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Improving the Performance of CI Engine by Using Turbo-charger with an Inter-cooler

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Abstract—**Medium-speed Diesel engine is one of the most important heat engines in a different fields of the power plants, such as, electric power generation and marine prime movers. In this paper, a medium-speed M.A.N production engine company with a turbocharger and an inter-cooler was selected to be modeled and simulated. FORTRAN language based on internal combustion engine applied thermodynamics is used to study theoretically the effect of the air temperature entering the engine cylinder from the inter-cooler on the volumetric efficiency. The results show that, the effect of air temperature from the inter-cooler to the engine cylinder has a significant impact on the engine performance. From results, the volumetric efficiency has increased by about 98% when operating at low exit air temperature of the inter-cooler with turbocharger system, this increase in the volumetric efficiency resulted in an increase in the indicated power (Pi) of the engine by about 107%. The rate of indicated specific fuel consumption (ISFC) of the engine also has been affected strongly by the air temperature entering the engine cylinder, at low air temperature from the inter-cooler to the engine cylinder, the indicated specific fuel consumption of the engine is decreased by more than 4% per cylinder.**

*Index Terms:***Diesel Engine; Turbo-charger; Inter-Cooler; Volumetric Efficiency.**

I. INTRODUCTION

Medium and slow-speed Diesel engines are among the most important engines used in power plants as well as marine prim-movers. Therefore, improvements in its performance are very important to improve its efficiency, specific fuel consumption reduction and reduce its polluting emmitions to the environment. One of the way to improve the performance of Diesel engines is to use forced air charging (Turbo-charging system) inside the engine cylinder, waste heat recovery from the exhaust gas of Diesel engine is used to drive the turbine of a turbo-charger.This energy recovered from the exhaust is a thermodynamic energy rather than a mechanical energy,this amounts of wasted energy is more than one third of the total energy given to the engine represented in the fuel energy[1], by using this technique a large amoumt of air will charge into the cylinder compared with the natural induction system, this method of process is called the volumetric efficiency of the engine. The gas turbine rotates an air compressor, where the compressor raises air pressure from atmospheric pressure to the required pressure inside the cylinder to improve its performance. By increasing the air charge inside the cylinder gives an opportunity to increase the amount of fuel injected into the cylinder, when the equivalence ratio of the air-to-fuel is kept constant, in this process the pressure and temperature of the combustion gases inside the cylinder will increase significantly, this causes the engine's power to increase significantly to a high level. A lot of researches have been done in this area, in this paper some of these related researches will be addressed.

Advanced combustion techniques for heat engines are intended to improve fuel consumption rate, and reduce the production of environmentally destructive pollutants from heat engines. One of these technique is the use of the super-charging system to charge the air into a cylinder of Diesel engines.

The maximum engine power depends on the amount of fuel being burned, which depends heavily on the amount of air inside the engine cylinder, thus increasing the amount of air is necessary to increase engine capacity[2].

In the last two decades, the performance of Diesel engine has been improved by increasing its power, and reducing its destructive emissions, by adding some accessories to the engine, including inter-cooling technology and air compressor. This will carry on in the future because in coming days there will be increase in the demand of fuel efficient engines with more power and minimum emissions, and this is possible with some advancements in turbo-charging technology[3].

One of the most important problems faced in turbo-charging systems is that air density, the density is decreasing while compressing air. Compressing the air via turbo-chargers creates apressure high and high

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temperature. The pressure creates more horsepower, but the high temperature reduces the density of the charged air. The less dense the air that enters combustion chamber, less power will be generated. Various methods have been developed to cool down charge air, which is heated during turbo-charging process. One of these methods is to use a compact heat exchangers called an inter-coolers to cool charging air. As the air is cooled, it becomes denser, and denser air makes better combustion to produce more power[4].

In this paper, the book titled "Internal Combustion Engine Applied Thermodynamics" by C.R. FERGUSON [6] used for studying the effect of the inter-cooler airtemperature on engine performance in terms of volumetric effiecncy,indicated power, and specific fuel consumption.

II. MATHEMATICAL MODEL OF THE CYLINDER FILLING PROCESS

The filling of the engine cylinder is assessed by the volumetric efficiency (η_V.) It is a quotient of the mass of the charge actually delivered to the cylinder of naturally aspirated or turbo-charged engine by the theoretical mass of the charge that could flow into the cylinder at the thermodynamic parameters prevailing in the intake system. The volumetric efficiency (η_V)is given by (1).

$$\eta_V = \frac{m_a}{m_{th}} \qquad (1)$$

Where:

$m_a$is the mass of the charge actually delivered to the enginecylinder.
$m_{th}$is the theoretical mass of the airwhich could occupy the piston swept volume under the conditions prevailing in the engine intake system.

Volumetric efficiency in a piston combustion engine depends on many factors, which can be classified as those related to the engine design. Design parameters that substantially affect the value of volumetric efficiency.[5]: All those factors are calculated based on the book of "Internal Combustion Engine Applied thermodynamics"[6].

For the calculations, a theoretical FORTRAN language has been developed, the model was built for working space of combustion chamber accordance with the real engine geometry of four-stroke MAN Diesel & Turbo engine [7]. This paper is a continuation of the previous paper, which will study the volumetric efficiency of the same specification of the engine in reference [8]. The theoretical model is used to study the effect of the inter-cooler temperature on the Engine performance in terms of volumetric efficiency,indicated power, and specific fuel consumption.

The governor equations of this model are applied on an open system first law of thermodynamicsfor the combustion chamber, typical calculations for a direct injection (DI) Diesel engine. The pressure inside the cylinder and the temperature as a function of crank angle are calculated by using the same FORTRAN language program simulation developed in reference [8].In the previous study of reference [8], the study was focused on the effect of the initial pressure of air in the cylinder at the beginning of the compression stroke, using a turbocharger, It was a comprehensive study to improve engine performance using a turbocharger system,in terms of mean effective pressure, indicated power, and thermal efficiency. In this paper, the effect of the air temperature from the inter-cooler to the engine cylinder on the volumetric efficiency, and the consequences on the engine performance will study, one of the ways to improve the volumetric efficiency, the inter-cooler is used after the turbocharger and before the engine cylinder. In this study, the mathematical analysis was used with the same equations for the fundamentals of thermodynamics of reference [6] and applied to the same engine specifications as the engine chosen by reference [8]. To illustrate the idea of the results, a common overlap is expected between this paper and previous study in reference[8].

The principle behind the operation of Diesel engine is the compression-ignition cycle(Diesel cycle),downward movement of the piston causes air to be drawn or air forced charged into the engine cylinder, where it is compressed on the upward stroke of the piston. Fuel is injected as the piston approaches the end of the compression stroke, and self ignites spontaneously due to high pressure and high temperature. The increase in pressure generated by the fuel burning provides the power of the engine during the expansion stroke.

If we consider an isentropic compression process from 0 to 1see Figure.1, the temperature increases due to an isentropic compression as in (2).

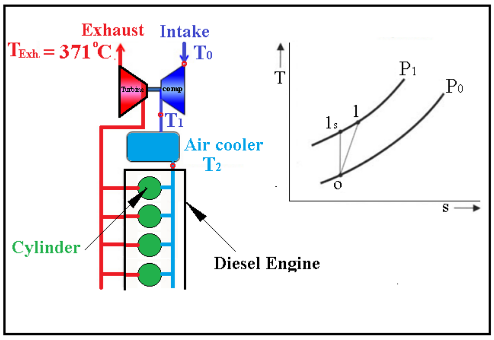

Figure 1. Constant Pressure Turbo-Charging and T-s Diagram of the Air Compressor.

$$\frac{T_{1s}}{T_0} = \left(\frac{P_1}{P_0}\right)^{\frac{k-1}{k}} \qquad (2)$$

Where:

T_0 is the Temperature upline of compressor
T_i is the Temperature downline of compressor
P_0 is the Pressure upline of compressor
P_i is the Charge pressure
k is the Isentropic exponent

The isentropic compression efficiency $\boldsymbol{\eta_{comp}}$ is calculated using (3).

$$\eta_{comp} = \frac{h_{1s}-h_o}{h_1-h_o} \cong \frac{c_p(T_{1s}-T_o)}{c_p(T_1-T_o)} \qquad (3)$$

Where:

h_o is the enthalpy upline of compressor
h_1 is the enthalpy downline of compressor
h_{1s} is the enthalpy downline of compressor, isentropic
c_p is the specific heat at constant pressure

From equation (3), if the isentropic efficiency of the compressor (η_{comp}) is 93%, T_0=300 [K]therefore:$T_{1s} = T_0\left(\frac{P_1}{P_0}\right)^{\frac{k-1}{k}} = 365.7[K]$, the maximum outlet temperature from the air compressor(T_1) at pressure ratio of $\left(\frac{P_1}{P_0}\right) = 2$:

$$T_1 = \frac{(T_{1s} - T_O)}{\eta_{comp}} + T_o = 370\ [K]$$

A Four-cylinder medium speed duty CI. engine have been selected (MAN Diesel & Turbo), and engine specifications are shown in Table 1:

Table 1:Engine Specifications

Engine cycle	4-Stroke
Engine Speed [rpm]	750
Bore [m]	0.225
Stroke [m]	0.3
Over-load rating (MCR) Brake Power [kW/cyl.]	150

The input data for engine are shown in the Table 2.

Table 2.Engineinput Data:

1	Compression Ratio.	r	13.5
2	Bore.	B [m]	0.225
3	Stroke.	S[m]	0.3
4	Half Stroke to Rod Ratio.	EPS	0.168
5	Engine Speed.	RPM [rev/min]	750
6	Equivalence Ratio	∅	0.8
7	Initial Pressure.	Pi [MPa]	0.2
8	Initial Temperature.	Ti [K]	300
9	Wall Temperature.	T_W [K]	650
10	Start of Injection.	θ_S [deg]	-18
11	Crank Advance Angle.	θ_{CA} [deg]	2
12	Fuel.	Diesel Fuel.	###

The results of this code are shown in the next section of results and discussions.

III. RESULTS AND DISCUSSIONS

Modern Diesel engines are always using the turbo-charger system withan inter-cooler to improve the engine performance. In this paper the focus was on the effect of the air temperature inlet to cylinder of four-stroke Diesel engine, where the M.A.N medium speed Diesel engine was selected with speed of 750 rpm. Its specifications are given in Table 1.After obtaining a pressure and temperature relationship as a function of crank angle using the mathematical model development in reference [8]. The air entry temperature using the inter-cooler was changing from the maximum temperature induced by the high pressure of the turbocharger compressor of 370 K at pressure ratio $\left(\frac{P_1}{P_0} = 2\right)$ to a low temperature of 300 K. For marine prime movers Diesel engines the seawater is usually used as a cooling fluid for the charging air system.

Figure. 2 shows the relationship between the crank angle and the pressure inside the cylinder at different air entry temperatures, using an inter-cooler to decrease the temperature of compressed air coming out of the compressor, the maximum temperature of air at a pressure ratio of 2 is 370K, and cooled down using inter-cooler to 300K.Also the pressure inside the cylinder without the turbo-charger is included in Figure. 2 at inlet pressure and temperature of 0.1MPa and 300K respectively.

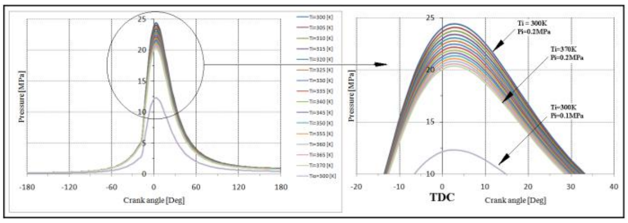

Figure 2. Effect of the Inter-Cooler Temperature (T_i) on the Pressure in the Cylinder (P) Versus Crank Angle (θ).

It is clear from the Figure. 2, that the turbo-chargerwith the inter-cooler has a strong effect on the maximum pressure of gases inside theengine cylinder. The maximum pressure increased from about 12MPa without the turbo-charger to about 24MPa with turbo-charging and in the presence of an inter-cooler, while the maximum pressure of the gases in the cylinder using the turbo-charger in the absence of an inter-cooler was 20MPa. Maximum pressure of gases in the engine cylinder plays a major role in the production of the engine's indicated power.

Figure. 3 illustrates the temperature of the gases inside the engine cylinder as a function of the crank angle at different inlet air temperatures of the inter-cooler. From the results; it is shown that the maximum temperatures inside the cylinder are influenced by the temperature of the air entering the cylinder at the beginning of the compression stroke.

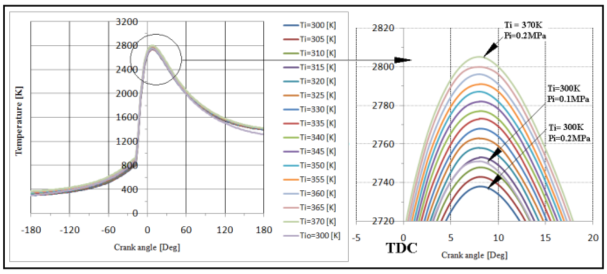

Figure 3. Effect of the Inter-Cooler Temperature (T_i) on the Combustion Temperature in the Cylinder (T) Versus Crank Angle (θ)

The maximum temperature inside the cylinder was at high air entry temperatures, and decreased by low air entry temperature. The maximum temperature is found about 2800K at the air entry temperature of 370Kat the beginning of the compression stroke, and the lowest was about 2740K at the air entry temperature of 300K.

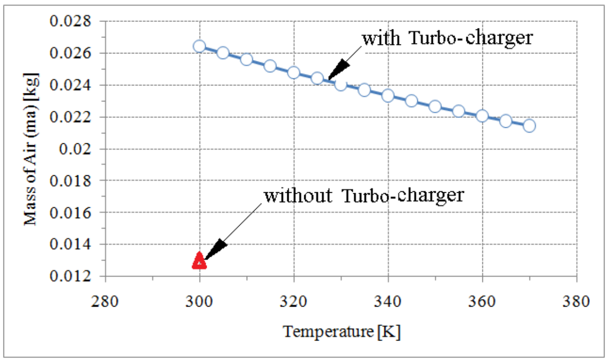

Figure 4. Effect of the Inter-Cooler Temperature (Ti) on the Mass of the Air in Cylinder (m_a).

Figure. 4 presents the relationship between the air temperature of the engine inter-cooler inlet to the engine cylinder and the amount of air entering the cylinder using the turbo-charger at 0.2MPa, as well as the amount of air entering the cylinder without the turbo-charger.

The results in Figure. 4 illustrate that the amount of air increased significantly using the turbo-charger. It increases by more than 100% at the same entry temperature, where the amount of air inside the cylinder without a turbo-charger (T=300K) was 0.013 kg while the amount of air using the turbo-charger at 0.2MPa and the air inter-cooler temperature of 300K was 0.0265 kg of the cycle per cylinder. Using a turbo-charger without an inter-cooler (P=0.2MPa and T=370K) the amount of air entering the cylinder was about 0.02143 kg, this addition in the amount of air gives an opportunity to increase the amount of fuel injected into the cylinder per cycle, if the air to fuel equivalence ratio is kept constant($\emptyset = 0.8$),and that will cause an increasing of the gases pressureinside the engine cylinder, resulting greater indicated power of the engine.

$$\phi = \frac{\left(\frac{A}{F}\right)_s}{\left(\frac{A}{F}\right)_a} = 0.8$$

$$Soichiometric\ Air\ to\ Fuel\ ratio = \left(\frac{A}{F}\right)_s for\ Diesel\ fuel = 14.6\ \frac{kg\ of\ Air}{kg\ of\ Fuel}$$

$$Actual\ \ Air\ to\ Fuel\ ratio = \left(\frac{A}{F}\right)_a for\ Diesel\ fuel = 18.25\ \frac{kg\ of\ Air}{kg\ of\ Fuel}$$

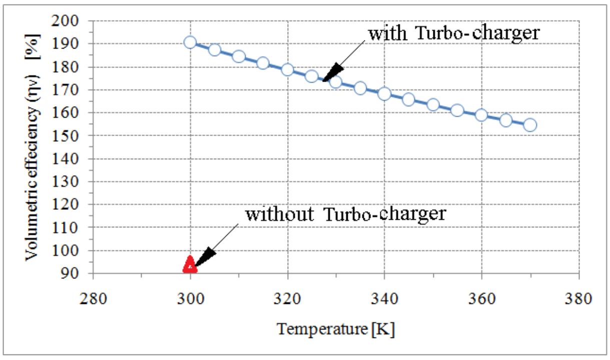

Figure 5. Effect of the Inter-Cooler Temperature (Ti) on the Volumetric Efficiency (η_V)

Figure. 5 shows the effect of the air temperature of the inter-cooler on the volumetric efficiency. To improve the performance of any heat engine comes by improving its volumetric efficiency, which plays a major role in increasing the power of the Diesel engine. Volumetric efficiency means the maximum amount of air is entered for engine cylinders. One of the most important ways to improve the performance of Diesel engines is to improve the volumetric efficiency, using the turbo-charger in the presence of a inter-cooler, where the volume efficiency has increased very strongly. It increased by 98% compared to the non-turbo-charger. Without turbo-charger, the volumetric efficiency was about 93%, but when using a turbo-charger with an inter-cooler (T=300K) it was about 191%, while without an inter-cooler was (T=370K) the volume efficiency was about 154%.

Figure. 6 shows the work done on and by the gas inside the engine cylinder for the strokes of compression and expansion as a function of the crank angle of the engine (-180^o at BTDC, 0^o at TDC, and 180^o at ATDC). At the beginning of the compression stroke the piston begins to move close to the top dead centre (TDC) and moves away from the bottom dead centre (BDC), in this case the work is done on the system with a negative work, when the piston reaches to the TDC the compression stroke at the end and then the piston starts of expanssion stroke, and the piston moves away from the TDC due to the force of combustion pressure, causing a work done by the System, it is a positive work.

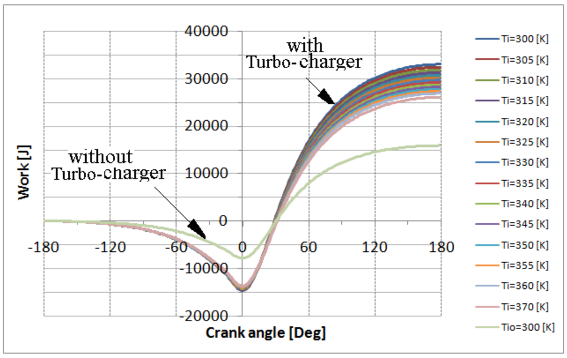

Figure 6. Effect of the Inter-Cooler Temperature (Ti) on the Work Done on and by Gas Inside the CyLinder (W) Versus Crank Angle (θ).

The result in Figure. 6 showsthat, the positive work occupancy is strongly influenced by the use of the turbo-charger with an inter-cooler. It has been noted from the results that, the high positive work occupancy when using the turbo-charger with an inter-cooler compared without the turbo-charger,also the strong effect of inter-cooler air temperature inlet to the cylinder on the work done by the system, the positive work is increased strongly at lower inter-cooler air temperature.

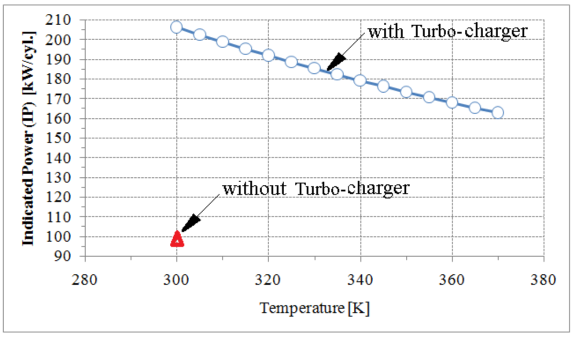

Figure 7. Effect of the Inter-Cooler Temperature (Ti) on the Indicated Power (Pi).

Figure. 7 demonstrates the effect of the air temperature entering the engine cylinder on the indicated power (Pi) of the engine. From the figure, the engine indicated power increases by more than 107% when using the turbo-charger with the inter-cooler without changing it's swept volume of the cylinders. The Pi increased from 99.4[kW/cyl.] Without turbo-charger to about 206.2[kW/cyl.],and with turbo-charger in absent of inter-cooler was about 162.7602[kw/cyl.].

Fiureg. 8 shows the effect of the air temperature of the inter-cooler on the indicated specific fuel consumption (ISFC). One of the very important fundamentals that needs to be taken into account in the metering of the engines is the specific fuel consumption, due to its interest in reducing the fuel consumption and obtaining the highest possible power of the engine, as well as reducing the specific fuel consumption causes a decrease in the pollutants produced by the engine from combustion process.

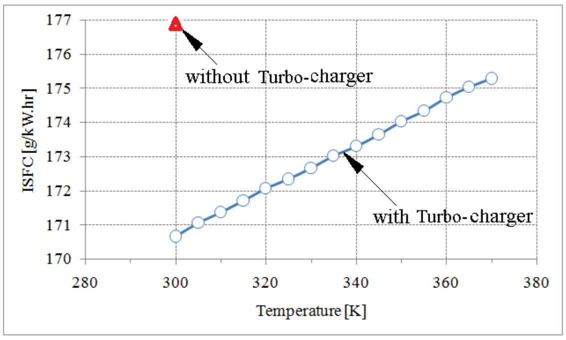

Figure 8. Effect of the Inter-Cooler Temperature (Ti) on the Indicted Specific Fuel Consumption (ISFC)

The resultin Figure.8 illustrates that the indicated specific fuel consumption is strongly influenced by the use of the turbo-charger with an inter-cooler. ISFC decreased by more than 4% per cylinder. ISFC decreased from 177[g/kW.hr] without turbo-charger to about 170[g/kW.hr]by using the turbo-charger with an inter-cooler, and about 175.2886[g/kW hr] without an inter-cooler.

IV. CONCLUSIONS

Based on the previous results of pressure, temperature and mean effective pressure of the gases in the engine cylinder of reference [8], the engine performance analysis was completed by calculating the volumetric efficiency of the engine, under different inlet air temperature conditions using an inter-cooler.

In this paper the purpose of using a forced charger by using turbo-charger is to increase the rate of air mass entering the engine cylinder and also using an inter-cooler to decreases the inlet air temperature, which that increases the air density, and that cause a remarkable increases in volumetric efficiency.

The following conclusions are recorded:

- The increase in indicated power (Pi) is limited by the increase in the amount of air and fuel inside the cylinder by using a turbocharger with an inter-cooler. That's what it's expressed by the volumetric efficiency of the engine, The engine indicated power increases by more than 107% when using the turbo-charger with an inter-cooler
- It has been noted from the results that, the positive work occupancy when using the turbo-charger with inter-cooler is too large compared with without the turbo-charger.
- The results, shows that the indicated specific fuel consumption is strongly influenced by the use of the turbo-charger with inter-cooling, where “ISFC” decreased by more than 4% per cylinder.Reducing of the specific fuel consumption causes a decrease in the pollutants produced by the engine from combustion process.

REFERENCES

[1] J. S. Jadhao, D. G. Thombare, “*Review on Exhaust Gas Heat Recovery for I.C. Engine*” International Journal of Engineering and Innovative Technology (IJEIT) Volume 2, Issue 12, June 2013.

[2] N.D. Patil., N.V. Hargude.and N.S. Mane, “*Turbo-charging of IC engines to save fuel consumption*”, International Engineering Research Journal (IERJ), Special Issue Page 151-154, ISSN 2395-1621,2015.

[3] D. W. Tathe and N.S. Bhalkikar, “*Effects of Turbo-charging on Performance of I.C Engine: a Review*” International Journal of Innovation in Engineering, Research and Technology [IJIERT] ICITDCEME’15 Conference Proceedings ISSN No - 2394-3696, Novateur Publication’s.

[4] E.Canli, S.Darici and M.Ozgoren, *“Inter-cooler Effect on Conventional Super-charging Systems*” International Scientific Conference, 19-20 November 2010, Gabrovo.2010.

[5] A. Ambrozik, D. Kurczyński, and P. Łagowski, "*Method for Determining Volumetric Efficiency and Its Experimental Validation" Transport and Aerospace Engineering* , vol. 5, pp. 5–17.2017.

[6] C.R.Ferguson, "*Internal Combustion Engine Applied Thermodynamics*" first edition John Wiley 1986& Sons Ltd,.

[7] MAN Diesel & Turbo, "*Project Guide – Marin for Four-stroke Gen-Set compliant with IMO Tier II"* Complete manual, 2014.

[8] M. S Oun, S. A. Farhat, M. A. lrabeei. “*The Effect of Turbocharger Pressure and Inter-cooler Temperature on Engine Performance*” Journal of Engineering Research (University of Tripoli, Libya), Issue (23), March 2017.