internal combustion engines using alternative fuels. Their analysis gives useful information on the distribution of supplied fuel energy in the engine systems and identifies the avoidable losses of the real engine process with respect to ideal process. There are some significant variations observed in energy balance when the engine operating fuel is changed and devices like turbocharger or supercharger are used to boost the intake air pressure. Shojaeefard et al. [11] investigated the thermal contact conductance between an exhaust valve and its seat in an internal combustion engine. Therefore, experimental study was conducted to acquire temperature in some interior points to be used as inputs to an inverse analysis. Yingjian et al. [12] examined the energy balance and the efficiency analysis for power generation in an internal combustion engine sets using biogas. Their results of energy balance and efficiency showed that the engine set could generate electricity of 70kW. Also, improving the energy efficiency of biogas was investigated in this research. Broekaert et al. [13] experimentally studied the heat transfer of the mass of gas in cylinder through walls in a compression ignition engine with homogenous fuel. The engine was single cylinder and the fuel was Heptane. In this research, effects of inlet air temperature, compression ratio and mass flow rate of the fuel was evaluated. Li et al. [14] studied energy distribution in a diesel engine using low heat rejection concepts. In this study, the low heat rejection operating condition is implemented by increasing the engine coolant temperature. Their results demonstrate that rising coolant temperature yields slight improvements in net indicated fuel conversion efficiency, with larger improvements observed in brake fuel conversion efficiency.

In previous studies, most of the researchers have conducted their experimental investigation with the assistance of motoring method, so the engine speed was extremely low. Also, investigations about valve cover heat transfer and thermal balance in an air-cooled small engines have not carried out. Meanwhile, researchers' attention was mostly about water-cooled engines. Therefore, studying air-cooled engines should be taken in the agenda.

This study intended to investigate valve cover thermal conduction and energy balance of an air-cooled, single cylinder, small engine experimentally. Experimental data were taken at steady state and various operation condition (load and rpm) similar to real condition.

2. Experimental Setup

The engine which is studied in this research is single cylinder, air-cooled and four-stroke which its technical specifications are provided in Table 1. In order to estimate fuel consumption, fuel delivery system is fabricated with the assistance of scaled one liter storage tank.

Specific measurement instruments are used in all experimental studies. In this research, temperatures are measured by K-type thermocouples and digital thermometer. These types of thermocouples can be used with a service temperature range between -200 ℃ and +1350 ℃. The sensitivity and Measurement accuracy of these thermocouples are 41 $\mu V/℃$ and $\pm$ 2.2 ℃ respectively [16]. The tip of these thermocouples has the width of 3mm and it works on the basis of the Seebeck effect which will convert the temperature gradient into electricity. The sample thermocouple and its sensor and socket are shown in figure 1.

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	Single Cylinder,Four-Stroke
Cylinder Volume	124.1 CC
Cylinder Layout	Single Cylinder Canted 15 Degrees
Weight	33 kg
Bore	56.5 mm
Stroke	49.5 mm
Valves Sorting	Two OHC Valves
Compression Ratio	9.1 to 1
Intake Valve Timing	5 Degrees BTDC/35 Degrees ABDC
Exhaust Valve Timing	30 Degrees BBDC/5 Degrees ATDC

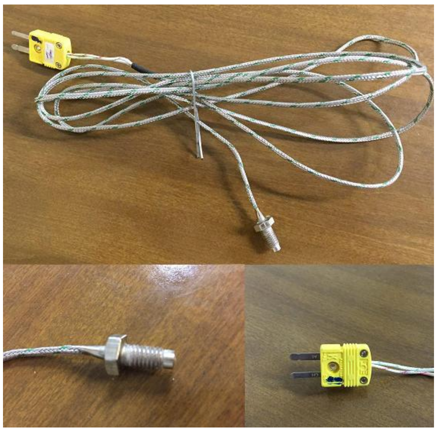

Fig1.. Sample Thermocouple and Its Sensor and Socket

Fig2.. Digital Thermometer

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In order to display measuring temperatures, thermocouples must be connected to a digital thermometer. K-type and J-type thermocouples are supported by provided thermometer and measurement accuracy of this thermometer is 0.1 ℃ . The thermometer which is used could be seen in figure 2.

Totally, five thermocouples are used in order to measure temperatures of different points. Two of them are located on the valve cover near the intake valve and the two other also on the valve cover near the exhaust valve. The other one is located at the outlet of the exhaust port. To measure the heat flux, one thermocouple should be installed on the surface of the valve cover and the other one should be placed in the valve cover depth. Thermocouples in each area should be mounted near to each other in order to more precise calculation of valve cover 1-D heat flux as it is shown in figure 3. Regarding to these two temperatures and Fourier's law which is given in equation 1, heat flux would be calculated. Heat flux highly depends on the materials which forms the valve cover (Aluminum Alloy), temperature gradient and thickness.

$$\dot{q} = -k\nabla T$$

$$\dot{q}_x = \frac{\dot{Q}}{A} = -k\frac{dT}{dx}$$

In this research, experiments are conducted in 3000, 4000 and 5000 rpm. A mechanical tachometer which is attached to the engine is used to display engine speed. The engine is connected to Prony brake dynamometer in order to measure the torque produced by the engine. Each experiment continued about 30 minutes and the temperature of 5 thermocouples was noted each 3 minutes. Actually, these experiments are conducted in transient situation until the engine reaches the steady state. Schematic diagram of engine test setup is shown in figure 4.

3. Theory of Energy Balance

The thermal balance analysis is a useful method to determine energy distribution and efficiency of internal combustion engines. Only limited part of the total chemical energy that enters an engine in the fuel is converted to useful crankshaft work and a large amount of energy is wasted in different ways such as exhaust, heat losses and friction. Preventing overheating is highly critical in order to maintain the engine. On the other hand, it is impractical to operate an engine as hot as possible to maximize thermal efficiency. Brake power is effective engine output and the rest of fuel energy could be divided into heat losses, parasitic loads, and what is lost in the exhaust flow. Figure 5 illustrates energy distribution in an air-cooled internal combustion engine.

The energy balance can be estimated by the steady flow energy equation as expressed in equation 3.

$$\dot{E}_{in} - \dot{E}_{out} = dE/dt = 0$$

In the steady flow process, the energy content of a control volume remains constant, so the rate of change in total energy is equivalent to zero. Therefore, energy balance can be written as equation 4.

$$\dot{E}_{in} = \dot{E}_{out}$$

In this case study, the steady flow first law equation for this control volume engine is provided in equation 5. Also, fuel energy which enters the engine is introduced in equation 6. Equation 7 is provided in order to determine exhaust power in steady state [14]. According to equation 8 and 9 friction power could be estimated too, so heat loss to surroundings will be determined due to the equation 5[17]. This parameter indicates thermal energy which is transferred by cooling air.

$$\dot{Q}_{fuel} = \dot{W}_b + \dot{Q}_{ex} + \dot{Q}_{HT} + \dot{W}_f$$

$$\dot{Q}_{fuel} = \dot{m}_f Q_{HV} \eta_c$$

$$\dot{Q}_{Ex} = (\dot{m}_a + \dot{m}_f) h_{ex}$$

$$fmep = 0.097 + \left(\frac{N}{100}\right)[0.015 + 0.05\left(\frac{N}{1000}\right)]$$

$$fmep = \dot{W}_f \Big/ [V_d(N/n)]$$

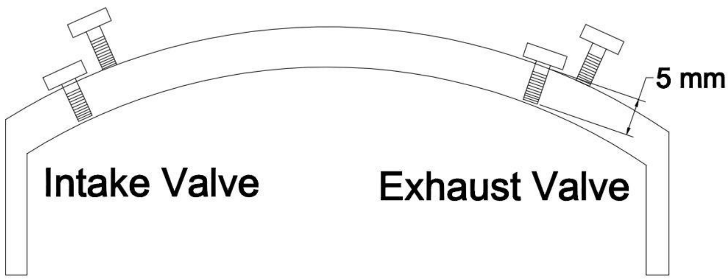

Fig3. Thermocouples Location on the Valve Cover

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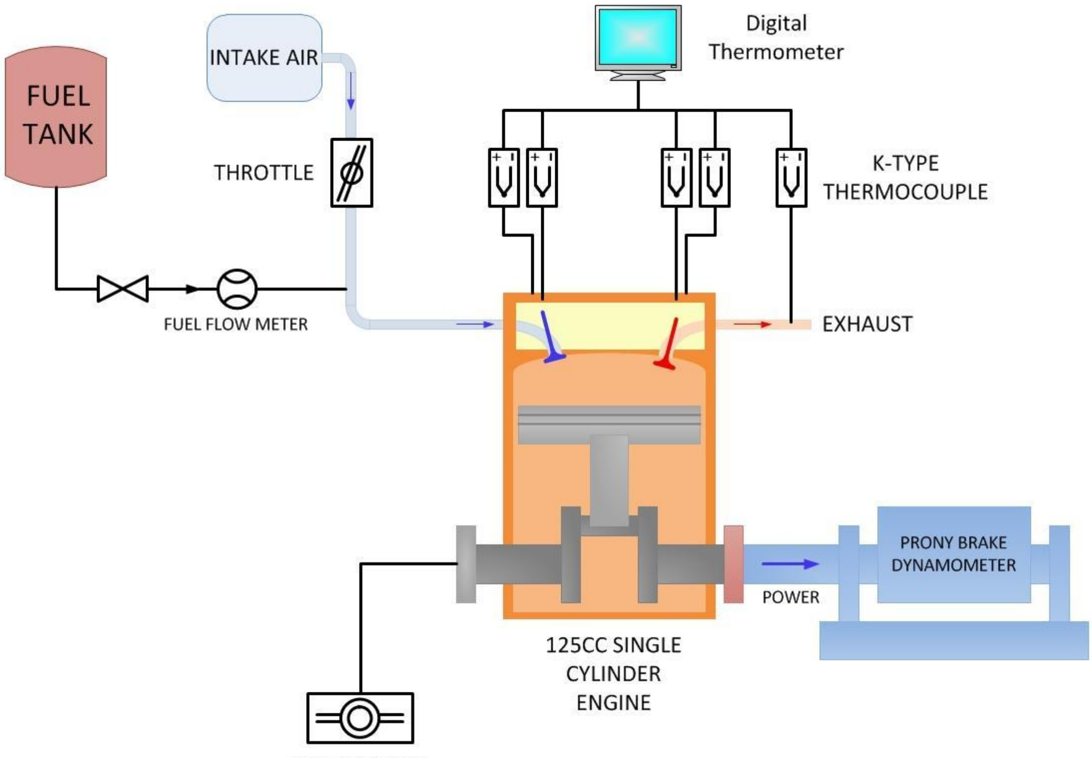

Fig4.. Schematic Diagram of Engine Test Setup

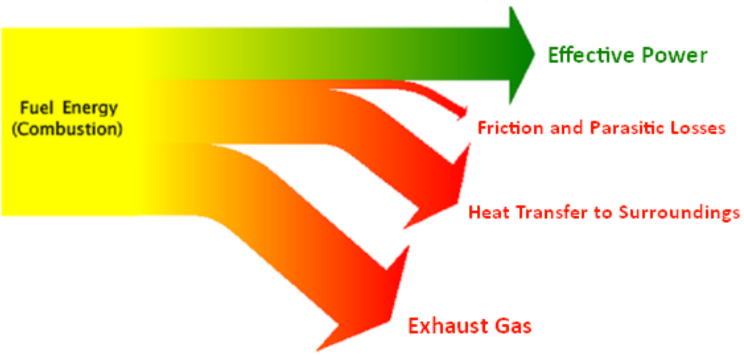

Fig5. Energy Distribution in air-cooled engines

In order to determine each term of energy distribution equation, some engine characteristics are needed which are introduced in the following. These characteristics consist of air to fuel ratio, equivalence ratio and volumetric efficiency which are given in equations 10 to 12.

$$AF = {\dot{m}_a}/{\dot{m}_f}$$

$$\emptyset = {(AF)_{stoich}}/{(AF)_{act}}$$

$$\eta_v = {n\dot{m}_a}/{\rho_a V_d N}$$

Another studied characteristic is brake thermal efficiency which gives the percentage of total energy converted to useful output at the crankshaft [2]. For all three speeds in these experiments, brake thermal efficiency is evaluated around 33%.

$$(\eta_t)_b = {\dot{W}_b}/{\dot{Q}_{in}}$$

4. Calibration and Error Analysis

Thermocouples calibration is one of the most significant processes in thermal investigations that should be carried out to estimate instruments

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accuracy. In order to calibrate the thermocouples, temperatures of four different points of water are measured with digital thermometer and mercury thermometer and compared. Also, each experiment is performed three times to achieve data with high accuracy.

The main purpose of error analysis is calculation of uncertainty of the results. According to theory of error distribution by Taylor series, equation 14 is used to calculate the uncertainty of a multivariable parameter with 95% certainty [18].

$$U_{95} = \left[\sum_{i=1}^{j}\left(\frac{\partial r}{\partial X_i}\right)^2 U_i^2\right]^{\frac{1}{2}}$$

In this equation U_{95} is the total error of a multivariable parameter r , X_i is an independent variable and U_i is its error and j is the number of variables. In this study, the error analysis is carried out for the two main measured parameters. The accuracy of each measuring parameters must be specified. According to equation 2, error analysis for heat flux depends on temperature and thickness. The accuracy of temperature measurement is 0.1 ℃ based on digital thermometer accuracy. Also, the accuracy of caliper which is used for measuring thickness of valve cover is 0.1 mm. Equation 15 indicates Taylor error analysis for heat flux in these experiments.

$$\frac{U_{q"}}{q"} = \sqrt{(\frac{U_{\Delta T}}{\Delta T})^2 + (\frac{U_{\Delta X}}{\Delta X})^2}$$

According to Taylor series, the calculation error of the measured heat flux is approximately 2.82%.

$$\frac{U_{q"}}{q"} = 2.82\%$$

5. Results and Discussion

Experiments are carried out in different engine speeds. Figure 6 indicates valve cover transient temperature in 4000 rpm for 4 different points of valve cover. As shown in figure 6, it takes 30 minutes for engine to reach to steady state. As mentioned above, temperatures are measured in points near valves on the surface and in 5mm depth of the valve cover. Surface and inside temperatures of valve cover near exhaust and intake valves have upward trend. The most heated point is in depth of valve cover near exhaust valve because of exhaust gas high temperatures.

Regarding to linear thermal conduction in valve cover near intake and exhaust valves, heat flux will be calculated as it is shown in figure 7 which illustrates instantaneous heat flux during 30 minutes in 4000 rpm. Heat flux near exhaust valve is higher than heat flux near intake valve due to the more temperature gradient. Meanwhile, both of them have similar trend and fluctuation. Heat fluxes in these two sides of valve cover have increased dramatically till they peaked at about 25 minutes of elapsed time. The maximum thermal conduction takes place in this moment. Then heat fluxes decrease because of temperature gradient reduction.

Also, figure 8 indicates steady state valve cover heat flux in different engine speeds. As it is shown, steady heat fluxes rise due to the upward trend of engine speed. The main reason refers to the friction and heat dissipation. Figure 9 illustrates dramatic rise of exhaust temperatures regarding to engine speeds.

Figure 10 demonstrates distribution of energy in studied small IC engine. As it is shown, all terms of energy balance equation consist of fuel energy, exhaust energy, brake power, heat transfer and friction power have upward trend with respect to the engine speed increment. Wasted energy terms such as exhaust power and heat transfer have similar trends. Fuel consumption in 4000 rpm has increased by 34.24% compared to 3000 rpm and useful power has risen about 33.48%. Meanwhile, exhaust power and heat transfer have increased by 38.11% and 15.49% respectively. In 5000 rpm, brake power and heat transfer have risen by 25.08% and 10.04% in comparison to 4000 rpm; thus, it could be expressed that growth rate of heat transfer term reduces due to the engine speed upward trend.

Figure 11 presents the percentage of thermal balance terms versus engine speed. As it is shown in this bar chart, the summation of distributed energies is 100% which equals to fuel energy. By increasing engine speed, the percentage of exhaust energy and friction power increases in contrast to heat transfer. In addition, the percentage of brake power in these engine speeds remains approximately constant without considerable variations. In other words, this parameter indicates brake thermal efficiency as it is given in equation 13. So, it can be concluded that at higher engine speed, lower percentage of energy in form of heat transfer will be lost and energy loss in form of exhaust increases instead.

One of the most significant performance characteristics of internal combustion engines is heat transfer to brake power ratio which is illustrated in figure 12. As it is seen, increasing engine speed leads to decreasing heat transfer to brake power ratio. This fact is in accordance with Heywood [1]. Although both brake power and heat transfer increase with

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engine speed, brake power growth is more than heat transfer; therefore the fraction will decrease.

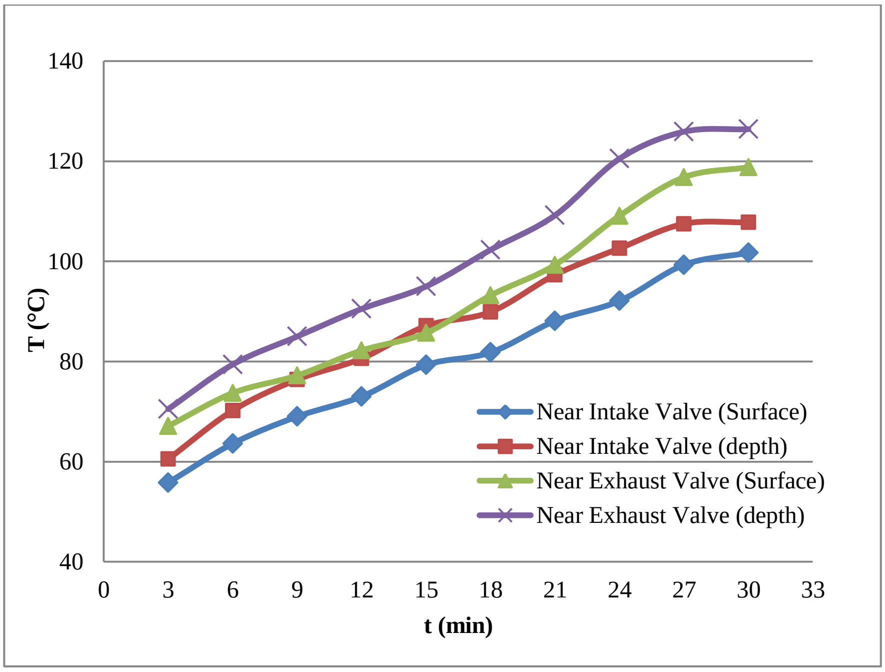

Fig.6. Valve Cover Transient Temperature in 4000 rpm

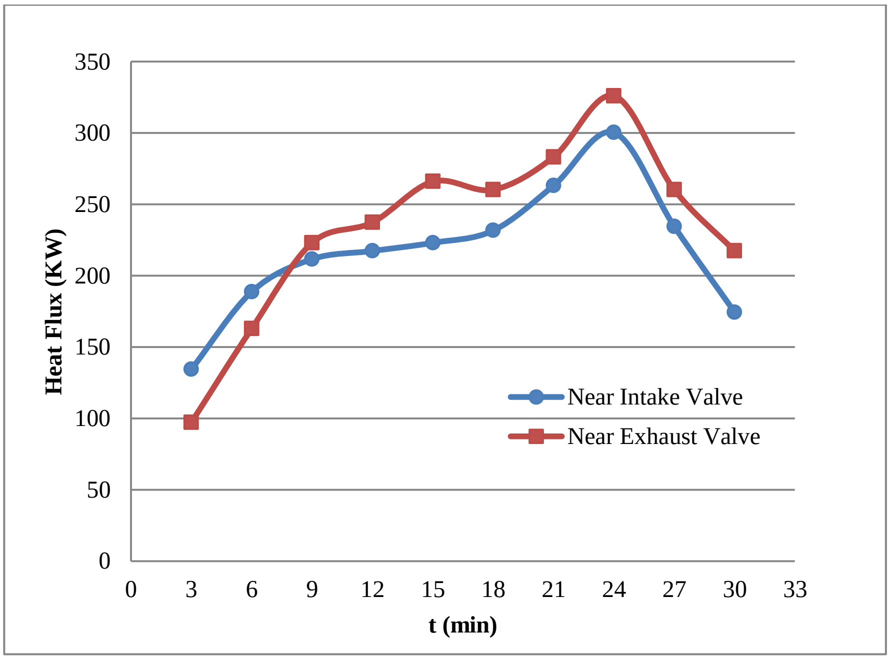

Fig.7. Valve Cover Transient Heat Flux in 4000 rpm

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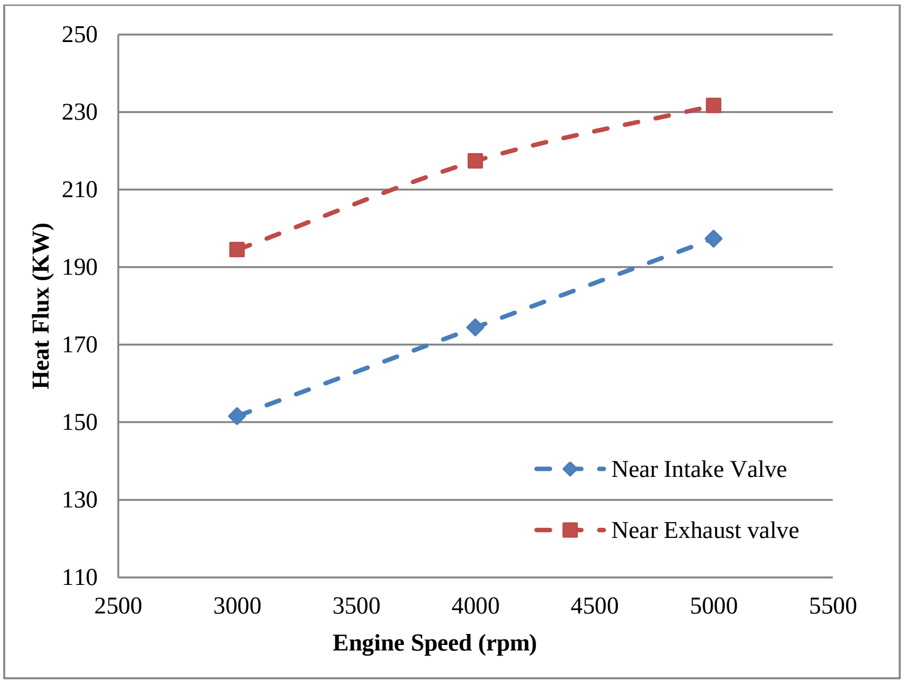

Fig.8. Steady State Valve Cover Heat Flux in Different Engine Speeds

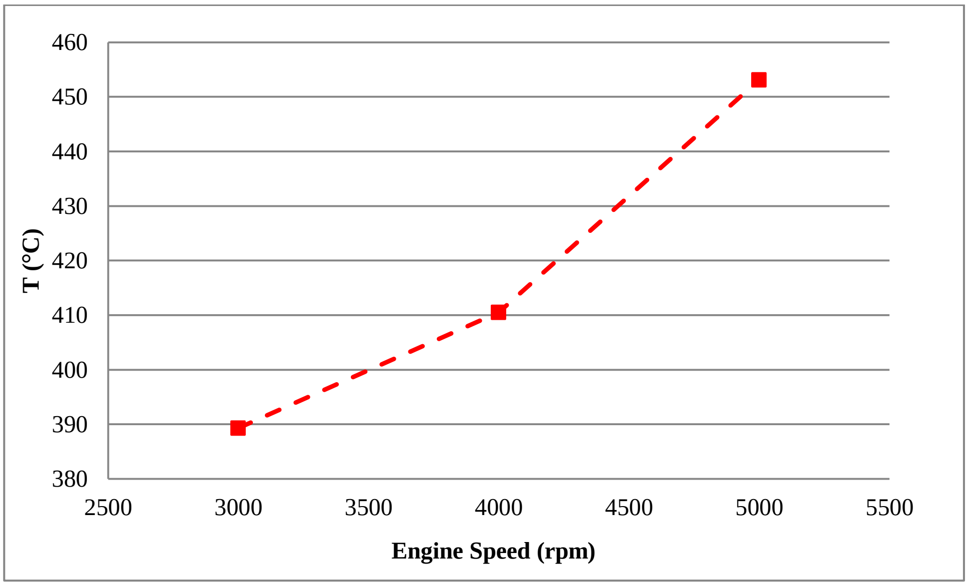

Fig.9. Steady State Exhaust Temperature

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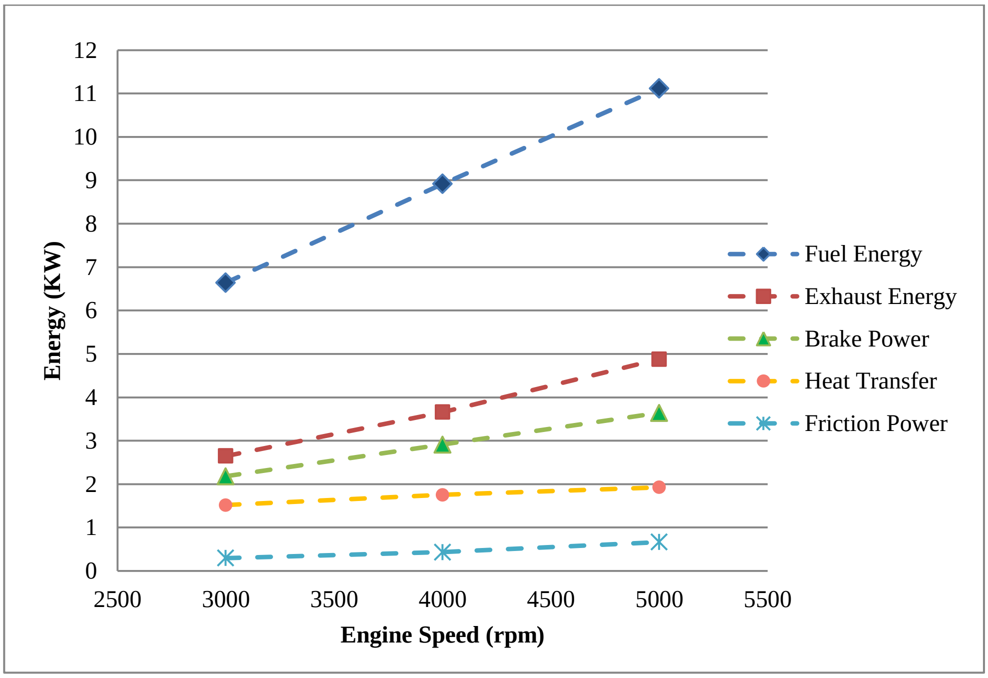

Fig.10. Distribution of Energy in CG125 Engine as a Function of Engine Speed

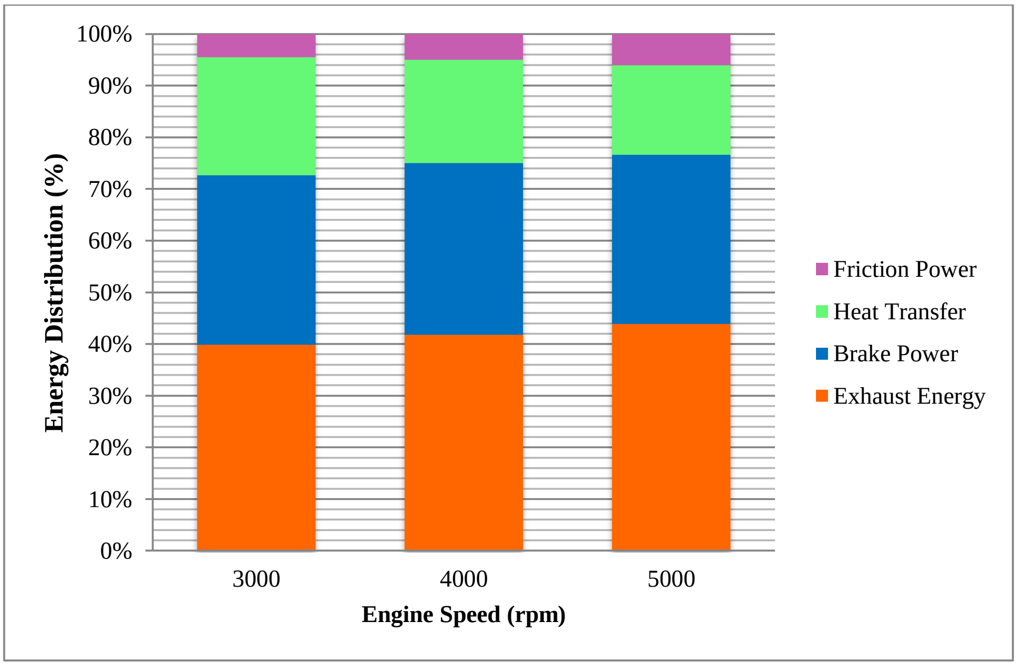

Fig.11. Percentage of Energy Distribution in Various Engine Speeds

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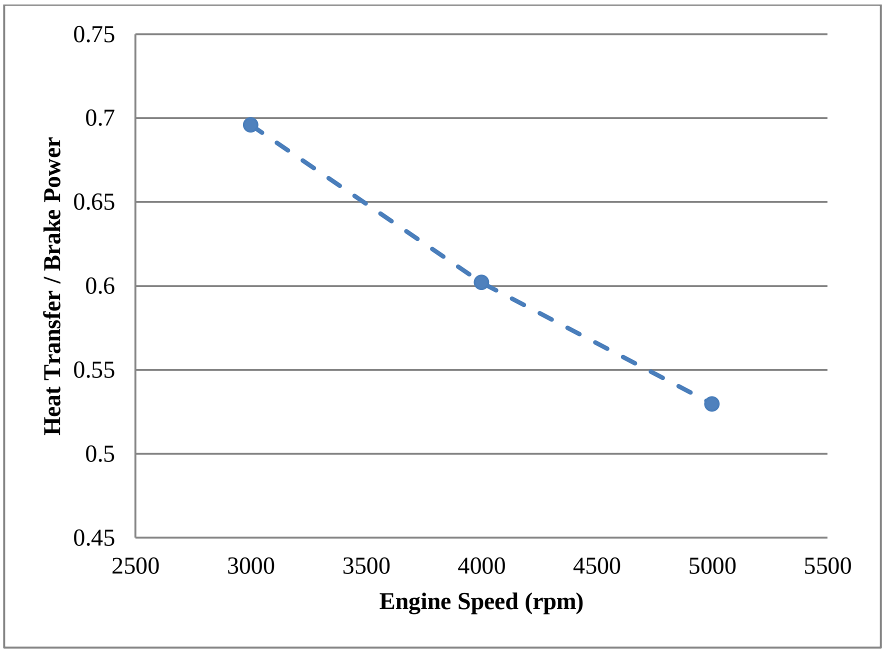

Fig.12. Heat Transfer to Brake Power Ratio

6. Conclusion

In this research, the thermal balance and the valve cover heat transfer of an air-cooled, small engine fueled with gasoline is investigated experimentally. In order to conduct experiments, setup is equipped with proper measuring instruments. In this research, experiments are conducted in 3000, 4000 and 5000 rpm till the results reached steady state. Regarding to measuring the temperature of different points of valve cover near intake and exhaust valves, linear heat fluxes are calculated. According to Taylor series with 95% certainty, the calculation error of the measured heat flux is about 2.82%. Also, due to the first law of thermodynamics and exhaust steady temperature, energy balance is studied. It is evaluated that for obtaining more effective power, fuel consumption will increase and it is impossible to prevent upward trends of exhaust power and heat transfer to the surroundings. Then the percentage of energy distribution terms is presented and it is specified that, by increasing engine speed, the percentage of exhaust energy and friction power grow. The results indicate that the brake thermal efficiency is approximately 33%. Furthermore, it can be concluded that at higher engine speed, percentage of energy loss through exhaust increases and on the other hand the heat transfer percentage decreases. Finally as the main goal of this paper, the value of heat transfer to brake power ratio decreases when engine speed increases.

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$\dot{q}$	Heat Flux
k	Thermal Conductivity Coefficient
T	Temperature
$\dot{Q}_{fuel}$	Fuel Energy
$\dot{W}_b$	Brake Power
$\dot{Q}_{ex}$	Dissipated Heat By Exhaust
$\dot{Q}_{HT}$	Heat Transfer to Surroundings
$\dot{W}_f$	Friction Power
Q_{HV}	Fuel Heating Value
η_c	Combustion Efficiency
$\dot{m}_a$	Mass Flow Rate of Air
$\dot{m}_f$	Mass Flow Rate of Fuel
h_{ex}	Enthalpy of Exhaust Gases
N	Engine Speed (rpm)
n	Number of Revolutions Per Cycle
f_{mep}	Friction Mean Effective Pressure
V_d	Displacement Volume
$(AF)_{stoich}$	Stoichiometric Air to Fuel Ratio
$(AF)_{act}$	Actual Air to Fuel Ratio
Ø	Equivalence Ratio
η_V	Volumetric efficiency
ρ_a	Density of Air
$(\eta_t)_b$	Brake Thermal Efficiency
U_{95}	Error With 95% Certainty

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