Experimental and Theoretical Study of Heat Liberation of Reciprocating Air Compressor

Haqi Ismael Qatta
Electromechanical Engineering Department, University Technology /Baghdad
Email:uot_magaz@yahoo.com

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ABSTRACT

In this paper an approach is presented to estimate the temperature , heat transfer rate and heat liberation of a reciprocating air compressor . The experimental work was performed by using double cylinder compressor working by three stages to reach the final pressure. In the experimental work, recording the final pressure for three stages ,and recording the temperature at suction valve, delivery valve and the cylinder wall . In the theoretical part a computer program used to solve model of single zone and depending on step by step , and calculating the amount of heat liberation by analysis pressure diagram ,the program depend upon the first law of thermodynamic and gases .

The result that shown the maximum temperature inside compression space from TDC , also the rate of heat liberation increased with increase of compressor speed.

دراسة عملية و نظرية للحرارة المتحررة من ضاغطة الهواء الترددية

الخلاصة

يتضمن البحث الحالي حساب درجة الحرارة, معدل انتقال الحرارة, كمية الحرارة المتحررة لضاغطة الهواء الترددية, نفذ تجريبا باستخدام ضاغطة هواء ذو اسطوانتين وتعمل بثلاث مراحل للوصول الى الضغط النهائي. و فى الجانب العملى تم تسجيل الضغوط النهائية لكافة مراحل الضاغطة ودرجات الحرارة عند صمام السحب والتصريف وجدران الاسطوانة اما في الجانب النظري تم بناء برنامج حسابي يستخدم نموذج المنطقة المنفردة ويعتمد اسلوب الخطوة اثر خطوة وفي استنتاجه لكمية الحرارة المتحررة وذلك خلال تحليل منحنى الضغط مع درجات عمود المرفق, ويعتمد البرنامج على القانون الاول لديناميك الحرارة والمعادلة العامة للغازات.

أوضحت النتائج بان اعلى درجة الحرارة تصل عند نقطة الميتة العليا وكذ لك معدل الحرارة المتحررة يزداد بزيادة سرعة الضاغطة.

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2412-0758/University of Technology-Iraq, Baghdad, Iraq

Nomenclature

D- Cylinder bore (mm)
L- Length of connecting rod (mm)
m- Mass (Kg)
N- Speed (rpm)
P_1- Inlet pressure (bar)
P_2- First stage pressure (bar)
P_3- Second stage pressure (bar)
P_4- Third stage pressure (bar)
P_5- Instantaneous pressure (bar)
P_6-pressure of compression space (bar)
q- Heat transfer (J)
dq- Heat Liberation (J)
R- Radius of crank (mm)
R- Gas constant (KJ/Kg.K)
S- Stroke (mm)
T_1- Instantaneous temperature (°C)
T_a-Stag temperature °C
Tc- Average temperature of the cylinder
T_L - Average temperature of the cylinder wall °C
V- Volume of compression m^3
V_s - Stroke volume m^3
V_C - Stroke volume m^3
V_i - Clearance volume m^3
V_4-Work done (J)
Z-Energy w

Greek
O –Crank angle (deg)
P –Density Kg/m^3
U –Viscosity (Kg/m.s)

Subscript
IC – internal combustion
TDC – Top dead center
BDC – Bottom d.ead center.

INTRODUCTION

The reciprocating air compressor is a machine to compress air, gas or vapor , a machine which takes air (or gas) in during suction stroke at low pressure then compresses it to high pressure in a piston cylinder arrangement is known as reciprocating compressor . The heat transfer between working of compressed air and internal surface of compression space is predominantly by forced convection and conduction heat transfer due to the movement of piston during compression stroke .The compressed air has wide application in industry as well as in commercial equipments .It is commonly used in shops for driving pneumatic tools , air operated controlling equipment .Compressor many be classified by the principle of operation under three main , positive displacement compressors ,dynamic -type and jet type .[1 , 2]. The heat transfer from the compression space to the cylinder wall in reciprocating air compressor is very importance because of its effect on compressor thermodynamic performance . It is useful to show some previous studies related to the present research .

Feingold .Used the first thermodynamic law to analysis pressure- time diagram of diesel engine and enter the effect of gases properties changes with temperature.[3] Woschni. Studied change of gases state and different looses for heat release inside cylinder as well heat transfer through cycle.[4] Zinner. Studied the rate of heat release from pressure curve with degree of the crank angle to prechamber engine size.[5]

In this work an approach is presented to estimate the temperature ,heat transfer rate and heat liberation of a reciprocating air compressor.

EXPERIMENTAL WORK

The experimental work is performed in the university of technology - Baghdad , the compressor type which used in the experimental work is a double cylinder in double acting reciprocating compressor the suction , compression and delivery of the air take place on both sides of the piston compressor working with three stage to generated the final pressure (150 bar). The data of experimental work were recorded mainly in two groups of examination.

1-First test was achieved at speed and constant load .

2. Second test was achieved at variable load and constant speed .

The variable speed tests were achieved by changing the speed of the compressor between (700- 800 – 900) rpm with constant load (50 N) . The constant speed tests were performed for chosen speed (700) rpm and the load was changed through the dynamometer control unit .The technical data of the compressor used in this work as shown in table (1) .

The following parameters were measured during each test .

1-The compressor speed in (rpm) by using electric tachometer .

2-The load on the compressor was measured from the dynamometer scale.

3-The air temperature by using a calibrated thermometer and thermocouple.

4-The final pressure from delivery value of three stages is measured by pressure gauge (150),the structure of the air compressor test as shown in Figure (1)

THEORETICAL ANALYSIS

In this work the heat liberation rate was calculated by using engine pressure data with an apparent heat liberation model .The model depends on the analysis of the pressure curve with crank angle .The calculations were made taking into consideration the following assumptions .[6,7,13] .

1-The gas is ideal ($pv = mRT$) .

2- The initial temperature is (25℃).

Stroke [6, 13]

$$S = R\cos q + \sqrt{L^2 - R^2 \sin^2 q} \qquad \text{……. (1)}$$

Volume of the compression space [7]

$$V = V_C + \left(\frac{pD^2}{4}\right)\left[L + \left(\frac{S}{2}\right)(1 - COSq) - \left(L^2 - \left(\frac{S^2}{4}\right)\right)(1 - COS^2 q)\right]^{\frac{1}{2}}. \qquad \text{…… (2)}$$

Pressure of the compression space [6]

$$P_{i+1} = P_i\left(\frac{V_i}{V_{i+1}}\right)^n \qquad \text{…….. (3)}$$

Temperature of the compression space [6]

$$T_{i+1} = T_i\left(\frac{P_{i+1}}{P_i}\right)^{\frac{n-1}{n}} \qquad \text{…….(4)}$$

Work

The work done of air delivered for three stages compression with external cooling by the air can be calculated using the following relation. [1]

$$W = 3.\frac{n}{n-1} m\bar{R}T_1\left[\left(\frac{P_4}{P_1}\right)^{\frac{n-1}{3n}} - 1\right] \qquad \text{…… (5)}$$

$$m = \frac{PV}{\bar{R}T} \qquad \text{…… (6)}$$

Energy

The energy (Z) expended during the compressor cycle in compressing and expelling one Kilogram of gas for first stage evaluated by the expression.[2]

$$Z_1 = \frac{n}{n-1} P_1 V_1\left[\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} - 1\right].N \qquad \text{………… (7)}$$

For 2nd stage

$$Z_2 = \frac{n}{n-1} P_1 V_1\left[\left(\frac{P_3}{P_2}\right)^{\frac{n-1}{n}} - 1\right].N \qquad \text{……… (8)}$$

For 3rd stage :

$$Z_3 = \frac{n}{n-1} P_1 V_1 \left[\left(\frac{P_4}{P_3} \right)^{\frac{n-1}{n}} - 1 \right] . N \quad \text{........ (9)}$$

HEAT TRANSFER

To calculate the heat transfer rate per unit area (q/A) between the compression space and the cylinder walls using the following relation, which include convention and radiation heat transfer will be used. [8, 11]

$q / A = Q_{con} + Q_{rad}$

$$(q / A) = a(K / D)(\text{Re})^b (T_C - T_L) + C(T_C^4 - T_L^4) \quad \text{....... (10)}$$

The parameter $(a = 0.26; b = 0.75; C = 3.88 * 10^{-11})$ are constants.
Reynolds number is given by:

$$\text{Re} = \frac{dV_p r}{m}$$

$$d = 46mm$$

$$r = 1.293..Kg / m^3 \quad \text{...... (11)}$$

The piston velocity is calculated using the expression:

$$V_P = \frac{2 * S * N}{60} \quad \text{.... (12)}$$

The viscosity of the compression space is calculated as:

$$m = m_0 (a) * T^d .$$

$$m_0 = 4.83 * 10^{-7} .....(Kg / m^2 .s) \quad \text{.... (13)}$$

The thermal conductivity (K) is evaluated by the expression:

$$K = (Cpxm / P_r) \quad \text{... (14)}$$

The parameter of the prandtl number is equal to (0.7)

Heat liberation

Using the first law of thermodynamics, heat liberation can be calculated with constant specific heat [9,10].

$(g = 1.35)$.

$$dq = \frac{g}{g-1}\left(\frac{P_3+P_2}{2}\right)(V_3-V_2)+\frac{1}{g-1}\left(\frac{V_3+V_2}{2}\right)(P_3-P_2)$$

…. (15)

For the first cylinder

$$dq = \frac{g}{g-1}\left(\frac{P_4+P_3}{2}\right)(V_4-V_3)+\frac{1}{g-1}\left(\frac{V_4+V_3}{2}\right)(P_4-P_3)$$

…… (16)

For the second cylinder

Volumetric Efficiency [4, 12]

$$h_r = \frac{\text{Volume of air pumped / cycle}}{\text{Stroke volume of cylinder}}$$

$$h_r = \frac{\text{Mass of air delivered / cycle}}{\text{Mass of air to fill stroke volume}}$$

$$h_r = 1-\frac{V_C}{V_S}\left[\left(\frac{P_4}{P_1}\right)^{\overline{n}}-1\right]$$

……. (17)

DISCUSSION OF RESULTS

The use of theoretical styles in evaluation of required information have many advantages by comparing with direct measuring method. Where this method have explicitly in calculation of required information by experimental factors concluded from laboratory experiments, by calculate these factor, these styles be ready to use where by these we obtain the required information easily with ability enter various changes of measure conditions in calculation ,where the direct measurement method deem complicated somewhat to measure all changes in addition to repeat measurement and obtain the required by changing conditions as changing the ambient pressure. The calculation program use the first thermodynamic low directly to evaluate heat rate and temperature rate, heat transfer through cylinder walls by Ann-ad equation.

COMPUTERS PROGRAM

The theoretical results are predicted from computers program.The following assumption are considered during calculation:

1. Variable speed (rpm) with constant load.
2. Variable load with constant speed.

PRESSURE CURVES WITH CRANK ANGLE DEGREES

Figures (2 to 7) indicate the pressure curve with the degree of the crank angle which resulting from laboratories experiments at the internal combustion engine by using reciprocating air compressor V-AK150 .Figures (2,3 and 4) represents the pressure curves with the degree of the crank angle to the variable speed with constant load and figures (5,6 and7) pressure curves with degrees of the crank angle to the variable load with constant speed, so the curves in the figures (2 to 7) are used to conclude the magnitude heat liberation , mean gas temperature and heat transfer with the degree of crank angle by computer program.

EFFECTIVE OF AIR COMPRESSOR SPEED (RPM)

1 .Temperature

The figures (8,9 and 10) of temperature degree shown increasing in temperature during compression strok ,the different start of temperature caused by different delay periods when increasing air compressor speed. Where the angle maximum temperature far from T.D. C region. Where the maximum temperature degree increase by increasing speed of air compressor and this caused by increasing amount of gas in compression atroke, as result of pressure raise and temperature degree. The temperature degree comparable in end of calculation with respect to temperature exhaust measured in exhaust pipe. It seem that coming with some sequence with observation of measured temperature degree from exhaust pipe less that calculated temperature in end angle of calculation which due to the heating losses and extension of gases.

2 .Heat liberation

When increasing air compressor speed this cause increasing of heat liberation as shown in Figures (11,12) . The proportional is due amount of gas compression in the stroke and this amount of heat is more than heat losses and heat friction.

3. Heat transfer

When increasing air compressor speed and constant load . This cause increasing heat transfer through cylinder walls as for two cylinder as shown in Figure (13,14) and this increasing as result of gas compression and temperature degree.

EFFECTIVE LOAD

1. Temperature

The maximum temperature increases as load increase. This is due to increase in amount of gas that compressed which result in high pressure and temperature as shown in Figures (15,16 and 17). The temperature degree comparable in end of calculation with respect to temperature exhaust measured in exhaust pipe. It seems that coming with same sequence with observation of measured temperature degree from exhaust pipe less than calculated temperature in the end angle of calculation which due to the heating losses and extension of gases.

2. Heat liberation

The maximum rate of heat liberation occur by increasing load where it reach to maximum level when load being (70 N) as shown in fig (18,19), and the maximum rate of heat liberation caused by increasing amount of gas compression andincreasing temperature degree through compression.

3. Heat transfer

When increasing load and constant speed, this cause increasing heat transfer through cylinder walls as shown in Figure (20,21) and this increasing as aresult of gas compression and temperature degree. Figures (22,23 and 24) shown the effect of air compressor speed on the energy for three stages , fig (25) shown the different between the theoretical and actual energy.

CONCLUSIONS

1- The maximum temperature inside compression space at (TDC).
2- The rate of heat liberation increases by increasing of the compressor speed.
3- The volumetric efficiency decreases when the clearance volume increases.
4- The volumetric efficiency decreases when the pressure ratio increases.
5- The results obtained has a good agreement with other literature.

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Table (1). Technical data of the compressor.

Open cylinder	dimension	Closed cylinder	dimension
Radius of piston	23 mm	Radius of piston	17 mm
Radius of crank	18 mm	Radius of crank	18 mm
Bore cylinder	46 mm	Bore cylinder	35 mm
Cylinder length	131 mm	Cylinder length	109 mm

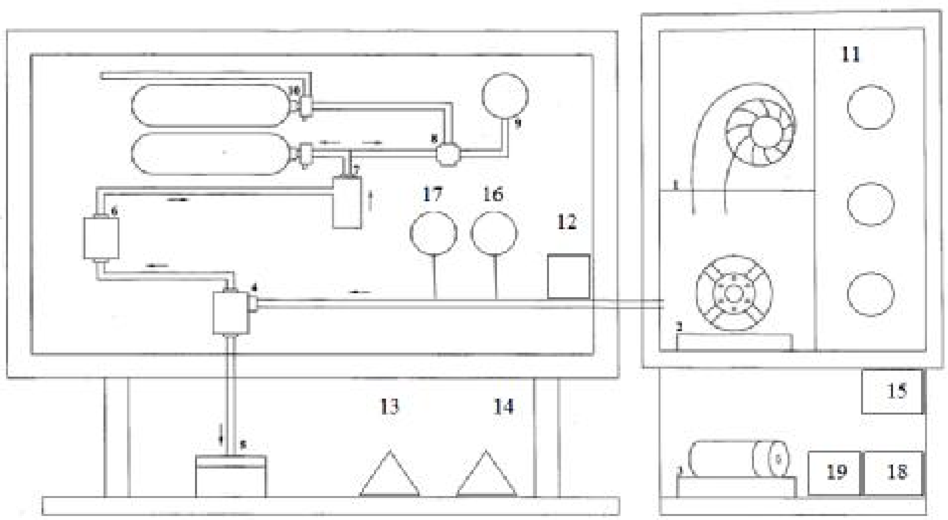

Figure (1). Structure of the air compressor test.

1.Cooling fan
2.Installation base.
3.Electrical motor.
4.Humidity and oil insulation .
5. Oil container
6. Pressure valve .
7.Humidity and oil insulation.
8. To reduce valve.
9. Pressure gauge.
10. Compression air cylinder .
11. Electrical control unit .
12. control valve .
13. Tachometer .
14. Electrical dynamometer .
15. Rota meter
16 .Oil temperature gauge.
17. Oil pressure gauge.
18. Spring balance.
19. Resistance loading unit.

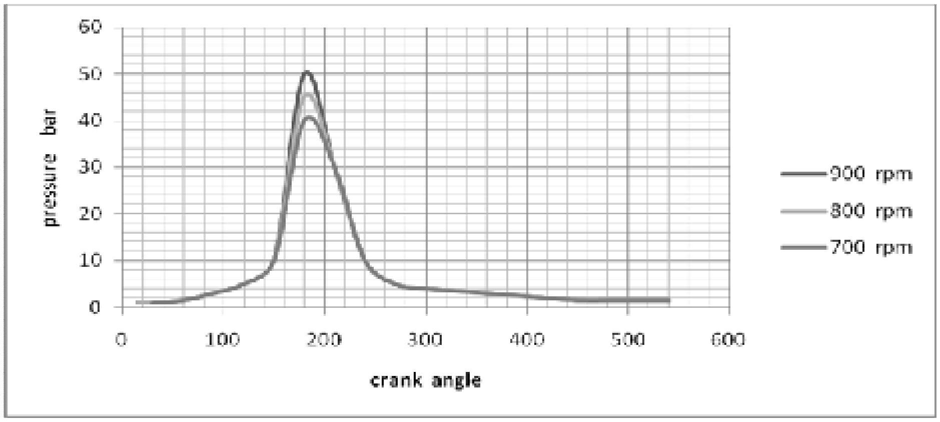

Figure (2). Pressure indicator diagram as a function of crank angle for different compressor speed with load (50N) for first stage.

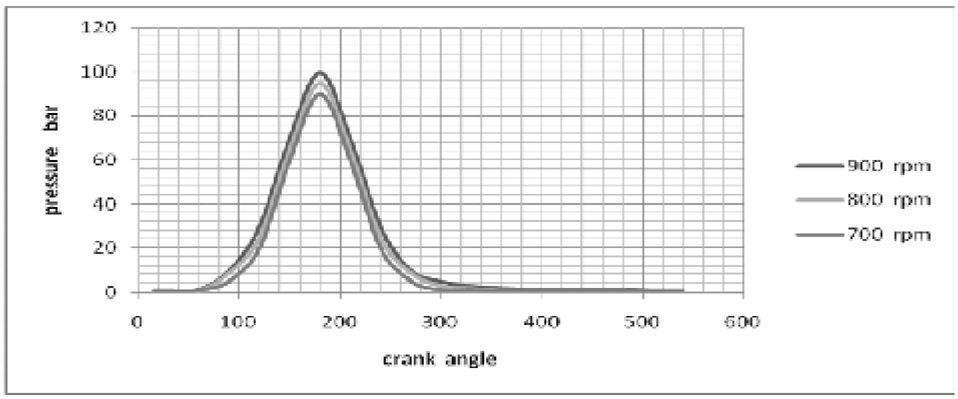

Figure (3). Pressure indicator diagram as a function of crank angle for different compressor speed with load (50N) for second stage.

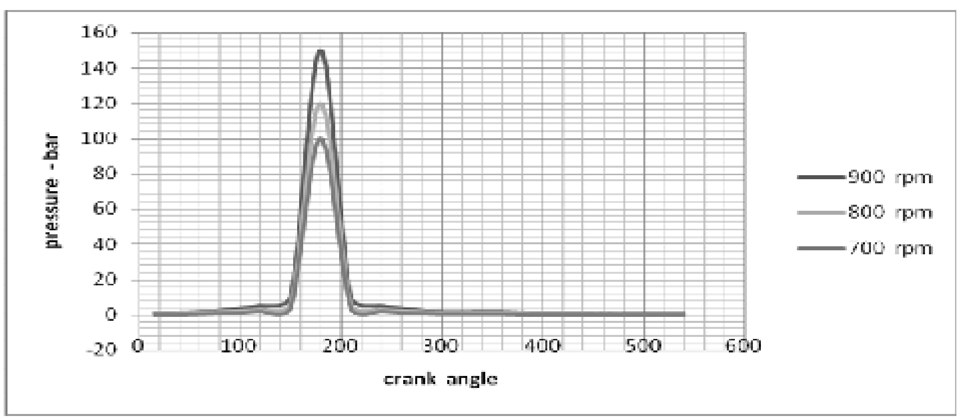

Figure (4) .Pressure indicator diagram as a function of crank angle for different compressor speed with load (50N) for third stage .

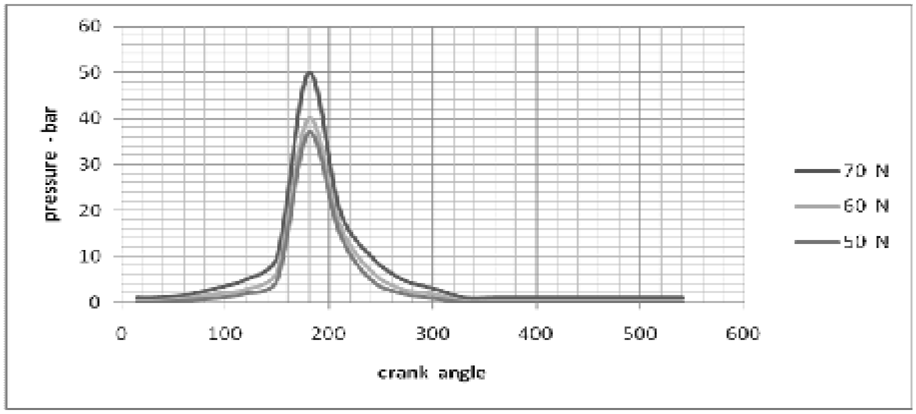

Figure (5). Pressure indicator diagram as a function of crank angle for different load with compressor speed (700 rpm) for first stage.

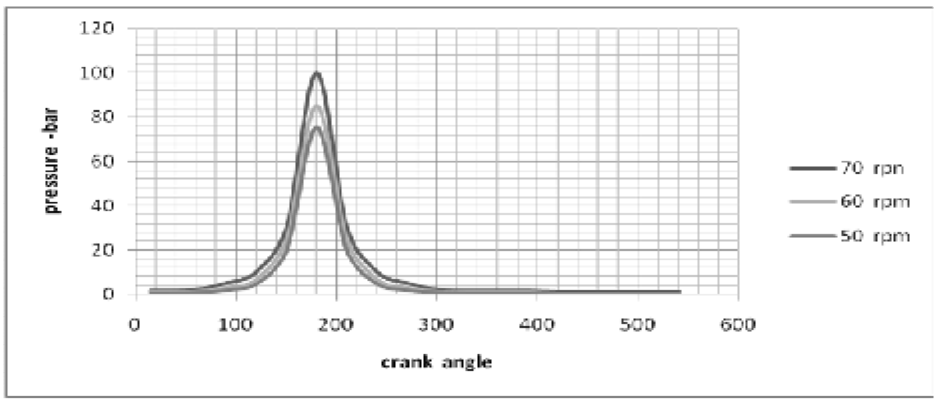

Figure (6). Pressure indicator diagram as a function of crank angle for different load with compressor speed (700 rpm) for second stage.

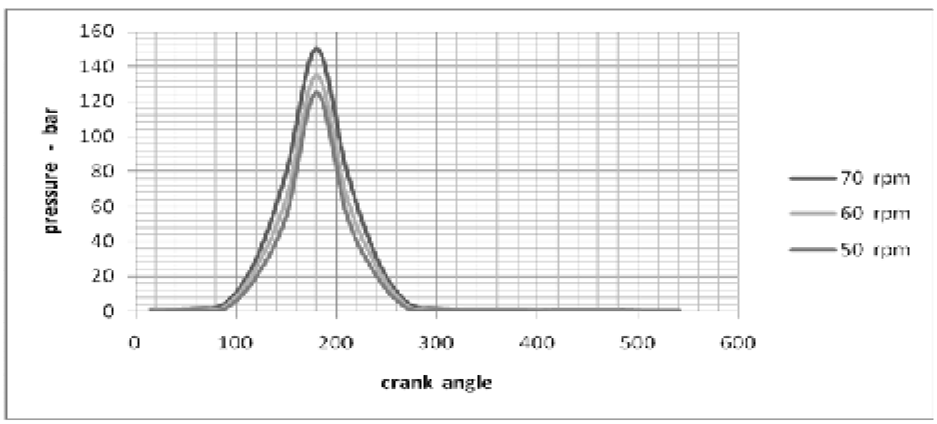

Figure (7). Pressure indicator diagram as a function of crank angle for different load with compressor speed (700 rpm) for third stage.

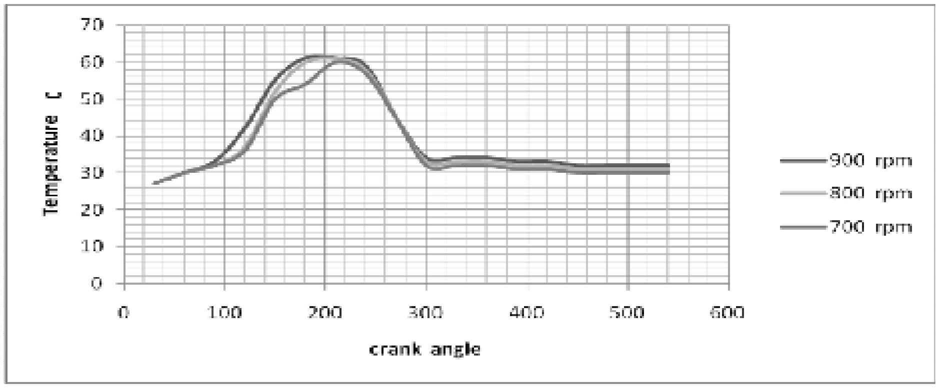

Figure (8) .Effect of compressor speed on the temperature of gas inside the cylinder as a function of crank angle with load (50N) for first stage.

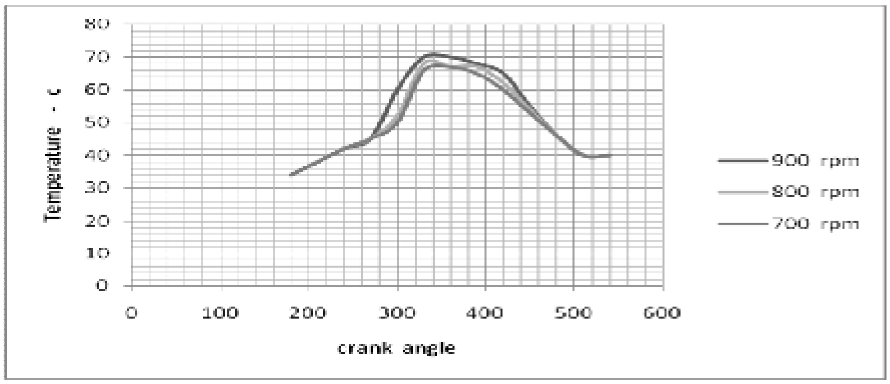

Figure (9) . Effect of compressor speed on the temperature of gas inside the cylinder as a function of crank angle with load (50N) for second stage.

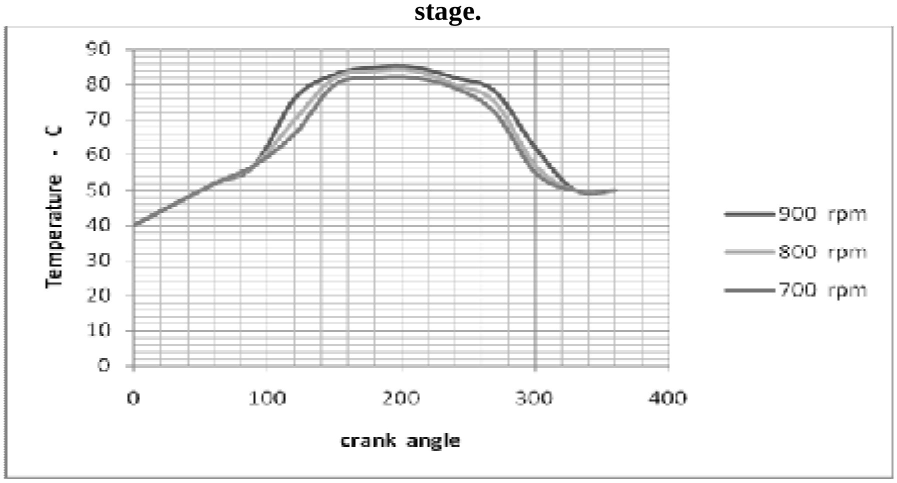

Figure (10). Effect of compressor speed on the temperature of gas inside the cylinder as a function of crank angle with load (50N) for third stage.

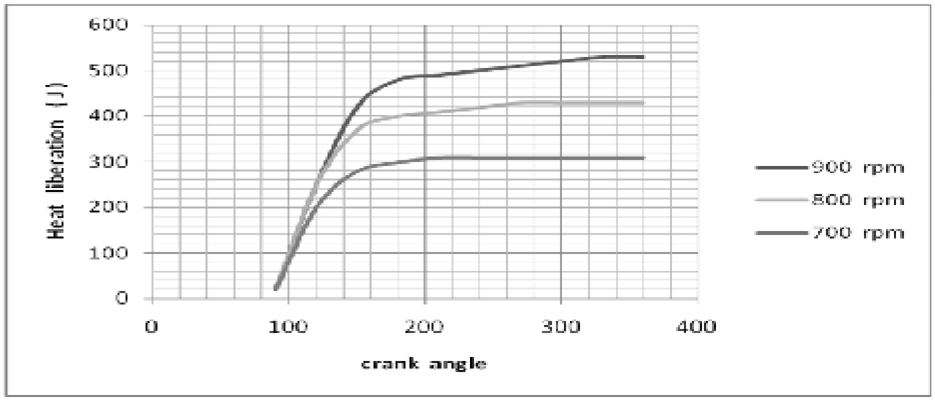

Figure (11). Heat liberation as a function of crank angle for different compressor speed with constant load (50N) for first cylinder.

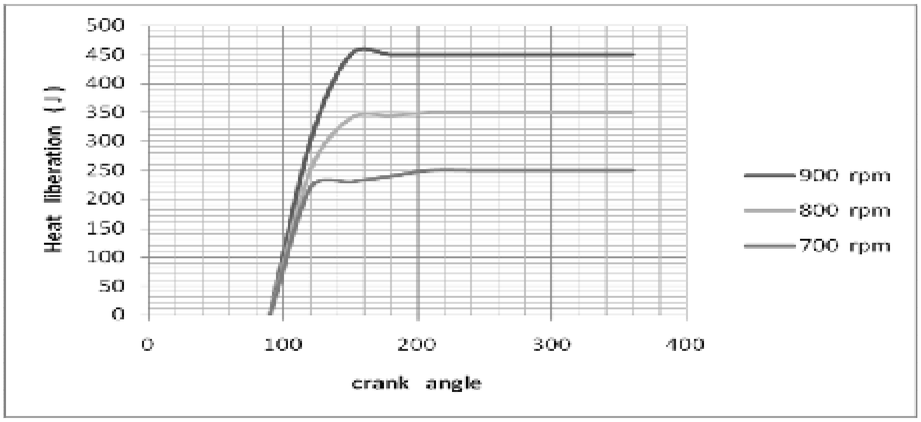

Figure (12). Heat liberation as a function of crank angle for different compressor speed with constant load (50 N) for second cylinder.

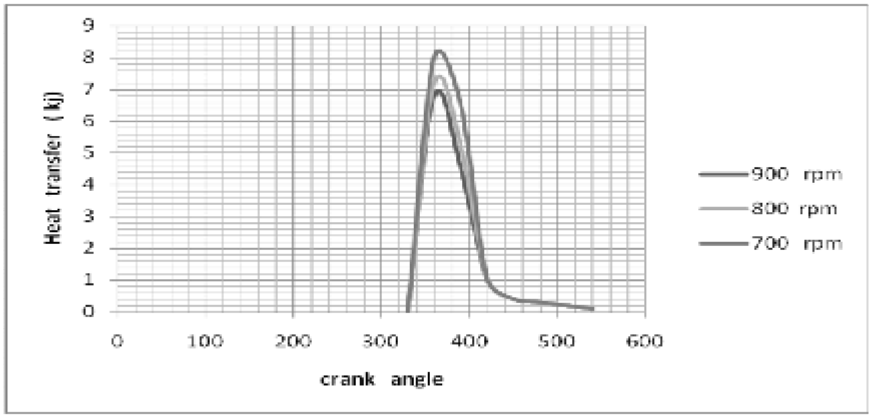

Figure (13). Heat transfer an function of crank angle for different compressor speed with constant load (50N) for first cylinder.

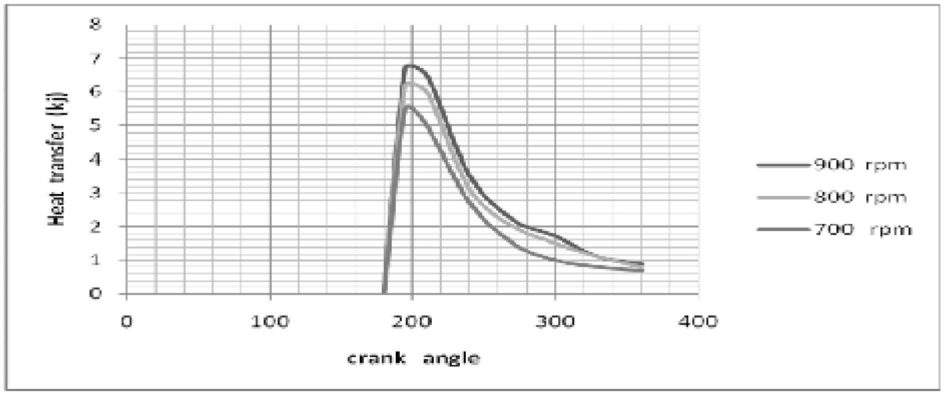

Figure (14). Heat transfer an function of crank angle for different compressor speed with constant load (50N) for second cylinder.

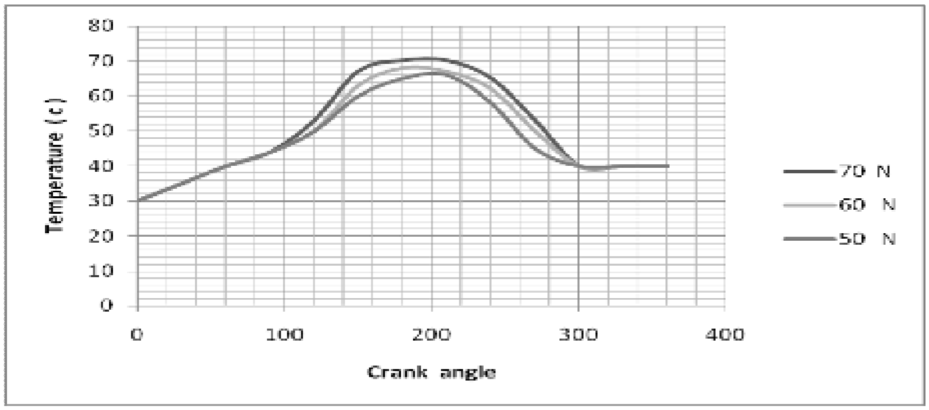

Figure (15) .Effect of load on the temperature of gas inside the cylinder as a function of crank angle with compressor speed (700 rpm) for the first stage.

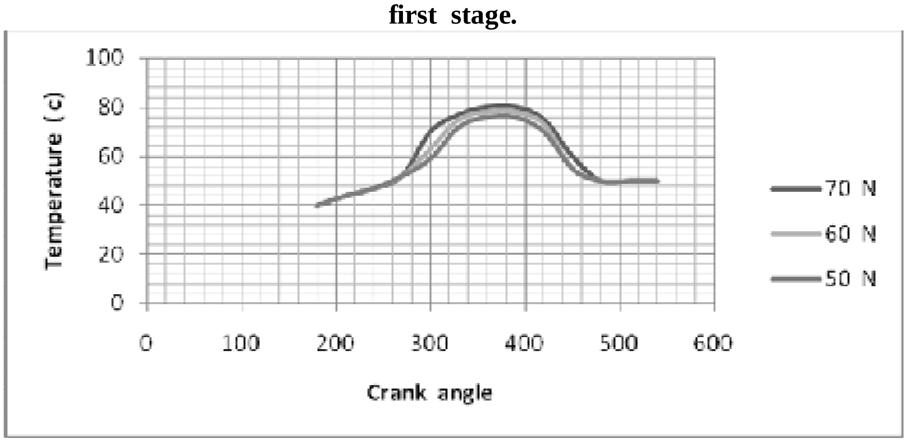

Figure (16). Effect of load on the temperature of gas inside the cylinder as a function of crank angle with compressor speed (700 rpm) for second stage.

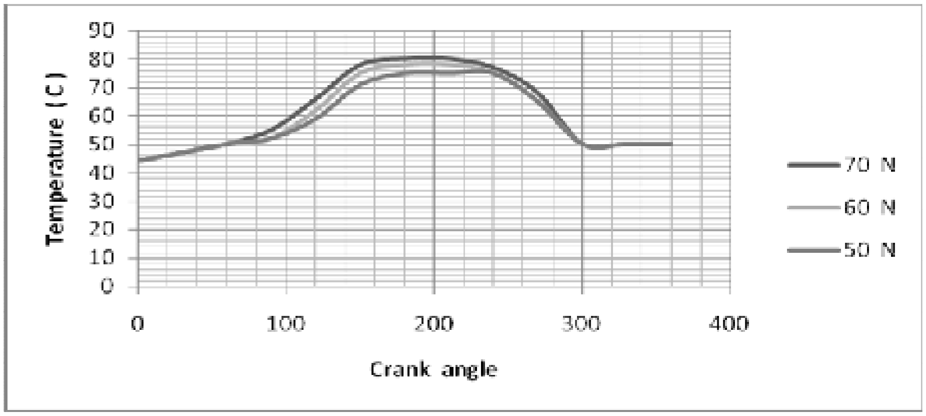

Figure (17) .Effect of load on the temperature of gas inside the cylinder as a function of crank angle with compressor speed (700 rpm) for the third stage.

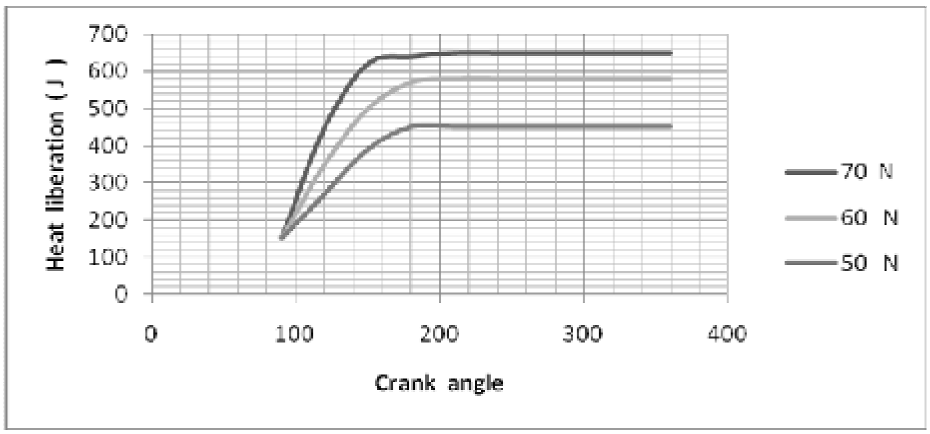

Figure (18) .Heat liberation as a function of crank angle for different load with compressor speed (700 rpm) for first cylinder.

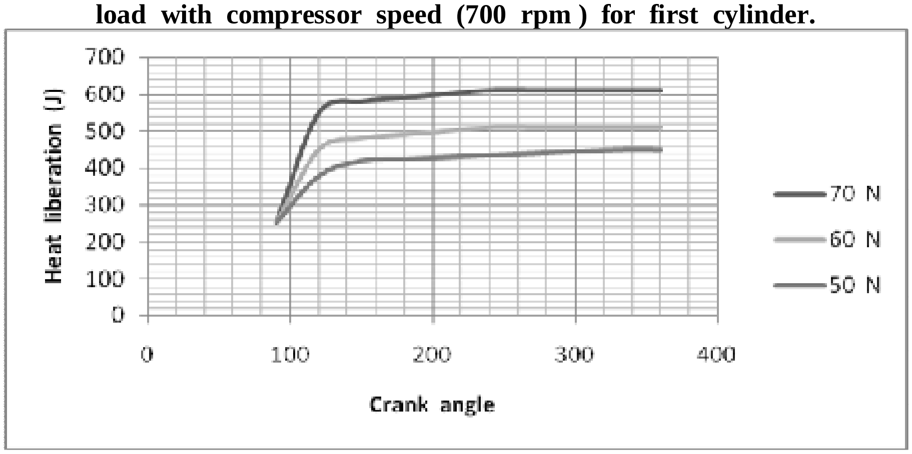

Figure (19) .Heat liberation as a function of crank angle for different load with compressor speed (700 rpm) for second cylinder.

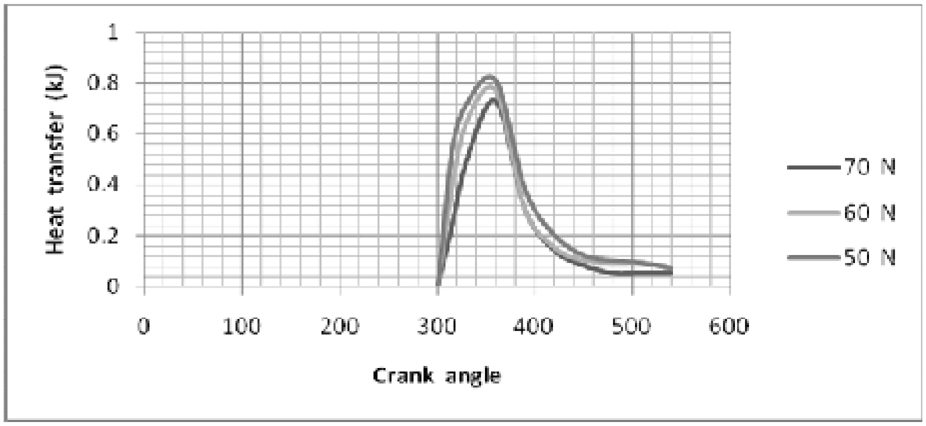

Figure (20) .Heat transfer as a function of crank angle for different compressor load with constantbspeed (700 rpm) for first cylinder .

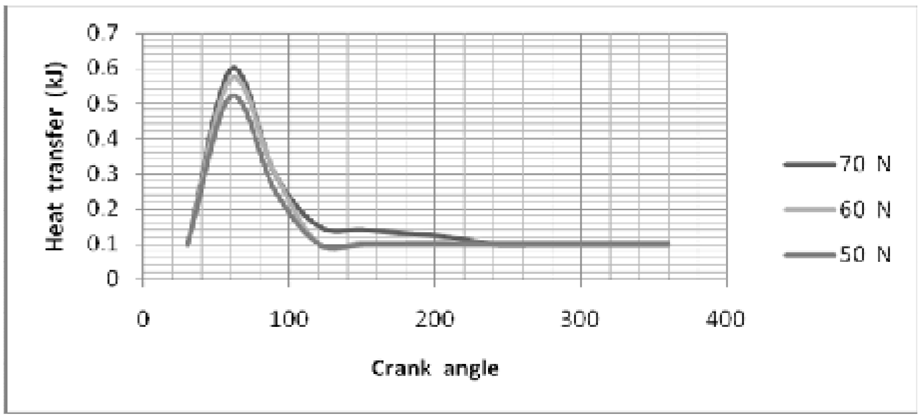

Figure (21) .Heat transfer as a function of crank angle for different compressor load with constant speed (700 rpm) for second cylinder.

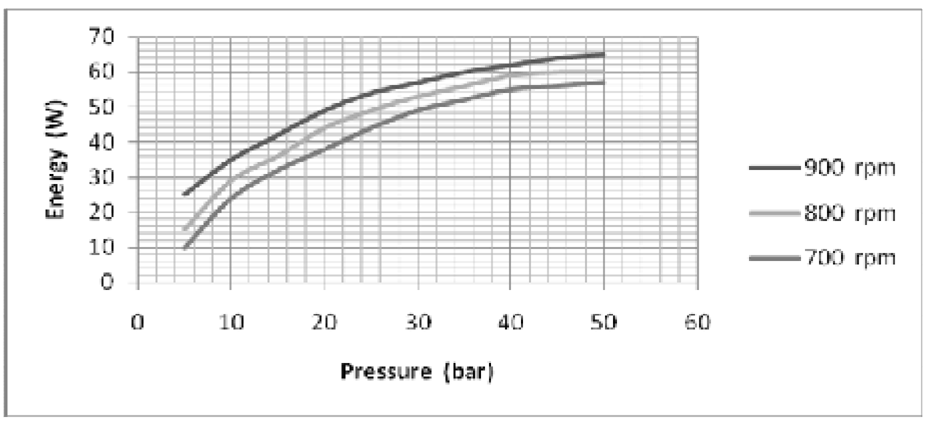

Figure (22). Theoretical energy as a function of pressure first stage with different compressor speed.

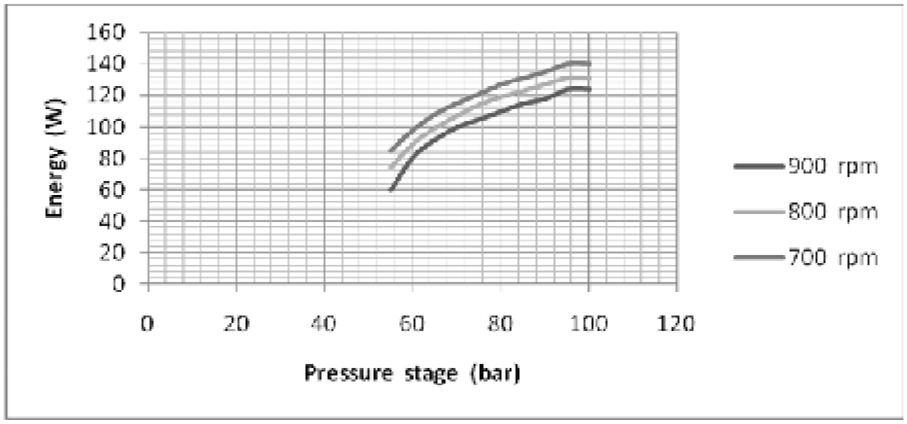

Figure (23) . Theoretical energy as a function of pressure second with different compressor speed.

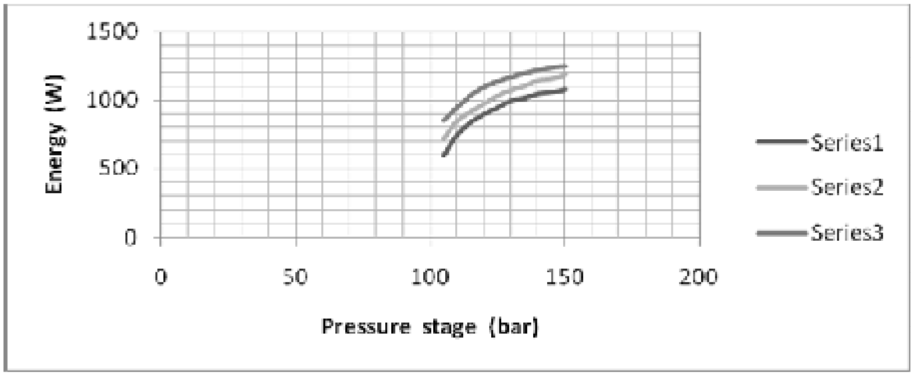

Figure (24). Theoretical energy as a function of pressure third stage with different compressor speed.

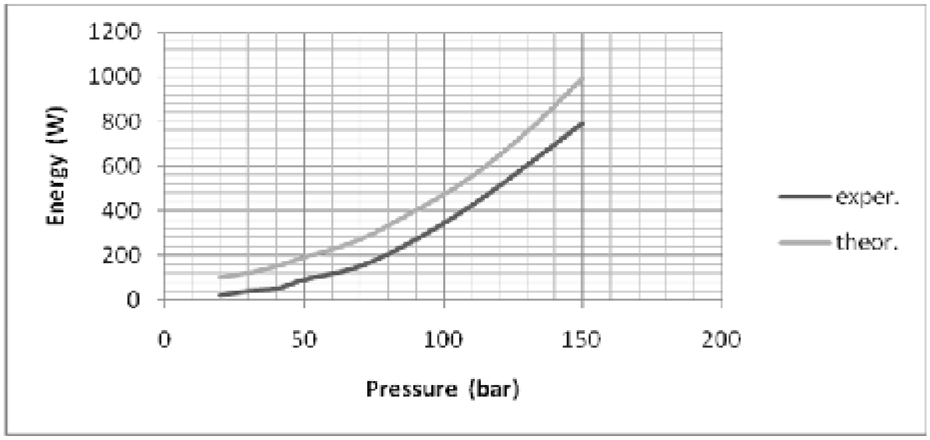

Figure (25). Experimental and theoretical energy as a function of pressure stage.