Thermal Effects on Diesel Engine Piston and Piston Compression Rings

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Abstract

This paper introduces an analytical study on the thermal effects on the diesel engine piston and its compresion rings during the contact between the piston and its compression rings .A three dimensional finite element model is built for the piston and its compression rings using the ANSYS v. 8 Finite Element Analysis Code that serves all engineering problems . The thermal analysis is made using contact case between the piston and its compression rings .The work in this paper did not include a convergence study.

The study includes the effects on the piston and piston compression rings of the thermal conductivity of piston material , and the contact area .The conclusions of this study are that the material type of high thermal conductivity is considered better than the material type of low thermal conductivity. This means that the aluminum alloy is considered better than the cast-iron alloy, and tapering the compression rings from the inner side by 1 mm , leads to a reduction in the temperature values by 1.6% , 0.84% and 0.37% compared to rectangle compression rings.

Keywords: Heat Transfer ; Solid Mechanics ; Finite Element Method.

التأثيرات الحرارية على مكبس و حلقات الضغط لمكبس محرك الديزل

الخلاصة

يقدم هذا البحث دراسة تحليلية عن التأثيرات الحرارية على مكبس و حلقاته الضغطية لمحرك الديزل نوع ريكاردو خلال حالة التلامس بين المكبس و حلقات الضغط . حيث تم بناء نموذج من العناصر المحددة ثلاثي الابعاد للمكبس و حلقات الضغط بإستخدام برنامج تحليل المسائل الهندسية بطريقة العناصر المحددة ال(ANSYS) ، التحليل الحراري نُفذ بإستخدام حالة التلامس (Contact) بين المكبس و حلقاته الضغطية ، العمل في هذا البحث لم يتضمن دراسة تقريبية .

أحتوت الدراسة التأثيرات على المكبس و حلقات الضغط للمكبس من ناحية التوصيلية الحرارية لمعدن المكبس ، و تأثير مساحة التلامس . أكدت الاستنتاجات في هذا البحث بأنه نوع المادة ذات التوصيلية الحرارية العالية تعتبر افضل من المادة اللازمة في تصنيع المكبس ذات التوصيلية الحرارية الواطئة ، هذا يعني معدن سبيكة الالمنيوم افضل من سبيكة حديد الزهر ، كذلك تتبير حلقات الضغط من الجانب الداخلي عند الزاوية العليا بمقدار 1مم يؤدي إلى إنخفاض في درجات الحرارة المكتسبة من المكبس خلال حالة التلامس و بنسبة 1.6 % ، 0.84 % و 0.37% مقارنة بحلقات الضغط الاعتيادية .

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Introduction

Among engine components exposed to thermal effects, the piston is considered to be one of the most severely stressed, where a high amount of the heat transferred to a coolant fluid goes through it, this amount depends on the thermal conductivity of the materials employed, the average speed and the geometry of the piston and rings.

In this work, the temperature distribution, and the contact effects are studied of a RICARDO engine piston shown in Figure (1), which is a test engine. In order to carry out the calculation of the analysis, a finite element code ANSYS version 8.0 is used. ANSYS has the capability to use the contact elements to simulate interaction between a piston and piston compression ringswhich come into contact during engine operation. The simulation performed in this work is in three dimensions with an appropriate one-half section of piston. A half section is drawn for the piston with oil jets due to the thermal symmetry existed in the geometry shape of the piston crown head regardless of the location of the pin boss in the piston skirt .It is illustrated from Figuren (1), that in the head of the piston a combustion chamber is formed in a symmetrical geometry shape which being distributed in piston head oppositically.Therefore the upper half section of the piston is taken to reduce the computational effort.

Theoretical Analysis

The function of the piston is to absorb the energy released after the Air/Fuel mixture is ignited by the high temperature .The piston then accelerates producing useful mechanical energy. To accomplish this, the piston must be sealed so that it can compress the mixture of air and fuel and does not allow gases out of the combustion chamber . This can be accomplished by the piston rings which also help to prevent oil from entering the combustion chamber from underneath the piston . Another function of the rings is to keep the piston from contacting the cylinder wall . Less contact area between the cylinder and piston reduces friction, thereby increasing efficiency [1] .

In the previous works a paper analysed thermally pistons made from cast iron and aluminum alloy . Their results are indicated that the thermal flux is very high in the center of piston crown and it is low at the piston skirt . The temperature of the cast iron piston is higher than the temperatures of aluminum alloy piston by a value about to 40-80 ºC [2] .

Also by carrying out an analysis and experiments on the piston, and depending on the principle of cooling piston with oil in order to permit the piston to carry more thermal loads without having more damages with increasing the engine speed rate . And there are two types of pistons according to the cooling case, the first type is the piston with the cooling gallery in which the cooling oil is passed, and the second type is the solid piston where the cooling is limited to the under crown surface only [3].

It has been developed a program for analysis diesel engine piston .This program depends on the Finite Elements method in the procedure of analysis . Using this program, a diesel engine piston with cooling gallery and a one-quarter 3-dimension piston model was designed, it was noted that the highest thermal deformations occurs a the piston crown region [4].

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Calculations of Heat Transfer Coefficients

The piston receives the heat from the hot gases formed by burning mixture of a particular air/fuel ratio , the boundary conditions around the piston body are different from region to region .In this work the calculations of the thermal analysis depends on the theories of the convection heat transfer analysis that could be applied to piston and piston rings [1] .

Calculation of the Heat Transfer Coefficient between the Hot Gases and the Piston Crown Surface

The mathematical describtion of the forced fluid flow on a cylinder surface is so complicated whereas in the parts of an internal combustion engine especially the piston, the effect of the hot gases on it is very complicated , and in order to calculate the heat transfer coefficient at the piston crown surface ,the heat transfer is described as a forced convection heat transfer inside a cylinder . The heat transfer from the combustion gases is assumed to be similar to the turbulent heat transfer of gases in a cylinder as follows:

$$Nu = C \ Re^{m} \ Pr^{n} \qquad \dots (1) .$$

where Nu is the Nusselt number , Re is Reynolds number and Pr is Prandtl number . The m exponent is typically assumed to be 0.8 for fully developed turbulent flow and n = 0.3 or 0.4 for the cooling or heating respectively .The constant C is to be found from the experimental studies [5]. Benson [6] mentioned that Gunter F.Hohenberg , presented a developed relationship for the equation (1) by using the cylinder volume as a function of the piston diameter **;**

$$h_g = 226.6 \ P^{0.8} \ T^{-0.4} \ (V_P + 1.4)^{0.8} \qquad (2)$$

Therefore equation (2) will be the basic equation for a heat transfer coefficient calculation at piston crown surface [7], [8], [9].

Calculation of Heat Transfer Coefficient at Ring Lands and Piston Skirt

The ring land heat transfer model is based on the flow between the two parallel plates ,as shown in Figure (2) . According to Reynolds number which is less than 2000, it could be assumed that the flow is laminar .To get the value of the heat transfer coefficient Nusselt number should be found for the laminar flow between two parallel plates [5] . where this number is ,

$$Nu = \frac{hD_h}{k} = 8.235 \qquad (3)$$

So the heat transfer coefficient will be equal to ,

$$h_r = 8.235 \frac{k}{D_h} \qquad (4)$$

Where , D_h , is the $D_h = \frac{4A}{P}$.

hydrulic diameter and is written as , Where , A , is the cross-section area in (m^2) and is equal to ;A = 2b*1 unit depth and , P , is the perimeter in (m) and is equal to ; P = 2, therefore the hydraulic diameter will be equal to ;

Eequation (4) will be the $D_h = 4b.$ basic equation for calculating the heat transfer coefficient at the ring land and piston skirt [7], [8], [9].

Calculation of Contact Conductance and Contact Coefficient

If the surfaces of two dry metal blocks are placed in contact , there remains a considerable resistance to heat flow from one block to the other , unless the surfaces are

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bonded together by a solid metal bond . The nature of the heat transfer between the piston and piston rings is contact heat transfer . This resistance is known as the contact resistance , which is a function of the actual contact area , the presence of a solid or fluid in the gap between the surfaces [10].

The contact resistance is written as follows ;

$$R_C = \frac{d}{k\,A} \; , \; in\left(\frac{^oK}{Watt}\right) \qquad (5)$$

where , δ , is the gap thickness , k is the thermal conductivity of the fluid in the gap , and A is the contact area . The reciprocal of the contact resistance is called the contact conductance and is written as,

$$C_C = \frac{k\,A}{d} \qquad (6)$$

The ratio of the thermal conductivity of the fluid to the thickness of gap refers to the contact heat transfer coefficient and is written as,

$$h_C = \frac{k}{d} = \frac{C_C}{A} \qquad (7)$$

From equation (7) the contact heat transfer coefficient can be calculated [7], [8], [9].

Calculation of Heat Transfer Coeffcient at Piston Under Crown Surface

The piston undercrown surface is considered a very complex geometry shape due to the existence of the ribs and the piston pin bosses ,where heat transfer calculations will not be easy to evaluate the heat transfer coefficient in each area at this region . Therefore according to these reasons , the assumption which is made here shows that the undercrown surface is assumed to be a cylinder and the lubricant oil moving along the surface of cylinder at a particular

velocity which is equivalent to the mean piston velocity at a particular temperature . According to this assumption the satisfactory correlation for this case is the Ditus-Poelter correlation which satisfied turbulent forced convection heat transfer on the cylinder surface , this correlation gives the Nusselt number , and hence the heat transfer coefficient can be obtained as shown below [11];

$$Nu = 0.023\,Re^{0.8}\,Pr^{0.3} \qquad (8)$$

$$Re = \frac{r_{oil}\,U_{oil}\,D_h}{m_{oil}} \qquad (9)$$

where ,

$$Nu = \frac{h_{oil}\,D_h}{k_{oil}} \qquad (10)$$

and ,

Substituting equations (8) and (9) into equation (10) , leads to ,

$$h_{oil} = 0.023\,D_h^{-0.2}\,k_{oil}\left(\frac{r_{oil}\,U_{oil}}{m_{oil}}\right)^{0.8}\,Pr^{0.3} \quad (11)$$

So equation (11) is the equation for calculating the heat transfer coefficient at the piston undercrown surface [7], [8], [9].

Development of the models of Piston and Compression Rings

This section consumed very much time and effort in building the models of piston and piston compression rings , where the piston is considered to have a complicated geometry , building of many volumes and these volumes are created from many areas . The starting point of building the piston and piston rings geometries brgins with the creation the areas and the finishing point ended with a comfortable volumes which will represent the piston and piston rings .

The final step in the building process is dividing the piston and   piston compression rings into finite elements using Meshing   process tool after choosing an element type in order to justify the thermal and analyses in 3-dimensions which is (SOLID98) element of a structural coupled field elements , the meshed volumes are shown in Figure (3).

In order to create the contact elements between the piston and the compression rings the contact pair tools must   be used , where   the piston will   become the target part and the piston compression rings will be the contact part , the procedure of   creating   the contact   pairs includes the selection of the target and   contact surfaces , where the upper surface of the piston ring grooves will be the target surface, then   the   upper   side of the compression rings will be contact surface .

Then the needed thermal conductance value is taken to be (1 Watt/ K) which is calculated from   equation (6) , the target element is (TARGE 170) and the contact element is (CONTA 174) these   elements are   bonded together by hidden bonds .

The Thermal Boundary Conditions

The thermal boundary conditions consist of applying a convection heat transfer   coefficient and the bulk temperature , and they are applied to the piston crown , piston ring land sides , piston   ring   groove   lands   , and piston under crown surfaces . At the outer face of the compression rings a constant temperature of about (373 K) is applied .The conditions are listed as follows :

Boundary Conditions on Piston Crown Surface

Depending on equation (2) and at the mean gas pressure equal to (7.16

bar) ,the bulk temperature is equal to (925 K) , and piston velocity equal to (5.5 m/sec) [12] , so the heat transfer coefficient is equal to :

$$h_g = 334 \quad \frac{W}{m^2 \ K}$$

Boundary   Conditions   on   the Piston Ring Land Sides and Piston Skirt

A convection   heat   transfer coefficient (h) equal to(1111.725 W/m² K) which is computed from equation (4) is applied to the areas which are signaled by white spots as shown in Figure (4) at bulk temperature equal to (393 K) .

Boundary Conditions on Piston Ring GrooveLands

Depending on equation (4) the heat transfer coefficient (hr) is equal   to (444.69 W/m² K) being   applied between the side land of the grooves and the inner face of the rings , and between   the   lower surface of the groove and the lower side of the ring . The heat transfer coefficient is equal to (823.5 W/m² K)   and   these conditions   are   then applied to   the four ring   groove   regions , In the fourth ring groove region there is no ring so the upper   surface of   the groove   is   then   substituted   by an equivalent convection heat transfer coefficient equal to (5625 W/m² K) which is computed from equation (6),at bulk temperature equal to (393 K) .

Boundary   Conditions   on Piston Under Crown and Inner Walls of the Piston Skirt

The heat transfer coefficient applied to the piston under crown surfaces and on the inner walls of the piston is computed from equation (11) according to the oil flow speed , the coefficients for   each speed are   shown   in the following table(1) .

Discussion of the Results

The temperature is defined as the measure of the molecular activity of a substance where the greater the movement of the molecules the higher the temperature . Since piston and piston compression rings are subjected to non constant thermal loads from region to region , the temperatures of the piston and the piston compression rings will not be constant but will be distributed along piston body from maximum values to minimum ones .The maximum values of the temperatures are studied according to their thermal effects on the temperature distribution.

Effect of Thermal Conductivity on Temperature Distribution in Piston and Piston Compression Rings

In this work , three material alloys are used in the thermal analysis of the piston where in the piston compression rings the material type is taken as a steel alloy and its grade is of(44K2 Steel-medium carbon alloy)[13],piston materials are of two Aluminum alloys , the first type is of (MSFC-388-T5) [14] having a thermal conductivity equal to(136 W/m K), the second type is of(NASA 398-T5)[14] having a thermal conductivity equal to (131.4 W/m K) and the third type is of a Cast-iron material of grade (20B) having a thermal conductivity equal to (50 W/m K)[13] . The temperature distributions in the piston and piston compression rings in a piston made of NASA 398-T5 aluminum alloy are shown in Figure (5) , the maximum temperature in the piston is equal to (457.306 K) and the minimum temperature is equal to (370.044 K).The maximum temperature in the first compression ring is equal to (391.88 K) in the second compression ring the maximum temperature is equal to

(385.067 K) and in the third compression ring the value of the maximum temperature is equal to (381.365 K) . In a piston made of cast-iron material the temperature distribution in the piston and piston compression rings are shown in Figure (6) , where the maximum temperature in the piston is equal to (508.935 K) and the minimum temperature is equal to (364.53 K) . The maximum temperature in the first compression ring is equal to (393.504 K) while in the second compression ring is equal to (383.482K) and in third compression ring is equal to (379.177 K) .

A comparison between a piston made of (NASA 398-T5) aluminum alloy and of cast-iron alloy ,shows that the maximum value of a temperature in the piston of cast-iron is higher than the maximum temperature in the piston of aluminum alloy of (NASA 398-T5) , whereas the minimum temperature in the cast-iron piston is smaller than the minimum temperature in aluminum alloy piston by (5.514 K) . This is due to the lowering value of the thermal conductivity for the cast-iron piston of that in the (NASA398-T5) piston . If the thermal conductivity is increased ,the amount of the heat flow will be high and this causes a temperature drop between the warm and cold walls while when thermal conductivity value is decreased the temperature drop is increased by a particular value . From this comparison it is noted that the first compression ring in a cast-iron piston has received a high quantity o f heat than the NASA 398 aluminum piston . The value of the maximum temperature is increased to about (1.624 K) in the first compression ring for cast-iron piston while in the second and third

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compression rings the maximum value of the temperature is reduced in the cast-iron piston to about (10.022 K) and (14.327 K) respectively ,where the heat quantity received in these rings are lower than the heat received in the first ring .

Effect of Contact Heat Transfer on the Temperature Distribution in Piston and Piston Compression Rings

When the piston is expanded due to the combustion pressure in the power stroke where the piston rings are in free motion inside piston ringgrooves , the piston will take the rings in its movement by the contact . In this case the contact region is located between the piston ring groove upper land and piston compression ring upper side wall .

As defined in the theoretical analysis the contact conductance is known as the ratio of the heat transfer rate by contact to the temperature drop in the contacting walls when a fluid material fills the gap space between the contacting walls .

The compression rings are considered as a passage for heat transfer so when the contact occurs between the piston and piston compression rings , the heat flux will pass the compression rings reaching the liner walls where the temperatures will be lower than the temperatures in the piston crown surface , in order to reduce the amount of heat flux passing the piston compression rings the attachment or contacting area of the compression rings must be reduced . As the contact conductance is a function of the contacting area , therefore the contacting area will be reduced and the contact conductance is reduced as well .To reduce the contacting area , the Recardo

compression rings are tapered from the upper left hand side .From Figures (7) which represents the temperature distribution for tapered face compression rings in a cast-iron piston it is noted that the maximum temperature in the piston is equal to (511.601 K) , in the first ring is equal to (387.118 K) , in the second ring the value of the maximum temperature is equal to (380.266 K) , and in the third ring the maximum temperature equals to (377.771 K) .

Comparison between the values of the maximum temperatures in the piston and piston compression rings , in the case of using tapered rings in a cast-iron piston and in the case of using rectangular compression rings for the same piston in the previous section is shown in Figures (6) respectively .They show that the value of the maximum temperature in the piston is increased by (2.666 K), while in the first ring it is lower by (6.386 K) , also in the second ring the maximum temperature is lower by (3.216 K) , and in the third ring it is lower by (1.406 K) , where the attachment area is reduced so that the contact area does not touch the maximum temperature area in piston ring grooves . This will cause the quantity of heat flow to the piston compression rings to be lower causing the maximum value of the temperature in the piston to be increased up to (2.666 K) .

Conclusions

The following can be concluded from the results of this work :

1.The material type of high thermal conductivity is considered better than the material type of low thermal conductivity . This means that the aluminum alloy is considered better than the cast-iron alloy.Where in using the cast-iron alloy in piston manufacturing the maximum

temperature in the piston is increased about (51.626 K) , in the first ring the increasing in maximum temperature is about (1.624 K) , while in the second and third rings the temperature is lowered about (1.585 K and 2.188 K) respectively.

2.Tapering the compression rings from the inner side by 1 mm , leads to a reduction in the temperature values of compression rings , where the first ring temperature is lowered by (6.386K) , in the second and third rings also lowered about (3.216 K, 1.406 K) respectively.While in the piston the maximum temperature is increased about (2.666 K).

Nomenclature
A : Flow cross-section area….m².
a,b : Constants.
C : Constant.
C1,C2 : Constants.
Cc : Thermal contact conductance….W/K .
D : Cylinder bore….m .
Dh : Hydraulic diameter….m .
h : Convection heat transfer coefficient….W/m²K.
hc : Contact heat transfer coefficient….W/m² K.
hg : Heat transfer coefficient of gas….W/m² K .
hoil : Heat transfer coefficient of oil….W/m² K .
k : Thermal conductivity….W/m K.
koil : Thermal conductivity of oil….W/m K.
m,n : Constants.
Nu : Nusselt number.
P : Cylinder gas pressure….bar.
Pr : Prandtle number.
qw : Heat flux on the wall….W/m².
Rc : Contact resistance….K/W.
Re : Reynolds number
Tb : Bulk temperature ….K.
Tg : Gas temperature….K .
Tw : Wall temperature….K.
Uoil : Oil flow speed….m/sec.
Vp : Piston mean velocity….m/sec.

ρoil: Oil fluid density….kg/m³.
μoil : The Dynamic viscosity of oil.kg/m sec.
δ : Gap thickness….m.

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Table (1): Distribution of heat transfer coefficient for oil with oil flow speed

Uoil , m/sec	hoil , W/m² K
30	584

Figure (1): Ricardo engine piston .
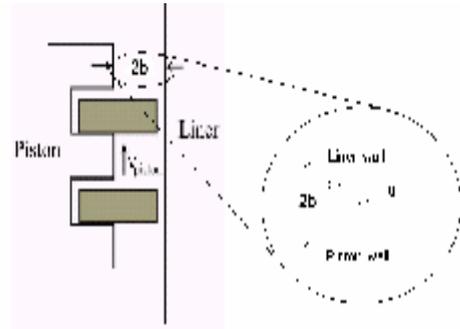
Figure (2) : Ring land cooling model schematic .
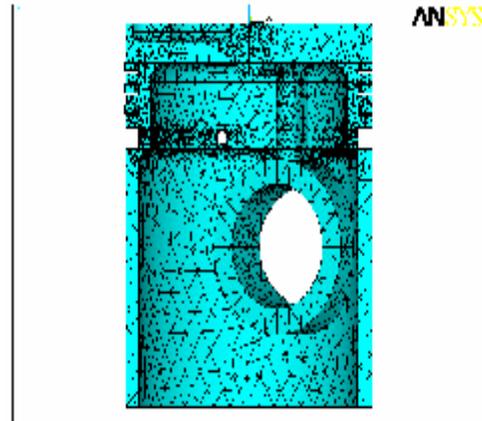
Figure (3): Piston Geometry .
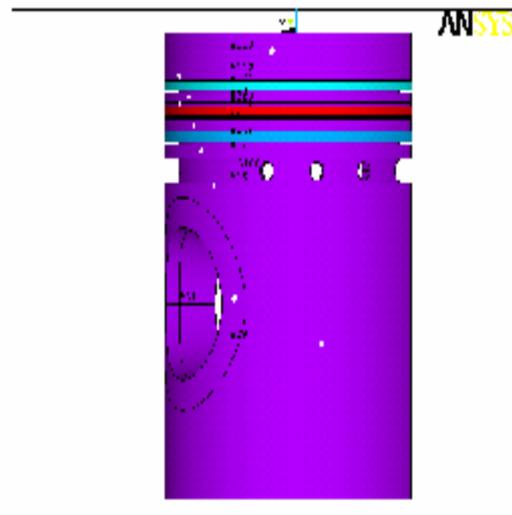
**Figure (4): Boundary conditions locations on the piston outside walls.**
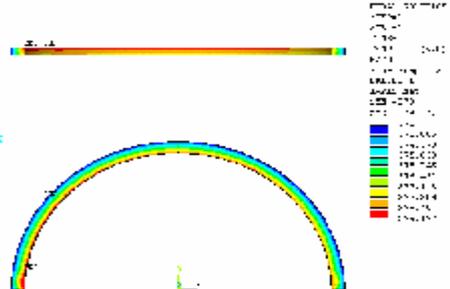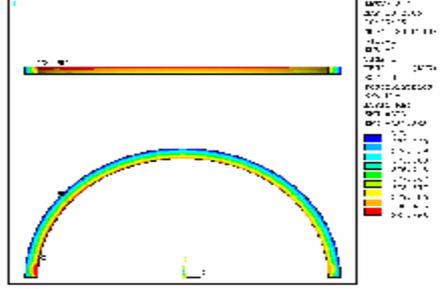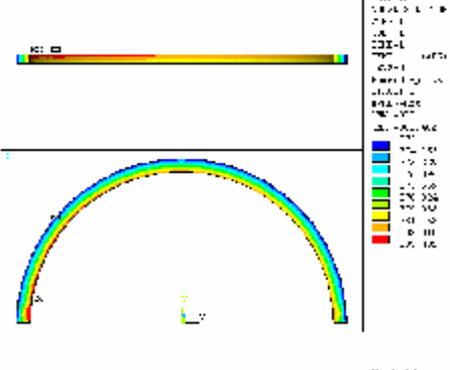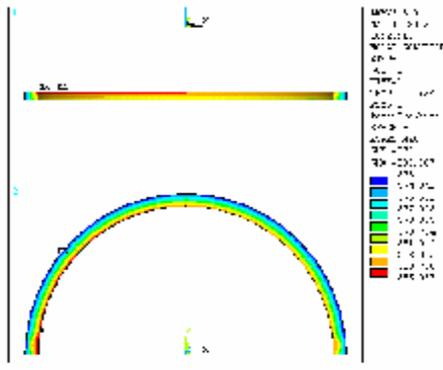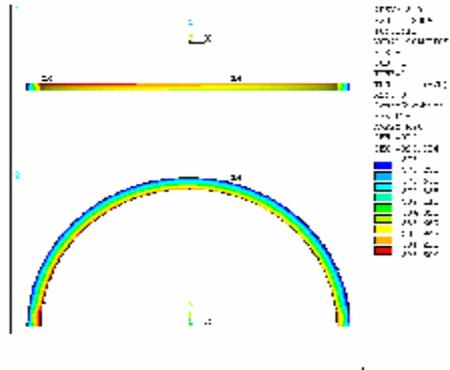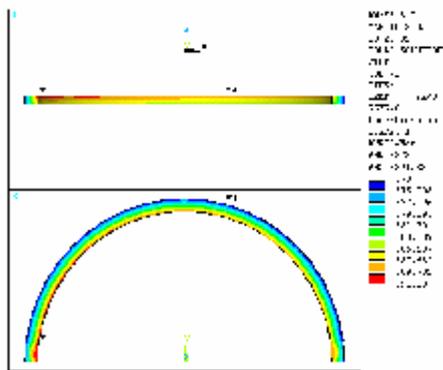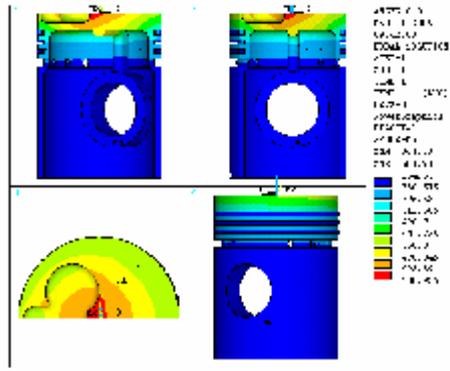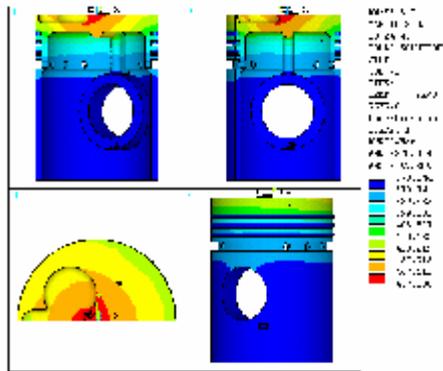
Figure (5):Temperature distribution in piston and piston compression rings where piston is made of aluminum alloy .

Figure (6):Temperature distribution in piston and piston compression rings where piston is made of cast-iron alloy .

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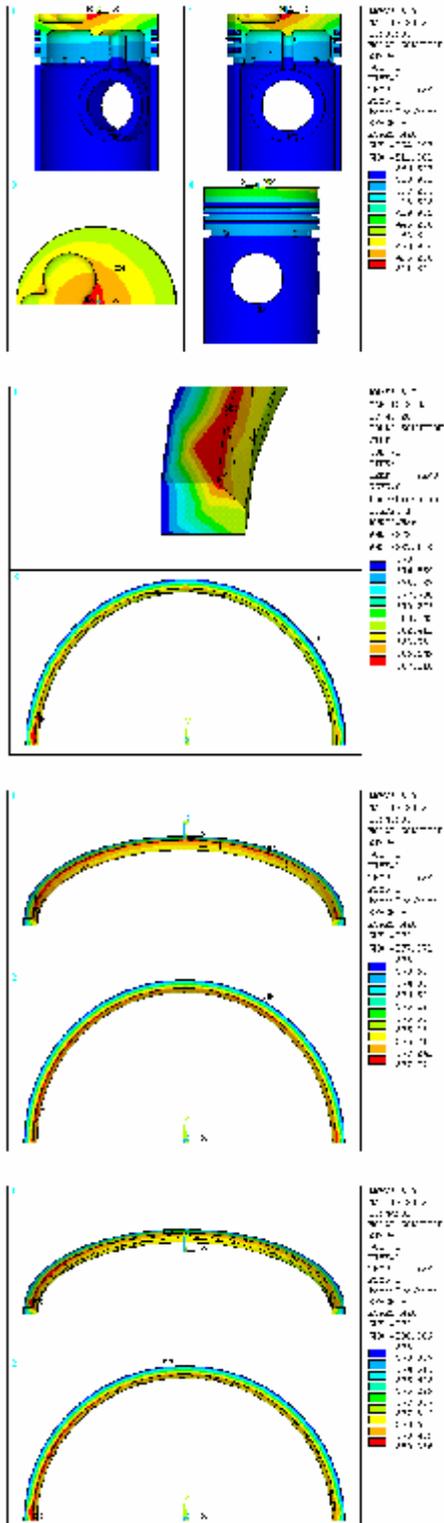
Figure (7): Temperature distribution in piston and piston compression rings with tapered face rings