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Experimental Investigation of Effect of Preheating of Air and Exhaust Gas Recirculation on Four Stroke Diesel Engine

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Abstract. This paper is concerned with means for heating the inlet air passed to the cylinder by using specifically designed and manufactured heat exchanger and also use of exhaust gas recirculation to investigate its effect on performance, combustion and emission characteristics of four stroke single cylinder diesel engine. A diesel engine having a cylinder,   3.5 KW power, constant speed of 1500 RPM , water cooled, Kirloskar make, diesel engine was selected as base engine and the experiments were conducted at part load and full load conditions. The diesel engine setup was modified with (i) incorporation of heat exchanger which was designed on the basis of availability of waste heat at the engine exhaust for preheating of air and (ii) exhaust gas recirculation for waste heat recovery and reduction in the NOx. The Experiments were conducted for six setups viz. i. Basic diesel engine setup   ii. Basic diesel engine setup with 6 % EGR   iii. Basic diesel engine setup   with 12 % EGR iv. Modified setup with heat exchanger v. Modified setup with heat exchanger and   6% EGR and vi. Modified setup with heat exchanger and 12% EGR .The experimental results obtained with modified engine setup with use of heat exchanger and EGR. The results obtained indicate thermal efficiency is decreased with heat exchanger and 12 % EGR compared to base diesel with 12% EGR. The volumetric efficiency is decreased   from base diesel by 16.87 % with heat exchanger and 6% EGR at 75% load. The NOx emission is increased with increase in load for all the configurations.

1. Introduction
The depletion of fossil fuel resources at faster rate is a global phenomenon and it has emphasized the need of finding alternative sources of energy and also emphasized to improve the performance, combustion and emission characteristics of existing internal combustion engines in order to save the primary fuel. The diesel engine is concerned with many heat losses which tend to reduce its

performance. The exhaust flue gas loss is the major loss that badly affect on the performance of the engine. Many researchers focusing on exhaust flue gas loss or exhaust gas loss utilization for improvement in performance, combustion and emission characteristics .Many techniques had been used to utilize exhaust gas heat potential for improving performance and reducing the emission level of diesel engine. Abd-Alla (2002) investigated on the use of exhaust gas recirculation (EGR) technique to check its potential of recovering exhaust heat from engine exhaust and reducing the NOx emissions. They suggested making optimum use of EGR by using it in airflow path rather than displacing part of inlet air. The use of EGR by this method substantially reduces NOx emissions [1]. Shi et al.(2006) made use of both internal and exhaust gas recirculation on HCCI engine and found reduction in NOx and smoke emissions due to use of homogeneous charged compression ignition system [2]. Hountals et.al (2008) verified effect of using cooled EGR gas temperature on turbocharged DI heavy duty diesel engine using multizone combustion model and shown its positive effect on brake specific fuel consumption and lowering the soot values [3]. The researchers investigated on different technologies for recovery of the exhaust heat from I.C.Engines. The techniques such as thermoelectric generation, bottoming Rankine cycle, six stroke cycle found opportunities for potential energy savings and improvement in the performance [4]. Researchers have been trying to improve thermal efficiency of diesel engines by applying different techniques. The effect of high injection pressure and cylinder air pressure have been investigated on combustion and heat release rate for DI diesel engines shown improved brake thermal efficiency [4]. Thakar et.al (2018) designed counter flow shell and tube heat exchanger and reported heating of inlet air upto $150°C$ [6]. Tilmann Abbe Horst et al (2013) developed dynamic model of heat exchanger for exhaust gas recovery. The dynamic heat exchanger model predicts heat recovery systems of automobile engines. This dynamic model developed was working on moving-boundary principle and is used to develop a control system for dynamic operation on test bench measurements. [7].Saiful Bari & Shekh Hossain (2013) experimented with two heat exchangers to estimate exhaust heat recovery from diesel engine where they used water as working fluid. Their experimental study found additional power of 16%. They found increased additional power from 16% to 23.7% after optimization.[8].Bumroongsri et al (2013) carried out experimentation on heat transfer coefficients of unit of waste heat recovery in the detergent manufacturing process, It resulted into reduction of heat loss by means of waste heat recovery process [9]. Hui Xie & Can Yang (2013) studied heavy duty diesel engines for waste heat recovery using Rankine cycle system to study its dynamic behavior.They defined four basic operating modes under driving cycles and established Rankine Cycle System(RCS) model. The four modes include startup mode, turbine turning mode, power mode and protection mode. The operating performances of established RCS model and actual driving cycle were discussed. The results indicate that Rankine Cycle system efficiency is as low as 3.63% which is less than half of the designed efficiency which is 7.77%.[10].Love et al (2012) carried out experimentation to improve performance of waste heat recovery systems. They tested thermoelectric devices on a bench-scale thermoelectric heat recovery apparatus and observed that simulates automotive exhaust. It is observed that thermo electric power output increases from 2 to 3.8w for higher exhaust gas flow rates and overall system efficiency decreases from 0.95% to 0.6%. There is degradation of the effectiveness of the Exhaust gas recirculation type heat exchangers over a period of time.[11] .Serrano et al (2012) introduced new solutions to the problems related to coupling between thermal engine and waste heat recovery Rankine cycle. to analyze alternative solutions for the problems related to the coupling between the WHR Rankine cycle and the thermal engine. They introduced the method of removing its turbine and adapting one of the turbochargers and trying to recover the energy by the Rankine cycle. [12].Srinivas Garimella (2012) studied simultaneoud chilled and hot water generation from the low-grade w a s t e h e a t recovery steam. The high heat at 120 deg Celcius recovered from a gas stream was supplied to an absorption cycle to simultaneously produce chilled water and hot water

to be used for process heating. [13]. Dae Hee Lee et al (2010) investigated experimentally on exhaust waste heat recovery of diesel engine. They employed the concept of cogeneration where electric power is generated by the generator connected to the diesel engine and the heat is recovered from exhaust gases as well as by the fin-and-tube and shell-and-tube heat exchangers. The effect of secondary combustion on efficiency and emission reduction observed. It is found total efficiency reaches a maximum 94.4% which is approximately 15-20% higher than efficiency of typical diesel engine [14] .Ismail Teke et al (2010) developed a model for determining type of heat exchanger and area for optimum waste heat recovery. Based on technical and economical parameters such as heating value of fuel, unit cost of heat exchanger etc a non-dimensional E number had been defined. This non-dimensional E numbers had been expressed in graphical forms as the functions of NTU ands ratio of heat capacities. The corresponding heat exchanger area for giving maximum heat gain can be obtained from these graphs. The efficient heat exchanger type and its area can be determined comparing or effectiveness of heat exchangers or net gains at NTU.[15].Gianfranco Caruso et al (2015) experimentally studied finned tube heat exchanger where water is used as heating medium and flowing inside the tube at different conditions. The air side heat transfer coefficients and the thermal constant conductance in the tube is studied. Petukhov's correlation was used to calculate the water heat transfer coefficient in the tube. Three tubes of different diameters 30 mm, 22 mm, and 15.6 mm were used and the fitting of the data provides a correlation that agrees very well with the experimental data. The thermal contact resistance based on Reynold's number is estimated and conformed.[16].Yakar & Karabacak (2015) investigated experimentally on perforated finned heat exchangers. They studied the thermal performance of perforated finned heat exchangers for two cases considering basic perforated finned heat exchangers and perforated finned heat exchangers with angle of Rotation 8. In order to find best angular location experiments were carried out at six different angular locations. They also compared imperforate finned heater with a perforated finned heater and observed the finned heater effectiveness is 18% higher at 608 and pressure drop is 1.16% lower than other angular positions. They concluded that the best angular position is 608. The results also shows increase in effectiveness with increase in number of transfer units.[17]. Pandiyarajan et al (2011) conducted experimental investigation on diesel engine for exhaust heat recovery using finned shell and tube heat exchanger and thermal storage system. IC engine setup with integrated shell and finned tube heat exchanger and a thermal energy storage tank used for experimentation. The designed, fabricated and tested thermal storage tank used for excess energy storage which is tested using cylindrical phase change material (PCM) capsules for sensible and latent heat storage system. The heat exchanger extract heat from the exhaust gas and excess energy is stored in thermal energy storage tank. The performance of the engine evaluated with and without heat exchanger. It is found that 10–15% of heat at higher temperature is stored the thermal storage tank.This available high temperature heat can be utilized for suitable application. The performance parameters amount of heat recovered, charging efficiency, charging rate, percentage energy saved related to heat exchanger evaluated [18].Iqbal et al (2011) considered steady, laminar, incompressible and fully developed flow subjected to constant heat flux boundary conditions in double pipe with parabolic fins and studied optimal convective heat transfer. Finite element method (FEM) is employed to compute field variables for providing function values to the optimizers.[19].Desai & Bannur (2001) conducted experimental investigation on a twin cylinder diesel engine using a shell and tube heat exchanger to recover heat from exhaust gas[20]. Lee et al (2010) carried an experimental study on the effects of secondary combustion pn efficiencies and emission reduction in the engine exhaust heat recovery system.[21].Talbi & Agnew (2002) studied turbocharged diesel engine interfaced with an absorption refrigeration unit for energy recovery from the engine exhaust gas. They estimated enhancement in the performance due to the engine exhaust heat recovery.[22]. Morcos (1998) investigated on shell and dimpled tube exchangers for waste heat recovery. They investigated exchanger heat duty, overall heat transfer coefficient, effectiveness

and tube side friction factor as functions of the tube surface geometry that is plain or dimpled and for the parallel and counter flow pattern and tube Reynolds number.[23]. The present paper is the result of experimentation on single cylinder, four stoke diesel engine with the incorporation heat exchanger and exhaust gas recirculation. The counter flow shell and tube heat exchanger is designed depending on the availability of engine exhaust heat which is mounted between outlet and inlet duct of the engine. The exhaust gas recirculation at 6% EGR and 12% EGR also has been used to minimize the emission level in the engine.

Nomenclature

CO   Carbon monoxide
NOx   oxides of nitrogen
CO2   carbon dioxide
HC   hydro carbon
EGR   exhaust gas recirculation
CA   crank angle
BTE   bake thermal efficiency
VCR   variable compression ratio
WHE   without heat exchanger
HE   with heat exchanger
BSFC   brake specific fuel consumption

2. Experimental details

The present experimentation is completed on 3.5 kw capacity 4-stroke single cylinder stationary diesel engine operating at injection timing 23° BTDC and injection opening pressure of 200 bar. The engine specifications are given in Table 1 and the engine setup is shown in Figure 1. The setup is equipped with data acquisition system for measurement of combustion pressure, crank angle and other performance, combustion and emission parameters The counter flow shell and tube heat exchanger was designed on the basis of potential heat available at the engine exhaust at full load .The designed heat exchanger was placed upstream of inlet and outlet duct of the engine. The other techniques of exhaust gas recirculation were used to evaluate the performance and emission characteristics of the engine. The experimentation carried out for total number of six configurations as i. Diesel without Heat Exchanger (WHE) ii. Diesel without Heat Exchanger (WHE) and 6% EGR iii. Diesel without Heat Exchanger (WHE) and 12% EGR iv. Diesel with Heat Exchanger (HE). v. Diesel with Heat Exchanger (WHE) and 6% EGR and vi. Diesel with Heat Exchanger (WHE) and 12% EGR.

Table 1. Engine Specifications.

| Title	Details
Product	VCR Engine test setup 1 cylinder, 4 stroke, Diesel (Computerized)
Product code	234
Engine	Make Kirloskar, Type 1 cylinder, 4 stroke Diesel, water cooled, power 3.5 kW at 1500 rpm, stroke 110 mm, bore 87.5 mm. 661 cc, CR 17.5
Dynamometer	Type eddy current, water cooled, with loading unit
Propeller shaft	With universal joints
Air box	M S fabricated with orifice meter and manometer
Fuel tank	Capacity 15 lit with glass fuel metering column
Calorimeter	Type Pipe in pipe
Piezo sensor	Range 5000 PSI, with low noise cable
Data acquisition device	NI USB-6210, 16-bit, 250kS/s.
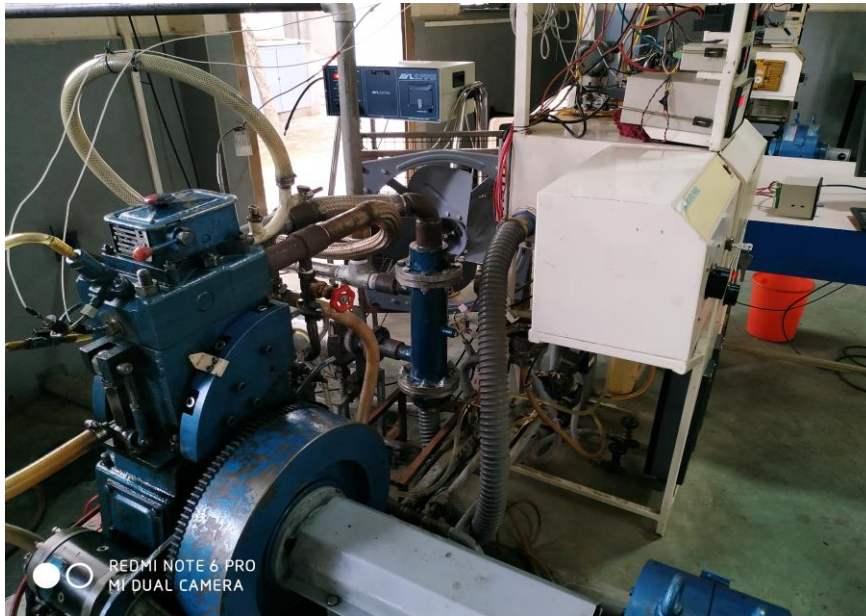
Figure 1. Modified Experimental Setup with Heat Exchanger.

3. Results and Discussion

The various performance and emission parameters of the engine for the six configurations were measured and the variation of these parameters with respect to load elaborated in details in the following section.

3.1 Brake Thermal Efficiency

The performance measurement parameter of the engine is thermal efficiency. It is measure of conversion of heat released during combustion to net work output. It is observed from figure 2 the brake thermal efficiency is decreased with diesel heat exchanger as compared to base diesel without heat exchanger. Thermal efficiency is decreased   from base diesel by with 2.94% with diesel without heat exchanger at part load and by 18% at full load. It may be mainly due to decrease in density of fuel at high temperature of heated air. It is also observed that thermal efficiency is also decreased with heat exchanger and 12 % EGR compared to base diesel with 12% EGR. This may be due to lower oxygen content with exhaust gas recirculation which results into lower combustion temperature. Similarly, it decreased with heat exchanger and 6% EGR compared to base diesel without heat exchanger and 6% EGR.
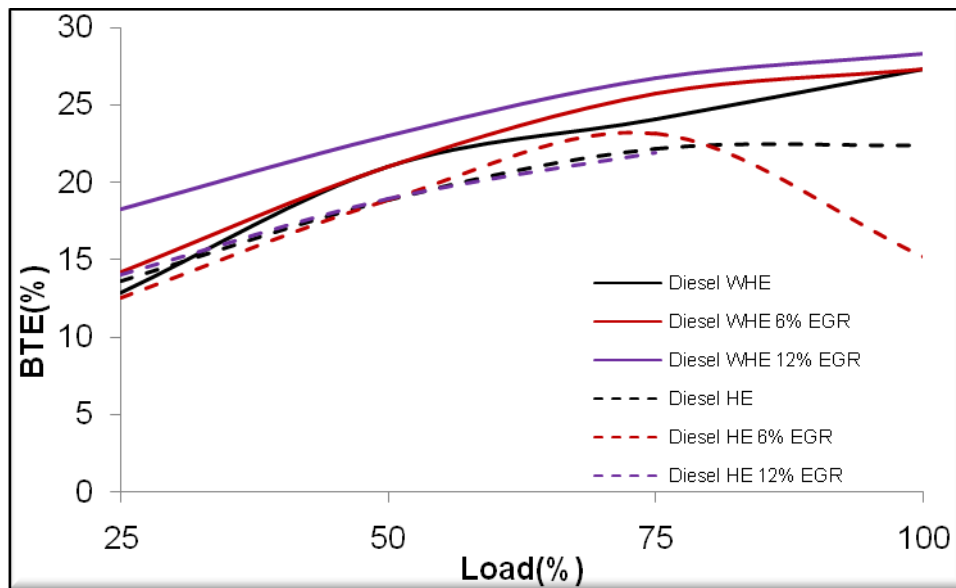
Figure 2 . Variation of brake thermal efficiency w.r.t load.

3.2 Volumetric Efficiency

The variation in volumetric efficiency verses load is shown in Figure 3 for base diesel and diesel with heat exchanger and exhaust gas recirculation 6% & 12% EGR for engine operating at 23° BTDC and 200 bar injection pressure. The figure 3   shows volumetric efficiency remains more or less same with respect to load for engine running at base diesel condition. The volumetric efficiency variation for normal engine lies between 74 to 55%. It is observed decreased volumetric efficiency with heat exchanger and exhaust gas recirculation as compared to engine running at base diesel with increase in load. This may be due to decrease in density of heating air in the heat exchanger which is passed inside the cylinder. The volumetric efficiency is decreased   from base diesel by 16.87 % with heat exchanger and 6% EGR at 75% load. It is also observed that volumetric efficiency almost remains same and lies between 65 to 66% at all loads.
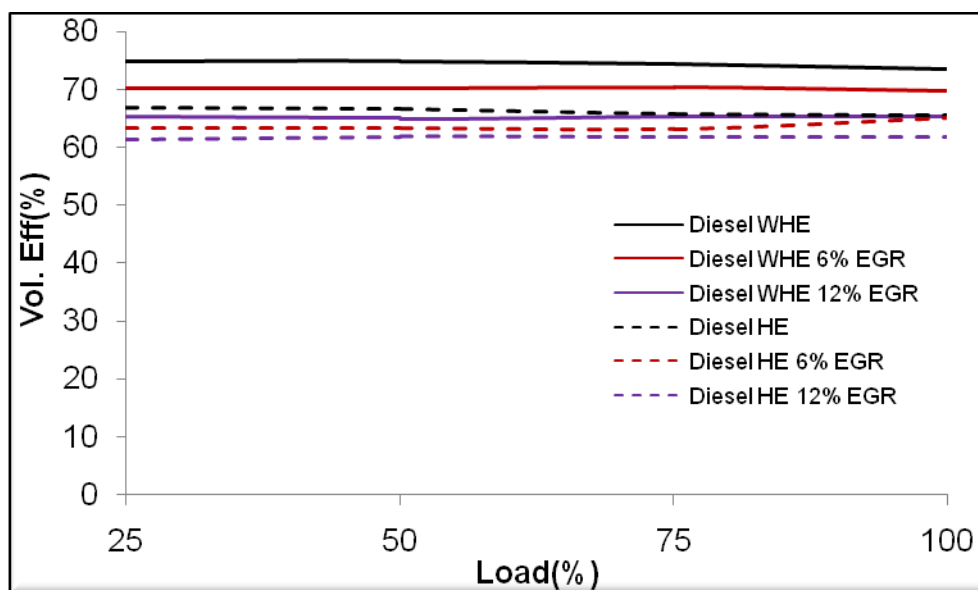

Figure 3. Variation of volumetric efficiency w.r.t load.

3.3 Brake Specific Fuel Consumption

The specific fuel consumption is derived directly from the mass of fuel consumed in the presence of oxygen and release the heat. This heat released during combustion is converted into power. It is observed from figure 4 that Brake specific fuel consumption is decreased with increase in load for base diesel without heat exchanger and similar trend of decrease in fuel consumption is also observed for diesel with heat exchanger. The brake specific fuel consumption (BSFC) is decreased   from base diesel by 53% with diesel without heat exchanger at full load. This improved value of BSFC is due to preheating of air in the heat exchanger which improves the combustion in the cylinder. It is observed that the brake specific fuel consumption is increased by 51% for diesel with heat exchanger and 6% (EGR) Exhaust gas recirculation. It is also observed that the specific fuel consumption remains same for diesel with heat exchanger and with 6% EGR and 12% EGR at 50% load.
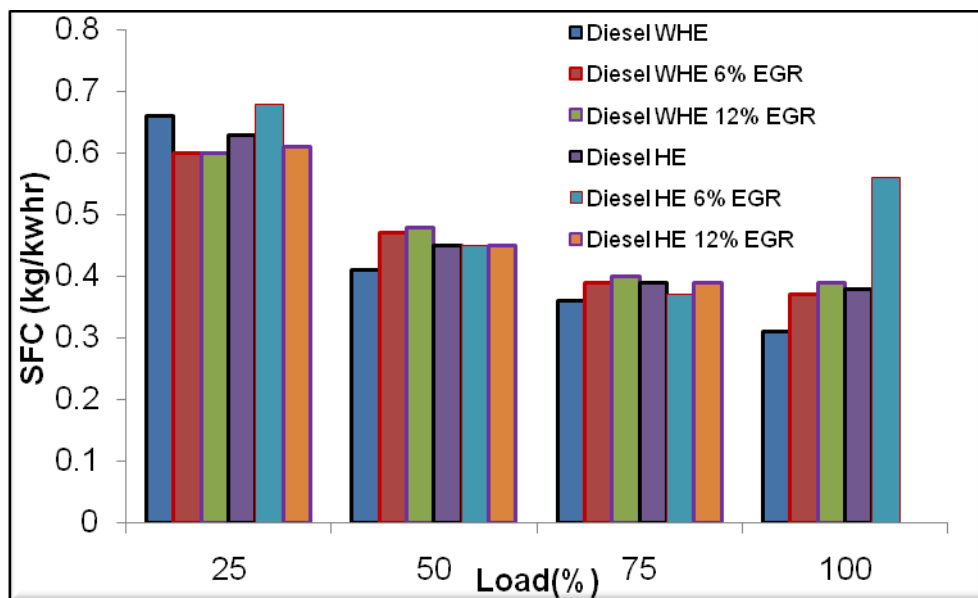

Figure 4. Comparison of Brake Specific Fuel Consumption w.r.t load.

3.4 Nitrides of Oxygen (NOx)

It is observed from figure 5 that NOx emission increases with all configurations (WHE, WHE 6% EGR, WHE12% EGR, HE, HE 6%EGR ,HE 12% EGR) as compared to base diesel. The increase in NOx is due to advancement in injection timing and availability of oxygen content in the fuel. The fixation of NOx generally takes place at higher temperature and advanced injection timings. The use of EGR and optimization of injection timing can be the solution to avoid the fixation of oxides of nitrogen as these methods tends to reduce the temperature of the charge.
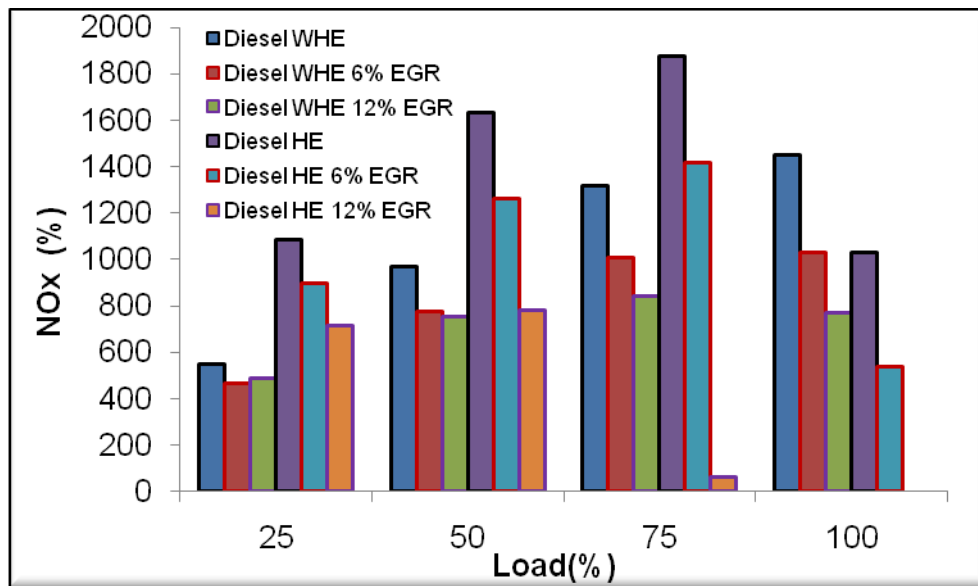
Figure 5. Comparison of NOx w.r.t load

4. Conclusions

The experimentation with use of heat exchanger for heating inlet air passed inside the cylinder does not finds fruitful results with the diesel as fuel. The brake thermal efficiency for base diesel is higher as compared to other configurations. The volumetric efficiency is decreased due to heating of air as density of heated air is decreased at higher loads.

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