Palestine Polytechnic University

College of Engineering & Technology
Mechanical Engineering Department

Graduation Project

Engine Head Thermal Loading

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Abstract:

The internal combustion (IC) engine is a heat engine that converts chemical energy in a fuel into mechanical energy, usually made of available on a rotating output shaft. The chemical energy of the fuel is converted to thermal energy by means of combustion or oxidation with air inside the engine. This thermal energy raises the temperature and pressure of the gases within the engine and the high-pressure gas then expands against the mechanical mechanisms of the engine. The mechanical linkages of the engine to a rotating crankshaft convert this expansion, which is the output of the engine. [2]

The aim of this project is to study the engine thermal loading specialized on the engine head, this study is important to determine the thermal temperature distribution on this component.

As a result of this study and according to the calculations and data specified for any certain engine head; it will be possible to apply the finite element analysis, CATIA software and ANSYS software to analyze, design and draw the distribution of heat flux on that specified engine head. Moreover, in this study, the pre-calculated values of combustion parameters were put to finite element analysis within the ANSYS software to get the thermal stresses on the engine head. which is the outcome, expected in this work.

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Chapter One

Introduction

1.1 ***Overview***

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1.1 Overview

The engine head (or, cylinder head) in the internal combustion engine are the subject of this project.

For engine performance calculations, it is important to represent heat flux versus time, because of its effects on the engine performance. The heat flux on the cylinder head is variable with the engine design and operating condition.

In internal combustion engines there are three locations that have the highest temperature concentration due to many reasons related to the engine's design limitations and lack of a sufficient cooling, those zones can generally be found around spark plug, exhaust valve (with its seat) and piston face.[2]

In general, related studies used measurement devices to investigate thermal stress behavior in such critical zones such as thermocouples and thin-film gauges. This study used the finite element analysis to predict thermal stresses on a CATIA designed model of cylinder head simulated by ANSYS to distribute pre-calculated temperature values during both combustion and exhaust phases to get the final heat distribution on the critical areas; namely hear the valves head and the exhaust valve seat.

1.2 Project Prominence:

In a spark ignition internal combustion engine (SI ICE), the optimum performance is achieved by setting the engine's parameters to meet with the instant operating condition under which the engine is running. Engine's parameters include variable quantities that are adjusted by the control unit or any other controlling or metering element; such as spark advance or retard, injection timing, injection duration (quantity of injected fuel), valves timing, etc…

Nonadjustable parameters including engine design also affects its operation, hence; poor design will result a harmful mechanical and thermal stresses causing low performance or even engine failure.

The main goal in adapting all those parameters is that the maximum pressure wave will be developed 10 to 20 degrees of crank angle after the top dead center in the power stroke, about ten degrees after, the maximum instantaneous heat release occurs as the combustion chamber temperature reaches its optimum. At such condition, the volume of the chamber is still relatively small so a grate thermal stress will develop on the nearby parts; namely: cylinder head, intake and exhaust valves heads, spark plug, cylinder wall and piston crown. On the other hand; during the exhaust process, a sudden exhaust gases blowdown through the exhaust port will cause an intensive thermal stresses on the exhaust valve seat and the adjacent valve bridges.

As a result; this study is implemented to conduct with thermal stresses on the cylinder head, intake and exhaust valves heads and exhaust valve seat, taken as a critically thermal loaded zones.

A previous study made by two of the PPU graduates two years ago studied the thermal loading on cylinder wall and piston face. The remaining parts after completion of this study are the spark plug and the valves, after which a complete view of the thermal loading on an SI ICE will be developed.

1.3 Chapter Tenor:

1.3.1 Chapter One "Introduction"
1.3.2 Chapter Two "PREVIOUS STUDIES "
1.3.3 Chapter Three "COMBUSTION AND HEAT RELEAS"
1.3.4 Chapter Four "HEAT TRANSFER"
1.3.5 Chapter five "THERMAL LOADING"

1.4 Projects Plane:-

- **From the beginning of the first week up to the end of the second week:**

  Registering the course of the graduation project and conducting with the project supervisor to discuss the introduction paper made in the previous semester, trying to clarify and enhance the final paper.

- **From the beginning of the third week up to the end of the fifth week:**

  Completing the corrections made by the discussion committee and documentation

- **From the beginning of the sixth week up to the end of the eighth week:**

  Looking for a model to work this project with, and taking measurements. Designing a model on CATIA program to be dealt with and loaded by ANSYS.

- **From the beginning of the ninth week up to the end of the eleventh week:**

  Conduct with ANSYS software and taking advises and guidance from our supervisor and Dr Haitham.

- **From the beginning of the twelfth week up to the end of the fifteenth week:**

  Completing the documentation work and writing the conclusion in this project.

Chapter Tow

Previous Studies

2.1 *Overview*

2.2 *Previous Studies*

2.1 Overview

Because of the grate importance of studying thermal loading on the various engine parts, many analytical and experimental studies were introduced.

Analytical studies, in general, used Fourier series to solve the heat equations to get a satisfactory heat flux model, still; those studies didn't reach that degree of satisfaction due to many relevant shortcomings; take the resolution of the outcome heat distribution as an example.

Experimental approach is used to actually study the changing heat flux and temperature distribution during engine operating cycles. The difficulties of having the measurement devices installed on the various engine parts "as shown in later sections in this chapter", and because of the fact that those devices have a relatively low response due to there lower band width or any other criteria of the device itself, it would be useless to relay on there readings when a serious design decision is to be made, especially in the presence of CAD based procedure aside with finite element analytical approach.

Loading a CAD model on the computational fluid dynamics program of ANSYS by the relevant heat and temperature quantities and relations can predict the actual heat flux as implemented in this study.

2.2 Previous Studies

In this section, a brief discussion illustrates some of the approaches used to determine or predict engine head heat flux and some of the critical zone's thermal loading.

The practical methods use measuring devices to determine the actual thermal distribution and heat fluxes in the location where the device is installed.

2.2.1 Thin film gauges [1]

Heat transfer between the working fluid and the combustion chamber in an internal combustion engine is one of the most important parameters for cycle simulation and analysis. Heat transfer influences the in-cylinder pressure and temperature levels, engine efficiency and exhaust emissions. Heat transfer is determined using platinum thin film resistance thermometers exposed to the combustion gases. These give a frequency response of greater than 100 kHz; hence can track heat transfer rate changes on the piston and cylinder head surfaces adequately. The thin film gauges overcome the problems of low bandwidths and large uncertainties associated with thermocouples.

Nearly all the reported experimental studies of in-cylinder heat transfer have been carried out with sparsely fitted fast response or eroding type thermocouples; however, even though many claim to achieve higher frequency responses, thermocouples are limited to an absolute maximum bandwidth of 10 kHz with most failing to achieve higher than 1 kHz. In addition these thermocouples are fragile, difficult to manufacture and difficult to replicate. Thin films therefore have obvious advantages, apart from their higher response rates, including being robust, highly repeatable, simple to instrument and calibrate and the ability to create densely packed arrays to look at local heat transfer rates.

In this study, a thin film gauge is attached to the cylinder heat as shown in Fig. (2.1).

Figure2. 1: A cylinder head instrumented with thin films

The measured surface temperature history from a thin film gauge and a thermocouple from the cylinder head are shown in Fig. (2.2). The data have been taken with the engine motored at 1500 rpm initially and then fired causing it to reach a given speed. The peak surface temperature during the motored run is about 10 K above the ambient temperature and rises to just over 120 K above ambient once the engine is fired. The surface temperature is lower for the initial two revolutions as the engine speed increases, and then settles at around 100 K above ambient; however, some fluctuations from cycle to cycle are still noted.

The reasons for the initial few cycles having a lower peak temperature are due to the engine being at a lower speed. Notably the minimum cycle temperature is almost constant later in the run at around 40 K. The thermocouple mounted in the cylinder head above the thin film gauge shows a slow rise of a few degrees as the cylinder head metal temperature rises.

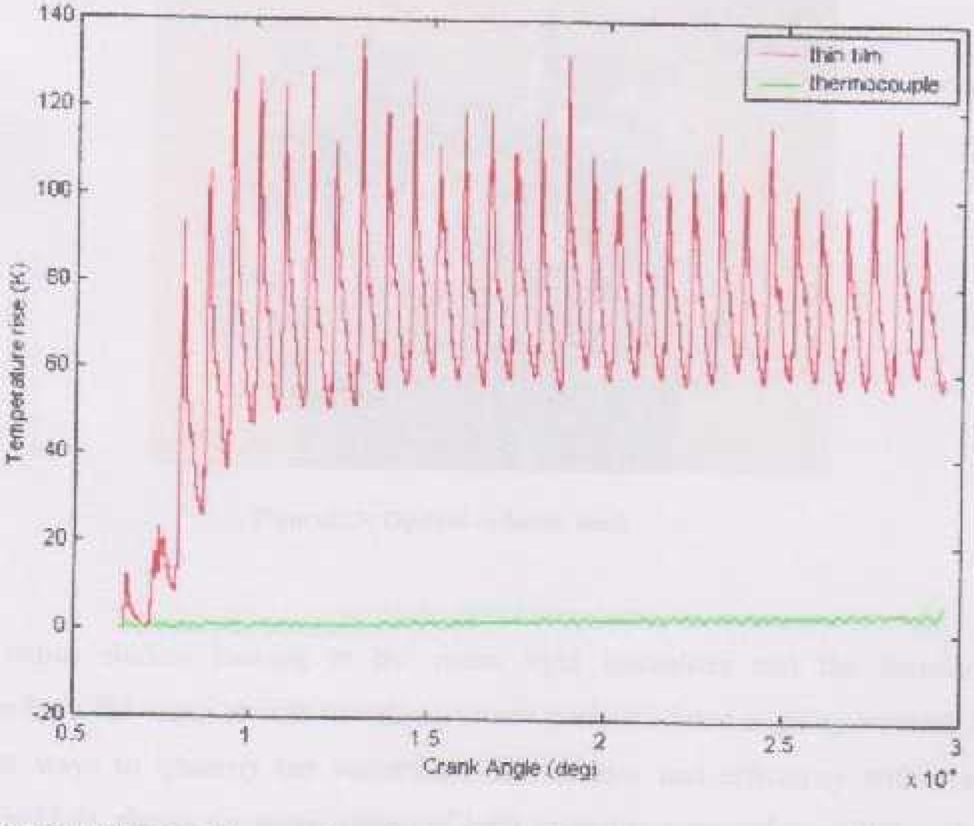

Figure2. 2: Measured temperatures from the thin film gauge and thermocouple.

2.2.2 Fiber optic instrumentation [1]

Combustion is a highly complex process where the mechanism of fuel oxidation causes many different chemical species to emit light on specific spectral lines; therefore, from a measured emission spectrum it is possible to infer the chemical species present. Measurements of the spectral content (300 to 850 nm) of the light intensities within the combustion chamber are presented.

In order to image the complete area of the combustion chamber, a transparent cylinder head was manufactured from Perspex, Fig.(2.3). Although Perspex is a thermoplastic material, the temperatures and periods of time for which the transparent cylinder head was used proved sufficiently low to prevent permanent damage. The spark plug thread was reinforced with epoxy resin to prevent melting. A Kistler spark plug was used without the fitted pressure transducer.

Figure2. 3: Optical cylinder head

Various studies looking at the mean light intensities and the Standard deviations from the mean at each wavelength were performed and ongoing research is looking at ways to quantify the variability, heat release and efficiency within an engine. Fig.(2.4), shows the mean values of light intensity, averaged over 200 cycles at each wavelength recorded, whereas, Fig.(2.5) shows the standard deviation from the mean of the same cycles, also plotted against crank angle.

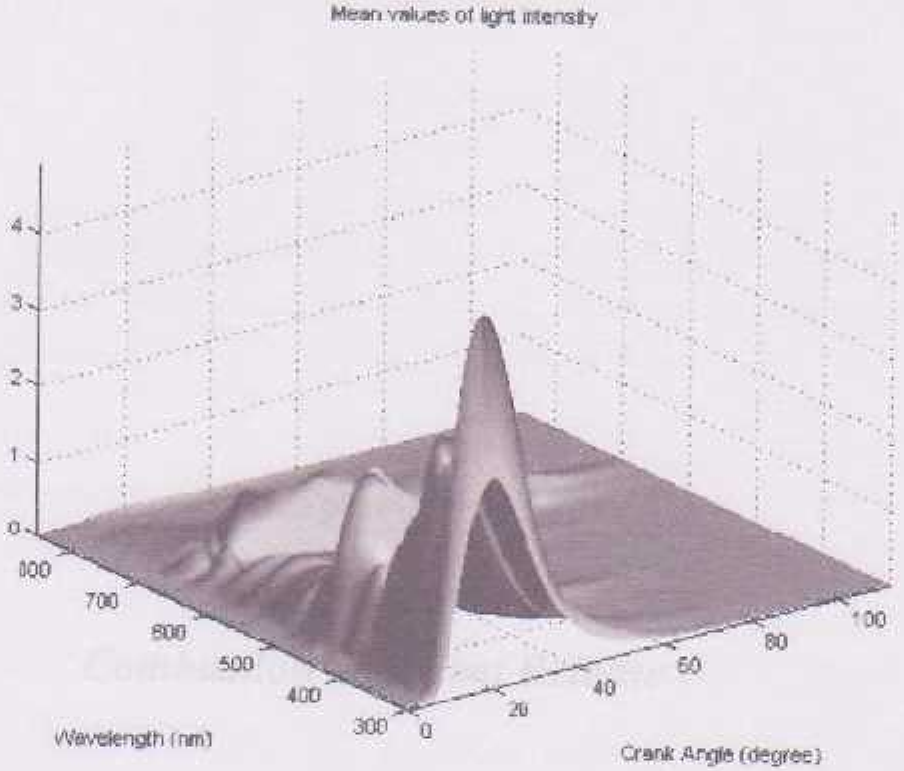

Figure2. 4: Mean values of light intensity at given wave lengths against CA

Figure2. 5: Mean Heat transfer rate against CA.

Chapter Three

Combustion and Heat Release

3.1 Introduction

The combustion mechanism can be defined from the point of chemical processes connected with formation of the combustion focus as a pre-oxidization reaction as a consequence of high potential electric discharge [2].

3.2 Combustion course of spark ignition engines [3]

3.2.1 Normal combustion

The term "combustion" can be defined such course in which the combustion is realized by average velocity 20 – 50 m/s in the area , where the piston is at TDC , the end of compression stroke, and at the beginning of expansion stroke.

When the piston is at TDC, the cylinder pressure rises and reaches the maximum value by 12 – 15 – 20 crank angles after top dead center "TDC".

The combustion can be divided into three phases:

1. *First phase – combustion delay*: (The preparation of the turbulent flame propagation).

This phase begins when the electric discharge crosses and ends in the moment of the compression curve deflection from the compression curve without combustion.

2. *Second phase – basic or main combustion*: (The propagation of turbulent flame almost in the whole combustion chamber).

This phase occurs as a consequence of burning of the substantial amount of mixture. It begins at the moment of the cylinder engine curve deflection and ends at the moment when the cylinder pressure reaches its maximum value, i.e. about 20 degrees after TDC.

3. *Third phase – burning out*: (The end of combustion of the individual volumes of working charge in the front of the turbulent flame and the combustion chamber walls).

It begins at the moment of maximum pressure and ends in the indefinites area of expansion stroke. The burning out velocity is affected by the turbulent diffusion, physical and chemical properties of working mixture.

The period of burning out must be small, because it's bulling through the expansion stroke, the total efficiency of engine working cycle gets worst.

From the ignition focus (centre), the combustion expands as the flame front propagates. The propagation velocity depends in the quantity of the activate element penetrating from the combustion zone to unburned mixture. The activated elements penetration is affected by the molecular diffusion.

There are many factors that affect the combustion course in any spark ignition internal combustion engine; some dominant factors are listed below:

1) *Ignition timing.*

1. Compression ratio (r_c).

With the same ignition timing angle and higher r_c, the combustion delay (early flame development) is shorter which results in faster flame penetration and heat development. As a consequence of this , pressure increase faster , engine work is hard , the main combustion is shorter , maximum pressure are near top dead centre and pressure in expansion stroke is lower .

2. Combustion chamber form:

The form of combustion chamber affects the heat development, combustion course and r_c.

3. Location of spark plugs:

Spark plug is recommended to be located at the centre of combustion chamber and in the hottest position.

4. Swirl working mixture:

Increasing the mixture turbulence accelerates the flame penetration and combustion period becomes shorter.

5. Cylinder size.

In large engines, the thermal loading of cylinder surface is higher, which results in pre-oxidizing reaction. It also results in longer flame line, which breaks the flame near cylinder wall.

6. Material of piston and engine head.

The thermal conductivity of material affects the wall surface temperature of combustion chamber, cylinder heads from an aluminum alloy with thermal conductivity about ($K=221 w/m^2.k$) gives lower wall temperature which gives possibility of using higher r_c.

2) Adjustable factors.

1. Ignition timing (advancing) :

Ignition timing affect temperature and pressure of the combustion start and intensity of mixture swirl , advancing ignition angle leads to shear pressure increasing , especially in the flame propagation period (phase) – p – near TDC. Small ignition advance causes a large thermal loading of cylinder group.

2. Engine speed :

Engine speed changes affect (with the same ignition timing) the pressure distribution in side cylinder engine, increasing speed causes turbulence increasing, which leads to velocity increasing of flame penetration.

3. Engine loading :

With partial engine loading, temperature and pressure decreasing, early flame development is longer which leads to lower combustion velocity, increasing exhaust gases ratio affects the active molecules.

The higher is loading, the optimum ignition timing is lower, with partial loading its necessary to rich the mixture in order to achieve the best engine stability, and it is necessary to increase ignition angle.

4. Mixture composition :

The early combustion delay occurs with mild mixture richness, with rich or lean mixture, the combustion delay is longer.

Mixture composition affects the exhaust gases formation (CO, HC, NO_x), with rich mixtures, a combustion velocity has a significant effect (fuel evaporation).

5. Engine heat (thermal) state :

The temperatures of cylinder head and cylinder wall affect the combustion course , with cold engine , the mechanical losses are higher and worse mixture preparation and more exhaust pollution (except NO_x) .

6. Carbon seats :

The thermal conductivity of carbon is very high and it is about 50 times higher than cast iron, so the temperature of mixture and combustion products are higher (during combustion) and the possibility of combustion detonation is higher.

7. Fuel properties.

8. Pressure , temperature and humidity of air :

Charging temperature and pressure increasing result in higher pressure and temperature of combustion by which the possibility of combustion detonation is higher.

Air humidity with form of small drops, significantly affect the internal cooling.

9. Inert gases :

Inert gases slowing the reaction processes of combustion which decreases the possibility of formation of combustion detonation.

3.2.2 Abnormal combustion – knocks and surface ignition

The two major phenomena of abnormal combustion processes are

a. Knocking, and

b. Surface ignition.

Abnormal combustion: a combustion process in which a flame front may start hot combustion chamber surface either prior or after spark ignition, or a process in which some part or all of the charge may be consumed at extremely high rates.

a. *Knock phenomena* :

It is a noise transmitted through the engine structure when essentially spontaneous ignition of a portion of the end gas occurs.

There is an extremely rapid release of much of chemical energy in the end gas, causing high local pressure and temperature and the propagation of pressure waves of substantial amplitude a cross the combustion chamber.

Two theories have been proposed to explain the origin of knock: [2]

1) The auto ignition theory :

When the air – fuel mixture in the end gas region is compressed to sufficiently high pressures and temperatures, the fuel oxidation process starting with pre-flame chemistry and ending with rapid energy release can occur spontaneously in parts or the entire end gas region.

2) Detonation theory :

The advancing flame front accelerates to sonic velocity and consumes the end gas at a rate much faster than would occur with normal flame speeds.

b. *Surface ignition phenomena* :

It is an ignition of fuel – air mixture by a hot spot on the combustion chamber wall as an over heated valves or spark plug , or glowing combustion chamber deposit i.e. , by any means other than the normal spark discharge.

3.3 Fuels

Any material which can be burned to release energy is called a fuel.

Familiar fuels consists primarily hydrogen and carbon , they are called hydrocarbon fuels are denoted by the general formula C_nH_m , and exist in all phases , some complex being coal , gasoline and natural gas.

Although liquid HC fuels are mixtures of many different hydrocarbons, they are usually considered to be a single HC for convenience. For example:

- Gasoline is treated as octane, C_8H_{18}.
- Diesel fuel as Dodecane, $C_{12}H_{26}$.
- Methyl alcohol, CH_3OH.

A chemical reaction during which a fuel is oxidized and a large quantity of energy is released is called "combustion".

In the analysis of combustion processes, the Argon in the air is treated as N_2, and the gases which exist in trace amounts are disregarded.

Then dry air can be approximated as 21% O_2 and 79% N_2 by moles numbers, therefore, each mole of O_2 entering a combustion chamber will be accompanied by 0.79/0.21= 3.76 mole of N_2, that is

$$1K_{mol}O_2 + 3.76N_2 \rightarrow 4.76K_{mol}Air$$

3.3.1 Spark – ignition engines fuels:

1- Gasoline :

Gasoline is a collective to denote hydrocarbons of various chemical structures, its produced by crude oil refining processes of distillation, cranking, reforming, ISO merization , polymerization.

2- Regular gasoline :

It's a gasoline whose anti-knock qualities are sufficient for many motor vehicle spark ignition engines.

3- Premium gasoline :

It's a mixture of highly knock- resistance components and its higher anti-knock qualities than regular gasoline. See table 3.1 for specification:

Table3. 1: Requirements of regular and premium gasoline

Requirements	Premium gasoline	Regular gasoline
	Summer & winter	Summer & winter
Density at 15 C (kg/l)	0.73-0.78	0.715-0.755
Anti-knock quality(min) RON	97.4	91
(min) MON	87.2	82
Load content (gPb/l)	0.15	0.15
Boiling curve:		
Total vaporization		
- Up to 70 c (vol.%)	15-40 & 20-45	15-40 & 20-45
-Up to 100c (vol.%)	42-65 & 45-70	42-65 & 45-70
-Up to 180c (vol.%)	90 &90	90 & 90
Final boiling point max. (c)	215	215
Distillation residue max. (vol.%)	2	2
Reid vapor pressure (bar)	0.45-0.6 &0.6-0.9	0.45-0.7 & 0.6-0.9
Existent gum:		
Evaporation residue max. (mg/100ml)	5	5
Sulfur content max. (% by wt)	0.1	0.1

4-Ethanol:

It is technically a pure ethyl alcohol C_2H_5OH, Produced by fermentation .and it has high knocking resistance.

5-Methanol:

It is technically a pure methyl alcohol CH_3OH, produced by synthesis and it has high anti-knock qualities.

6-liquified petroleum gas LPG:

It is a mixture of butane, propane, propylene, and it is obtained from natural, refinery and cracked gases, as well as by hydrogenation and synthesis.

3.3.2 Gasoline properties:

The following properties are decisive for use in engines; volatility and mixture formation calorific value.

The gasoline sold in the market is a blend of a number of products in several processes .By such blending, the properties of the fuel are adjusted to give the desired operating characteristics, and its characteristics that are of special interest to the engineer. Thus, the gasoline, irrespective of its origin should have the following properties:

1-Boiling curve and vapor pressure:

The boiling curve indicates the quantity of vaporized in the boiling vessel at a particular temperature.

With regard to behavior in the engine three regions on the boiling curve are important, this can be characterized by the percentage vaporized at three temperatures.

The vaporized volume up to 70 °C should be large to ensure easy starting of the cold engine; it shouldn't however, be excessive so as to prevent vapor lock with hot engine.

The vaporized volume up to 180 °C should not be too small to prevent dilution of lubricating oil, especially when engine is cold.

The vaporized percentage at 100 °C determines not only the heating up behavior; in addition, the vapor pressure is also a measure of the carburetion capability of fuel .Fuels with high vapor pressures can form vapor locks in the flow line system and thus interrupt the fuel supply. For this reason the vapor pressure is limited to = 0.7 bar in summer, it can rise by = 0.2 bar in winter.

2-Heat evaporation:

The air – fuel mixture cools down due to evaporation of the fuel, which is initially is only atomized in the carburetor .for racing fuel the high heat evaporation methanol and ethanol is utilized by increasing the cylinder charge.

3-Calorific value and heating power:

The specific calorific value C_v and the specific heating power C_{vo} are a measure of the energy content of fuels.

The calorific value is defined as amount of energy released when fuel is burned completely in a steady flow process and the product are returned to the state of the reactant.

4-Air requirement:

The relationship between the actual quantities of air supplied for combustion to theoretical air requirements is called the excess air ratio.

The theoretical air requirements is the minimum quantity of air needed for complete combustion of fuel, in the case of the gasoline this stoichiometric air – fuel ratio is approximately 14:1.

5-Ignition limits:

The richer or leaner the air – fuel mixture, the harder it is to ignite and the slower the combustion process.

At lower and upper ignition limits the mixture is no longer ignitable.

The lower ignition limit often makes starting a cold gasoline engine more difficult due to an over lean mixture.

6-Auto ignition temperature:

It is the temperature at which the fuel in contact with air ignites and continues to burn, this temperature is not physico- chemical constant of the particular fuel, but is dependent upon the respective condition and is severely affected by foreign matters.

7-Density:

Particular types of fuel or fuel component are designated on the basis of their density; a lower density increases fuel combustion.

3.4 Heat release analysis

After covering the factors affecting or relating to the combustion process in any spark ignition internal combustion engine, it is intended now to determine analytically the heat release sequence and to make a quantity solution of the actual temperature produced in the combustion chamber during the sequenced events that characterize the combustion process. In later chapters the values of temperature calculated in this section, and further, analyzed using "Microsoft excel" with many other parameters to get the combustion chamber temperature content at every crank angle.

The first step is to calculate the air-fuel ratio (A/F), which is defined to be the quantity of air wanted to burn a possible quantity of fuel. The burning of gasoline occurs according to the following equation: [9]

$$C_{8.25}H_{15.5} + 12.135(O_2 + 3.76N_2) \rightarrow 8.26CO_2 + 7.75H_2O + 45.6272N_2$$

A/F = mass of air / mass of fuel

Taking the molar weights of each above species and element, we get

$$m_{fuel} = 8.26 * M_C + 15.5 * M_H = 8.26 * 12 + 15.5 * 1 = 114.62 Kg$$
$$m_{air} = 12.135 * (2 * M_O + 2 * 3.76 * M_N) = 12.135 * (2 * 16 + 2 * 3.76 * 14) = 1665.8928 Kg$$
$$\Rightarrow \frac{A}{F} = \frac{1665.8928}{114.62} = 14.54$$

So; 14.54 mass of air is needed to completely burn 1 mass of gasoline fuel.

The lower heating value is defined as the amount of energy released when fuel is burned completely; i.e. air-fuel ratio is 1, in a steady flow process and products are returned to the state of reactant.[2]

$$LHV = H_{products} + H_{mixture}$$

$$Q - W = \sum Np\left(\bar{h}_f{}^{o} + \bar{h} - \bar{h}^{o}\right)p - \sum Nm\left(\bar{h}_f{}^{o} + \bar{h} - \bar{h}^{o}\right)m$$

Where:

M_X: species molecular weight…. Kg/Kmol

H is the enthalpy….. $kJ / kmol$.

Q is the heat content….. $kJ / kmol$.

W is the work….. $kJ / kmol$.

N_p is the number of moles of products species.

N_m is the number of moles mixture species.

$\bar{h}_f{}^{o}$ is the enthalpy of formation at the slandered reference state….. $kJ / kmol$.

$\bar{h}$ is the sensible enthalpy at the specified reference state of 298 °K and 1atm….. $kJ / kmol$.

$\bar{h}^{o}$ is the enthalpy at the reference state….. $kJ / kmol$.

$$Q - W = (8.26 * -393520 + 7.75 * -285830) - (-294950) = 5215707.7 kJ / kmol$$

Hence;

$$LHV = \left(\frac{Q - W}{m_f}\right) = \frac{5215707.7}{114.64} = 45.5 MJ / kg$$

During combustion, the value of adiabatic flame temperature, which occurs in the limit case of no heat loss to surrounding (Q=0), the temperature of the products will reach maximum.

The balanced equation for the combustion process with the theoretical amounts of air is:

$$C_{8.26}H_{15.5} + 12.135(O_2 + 3.76N_2) \rightarrow 8.26CO_2 + 7.75H_2O + 45.6272N_2$$

The adiabatic flame temperature relation in this case reduces to:

$$\sum Np\left(\overline{h}_f^{\,o} + \overline{h} - \overline{h}^{o}\right)p = \sum Nm\left(\overline{h}_{reac\tan ts}\right) = \left(N * \overline{h}_f^{\,o}\right)_{C_{8.26}H_{15.5}}$$

Since all the reactants are at the standard reference state and $\overline{h}_f^{\,o} = 0$ for O_2 and N_2.

$\overline{h}_f^{\,o}$ and $\overline{h}$ values of various components at 298 K are illustrated in table 3.2. [9]

Table3. 2: Values of enthalpy of formation and sensible enthalpy of different specie

Substance	$\overline{h}_f^{\,o}$ $kJ/kmol$	$\overline{h}_{298}$ $kJ/kmol$
$C_{8.26}H_{15.5}$	-249950	
O_2	0	8682
N_2	0	8669
H_2O	-241820	9904
CO_2	-393520	9364

Substituting the last equation, we get;

$$\begin{aligned}
&(8.26KmolCO_2)\left[(-393520 + \overline{h}_{CO_2} - 9364)kJ/kmolCO_2\right] \\
&+ (7.75kmolH_2O)\left[(-241820 + \overline{h}_{H_2O} - 9904)kJ/kmolH_2O\right] \\
&+ (45.62kmolN_2)\left[(0 + \overline{h}_{N_2} - 8669)kJ/kmolN_2\right] \\
&+ (1kmolC_{8.26}H_{15.5})\left[(-249950)kJ/kmolC_{8.26}H_{15.5}\right]
\end{aligned}$$

That yields;

$$8.24\bar{h}_{CO_2} + 7.75\bar{h}_{H_2O} + 45.627\bar{h}_{H_2O} = 5424278.504kJ$$

A first guess is obtained by dividing the right hand term of this equation by the total number of moles, which yields:

$$\frac{5424278.504}{8.26+7.75+45.6276} = 88002.75326kJ/kmol$$

This enthalpy value will correspond to about 2650 ok for N_2, 2100 ok for H_2O and 1800 k for CO_2. Noting that the majority of moles are N_2, we see that Tprod. Will be closed to 2600 k, but some where under it. Therefore, a good first guess 2400 ok is. At this temperature:

$$\begin{aligned}&8.26\bar{h}_{CO_2} + 7.75\bar{h}_{H_2O} + 45.6276\bar{h}_{H_2O}\\&= 8.26*12512 + 7.75*103508 + 45.6276*79320\\&= 5455123.752kJ\end{aligned}$$

This value is higher than 5424278.504 kJ. Therefore, the actual temperature will be slightly under 2400 k. Next, we choose 2350 k. It yields:

$$8.26*122091 + 7.75*100846 + 45.6276*77496 = 5325984.65kJ$$

Which is lower than 5424278.504 kJ, therefore, the actual temperature of products is between 2350 and 2400 ok. By interpolation, it is found to be

$$T_{Products} = 2394.5K$$

3.5 Conclusion

In this chapter, the study of the combustion process of all its courses and factors that affect its development and quality, made it possible to imagine how it is important to study the thermal loading on each zone on the combustion chamber since the instantaneous rise in temperature is large enough to increase thermal stresses on a specific critical areas which leads, if repeated, to material deformation or even collapse.

In later chapters, an exact models and analysis of heat transfer and thermal loading on cylinder head will be implemented.

Chapter Four

Heat transfer

4.1 Introduction

4.2 Heat Transfer Mechanisms

4.3 Parameters Affecting Engine Heat Transfer

4.4 Cylinder head heat transfer

4.5 Exhaust valves seat heat transfer

4.1 Introduction

In most common internal combustion engines, air-fuel mixture is the medium used to produce mechanical work through chemical reactions. For typical four-stroke reciprocating engines, the mixture in the combustion chamber is compressed and then ignited, resulting in a tremendous increase of pressure and temperature. Pressure difference between the combustion chamber and the ambient forces the piston to move up and down, producing mechanical work.

The second law of thermodynamics states that a certain amount of heat generated from the combustion products must be rejected. Coolant is typically used in the engine-cooling jacket as a medium of accommodating the heat rejection. An insufficient heat removal rate could result in higher thermal stress in the engine.

An improved cooling system can potentially reduce the thermal stress, especially on critical zones with insufficient cooling, resulting in a longer engine lifetime. A smaller electronically controlled pump, which requires less power, can now be used to substitute the old inefficient mechanical pump to improve engine efficiency. This can be accomplished by understanding the physical processes occurring in the engine itself. Fast transient heat flux from the combustion products to the combustion chamber interior and transient heat loss to the cooling passages are important factors affecting the heat transfer process in IC engines. The objective of this study is to predict transient thermal behavior in the solid part of the engine. It should be noted that steady state condition would never be attained in this type of application due to the moving pistons and valves; therefore, from an engineering point of view, it is good enough to consider the cyclic or periodic thermal behavior in the engine as an appropriate direction to look for hot spots.

The internal combustion engine is a rich source of examples of almost every conceivable type of heat transfer. There are a wide range of temperatures and heat fluxes in the various components of the internal combustion engine. Internal combustion engines come in many sizes, from small model airplane engines with a 0.25 " (6 mm) bore and stroke to large stationary engines with a 12" (300 mm).

In this chapter, the heat transfer is to be realized and studied over a cylinder head model, 12mm thick and 80mm diameter, made from an aluminum alloy pressed in the engine head, an intake and exhaust valves with valves head diameters of 35mm and 30.02mm respectively forged from cast iron and exhaust valve seat is being cut in the cylinder head with an angle of 45° and 2mm width.

Fig (4.1) shows thermal network model for wall heat transfer. Heat transfer begin from the center of the combustion chamber ,it has high temperature values (T_g) , then heat transfers with convection (gas has convection heat transfer coefficient (h_g)) from the center of the combustion chamber to the piston face, cylinder head and cylinder wall, then conduction throw walls with cylinder, piston and cylinder head which have thermal conductivity (k), then convection from these walls to cooling water into water jackets which have convection heat transfer coefficient (hc) and the temperature of cooling water is (T_c) , then radiation to outer environment.

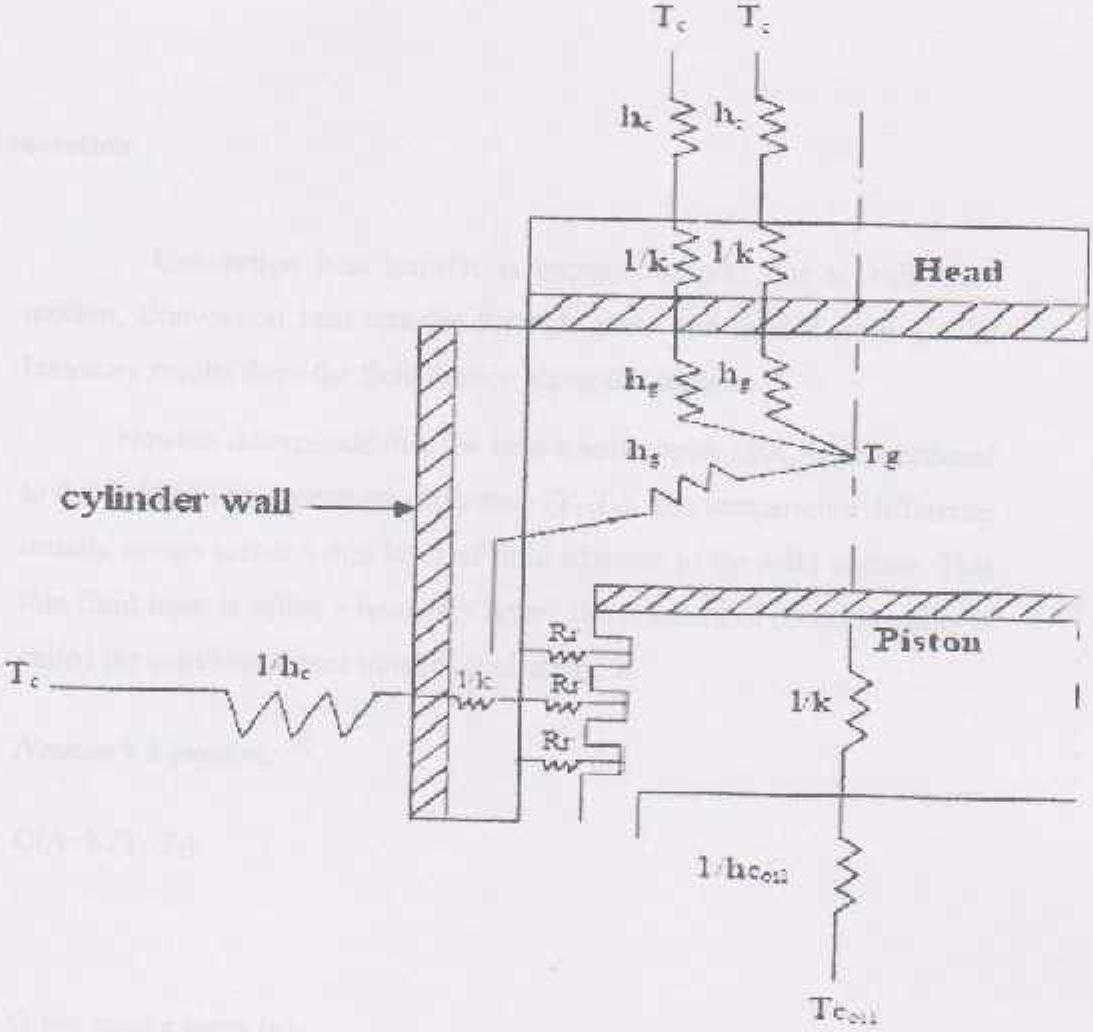

Figure 4. 1: Thermal Network for wall heat transfer

4.2 Heat Transfer Mechanisms

In the internal combustion engine, there are three mechanisms of heat transfer:-

1. Convection
2. Conduction
3. Radiation

4.2.1 Convection

Convection heat transfer is energy transport due to bulk fluid motion. Convection heat transfer through gases and liquids from a solid boundary results from the fluid motion along the surface.

Newton determined that the heat transfer/area, Q/A, is proportional to the fluid solid temperature difference (T_s-T_f). The temperature difference usually occurs across a thin layer of fluid adjacent to the solid surface. This thin fluid layer is called a boundary layer. The constant of proportionality is called the convection heat transfer coefficient, h.

Newton's Equation: [4]

$$Q/A=h\,(T_s-T_f)$$

Where:-

Q: heat transfer energy (w).

A: inside surface area of combustion chamber (m^2).

h: convection heat transfer coefficient (w/m^2k).

$(T_s - T_f)$: the fluid (gas) solid (wall) temperature difference (k).

The convection heat transfer coefficient depends on the type of fluid (density) and the fluid velocity. The heat flux depends on the area of interest either the local or the average area. The various types of convection heat transfer are usually categorized into the following areas illustrated in table (4.1). [4]

Table 4. 1: Convection types and typical values

Convection type	**Description**	**Typical value of h (W/m^2K)**
natural convection	fluid motion induced by density differences	10 (gas) 100 (liquid)
forced convection	fluid motion induced by pressure differences from a fan or pump	100 (gas) 1000 (liquid)
boiling	fluid motion induced by a change of phase from liquid to vapor	20,000 or greater
condensation	fluid motion induced by a change of phase from vapor to liquid	20,000 or greater

4.2.2 Conduction

Before considering conduction heat transfer in engine, it will facilitate the discussion to first consider heat transfer within an infinite slab, this can make the convection itself to be considered as conduction heat transfer, because the gases make boundary layers.

Conduction heat transfer is energy transport due to molecular motion and interaction. Conduction heat transfer through solids is due to molecular vibration. Fourier determined that **Q/A**, the heat transfer per unit area (W/m^2) is proportional to the temperature gradient dT/dx. The constant of proportionality is called the material thermal conductivity k.

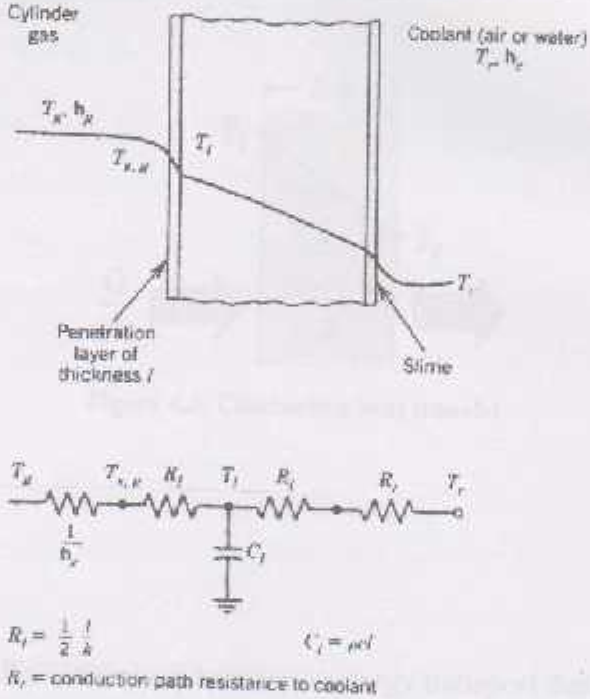

Figure 4.2: A one-dimensional representation of the heat loss from the cylinder gas

Fourier's equation: [4]

$$Q / A = -k \frac{dT}{dx}$$

Where:

Q: heat transfer energy (w).

A: inside surface area of combustion chamber (m^2).

K: thermal conductivity of cylinder wall (w/m.k).

dT: temperature difference (k).

dx: thickness of cylinder wall (m).

The thermal conductivity also depends somewhat on the temperature of the material.

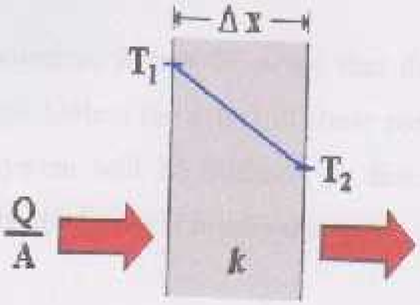

Figure 4.3: Conduction heat transfer

4.2.3 Radiation

Radiation heat transfer is energy transport due to emission of electromagnetic waves or photons from a surface or volume. The radiation does not require a heat transfer medium and can occur in a vacuum. The heat transfer by radiation is proportional to the fourth power of the absolute material temperature. The proportionality constant σ is the Stefan-Boltzman constant which equals to $5.67 * 10^{-8}$ W/m^2K^4. The radiation heat transfer also depends on the material properties represented by ε, the emissivity of the material.

$$Q / A = \varepsilon \sigma T^4 \qquad 4\text{-}3$$

Where:-

Q: heat transfer energy (w).

A: outer area (m^2).

T: outer surface temperature (k).

σ: is the Stefan-Boltzman constant, equal to 5.67×10^{-8} W/m^2K^4.

ε: the emissivity of the material (dimensionless).

4.3 Parameters Affecting Engine Heat Transfer

From the above discussion, it may be noted that the engine heat transfer depends upon many parameters. Unless the effect of these parameters is known, the design of a proper cooling system will be difficult. In this section, the effect of various parameters on engine heat transfer is briefly discussed.

4.3.1 Fuel-Air Ratio

A change in F/A ratio will change the temperature of the cylinder gases and affect the flame speed. The maximum gas temperature will occur at an equivalence ratio of about 1.12 i.e., at F/A ratio about 0.075. At this F/A ratio ΔT will be a maximum.

4.3.2 Compression Ratio

An increase in compression ratio causes only a slight increase in gas temperature near the top dead center; but, because of greater expansion of the gases, there will be a considerable reduction in gas temperature near bottom dead center where a large cylinder wall is exposed.

4.3.3 Spark Advance

A spark advance more than the optimum as well as less than the optimum (retard) will result in increased heat rejection to the cooling system. This is mainly due to the fact that the spark timing other than MBT (Minimum spark advance for Best Torque) will reduce the power output and thereby more heat is rejected

4.3.4 Pre-ignition and Knocking

Effect of Preignition is the same as advancing the ignition timing. Larger spark advance might lead to erratic running and knocking. Though knocking causes larger changes in local heat transfer conditions, the over-all effect on quantitative information is available regarding the effect of Preignition and knocking on engine heat transfer.

4.3.5 Engine Output

Engines which are designed for high mean effective pressure or high piston speed, heat transfer will be less. Less heat will be lost for the same indicated power in large engines.

4.4 Cylinder head heat transfer

The air-fuel mixture entering a cylinder during the intake stroke may be hotter or cooler than the cylinder head, with the resulting heat transfer being possible in both directions. During the compression stroke, the temperature of the gas increases and by the time combustion starts, their already will be a convection heat transfer to the cylinder head, the temperature on the head can be calculated by using equation:

$$\frac{Q}{A} = h \times (T_g - T_{head}) \qquad 3\text{-}1$$

Where

Q/A: The convection heat flux (W/m^2)

h: The convection heat transfer coefficient (W/m^2.K)

$T_g - T_{head}$: the temperature difference between cylinder head and the combustion chamber gas content ($^\circ$k)

Considering the dimensions of the cylinder head, we get:

$$Q_{total}/A = h(T_g - T_{coolant}) = \frac{(T_g - T_{coolant})}{(R_{h,g} + R_{c,head} + R_{h,coolant})}$$

Where:

R_x : Thermal Resistance

$$R_{cond} = \frac{L}{k}$$

$$R_{conv} = \frac{1}{h}$$

The gas convection resistance is a function of the convection heat transfer for the gas. which is a function of the crank angle 0, at (384 crank angel) the gas temperature is (T=2564.3497 K), convection heat transfer (h=659.8405 W/m^2.K)

$$R_{h,g}=\frac{1}{659.8405}=1.515*10^{-3}m^2K/W$$

For the aluminum alloy cylinder head, the thermal conductivity (221W/m.K)[5] and its thickness $d=0.012m$, the conduction thermal resistance is:

$$R_{c,head}=\frac{d}{k}=\frac{12\times10^{-3}}{221}=54.3*10^{-6}mK/W$$

The thermal resistance for the water coolant ($h_{h,coolant}$ =1462W/K.m^2) [3] gives:

$$R_{h,coolant}=\frac{1}{1462}=6.84\times10^{-4}m^2K/W$$

$$Q_{total}/A=\frac{(2564.3497-350)}{(1515\times10^{-6}+54.3\times10^{-6}+684*10^{-6})}=982714.1082kW/m^2$$

We can calculate the temperature on the cylinder head, by using the heat flux equation, temperature on the Cylinder head gives:

$$T_{head}=T_g-Q_{total}R_{h,g}=2564.3497-982.714\times10^3*1.515\times10^{-3}=1075.53799°K$$

The gas convection heat transfer coefficient h_g, has a varied value over the crank angle, due to variations in the gas properties and conditions.

Eichelberg proposed a correlation that describes the effects of the instantaneous combustion chamber pressure P_α and temperature T_α, and the mean piston speed C_m on the instantaneous h_g, Ganesan modified that relation to the following form [4]

$$h_g=2.1*(C_m)^{2/3}*(P_\alpha*T_\alpha)^{1/2}$$

Where:

C_m is the mean piston speed (m/sec), $C_m=2*L*N$ [3]

L: connecting rod length (m)

N: engine speed of rotation in (rps)

P_α: pressure at the crank angel position (kPa) [8]

$$P_{\alpha+1} = P_\alpha * [\frac{V_\alpha}{V_{\alpha+1}}]^{K\alpha} + \frac{R_{air}}{(V_\alpha + 1) * C_{air} * M_{act}} * W_{\alpha+1} * \Delta\alpha \ldots\ldots\ldots\ldots MPa$$

***R**: Bore (m)*

T_α: temperature at the crank angel position (K)

$$T_{\alpha+1} = \frac{P_\alpha * V_\alpha * 10^6}{R_{mix}} \ldots P_\alpha(MPa) \ldots\ldots R_{mix}(J/Kg.K) \ldots\ldots\ldots\ldots K$$

However, the pressure and the temperature in the combustion chamber both are functions of crank angel. Moreover, the values of all parameters which appeared and will appear in this chapter; namely, temperature, pressure, convection heat transfer coefficient, mean piston speed and combustion chamber volume all versus crank angel, will be found in the appendix starting on page 83

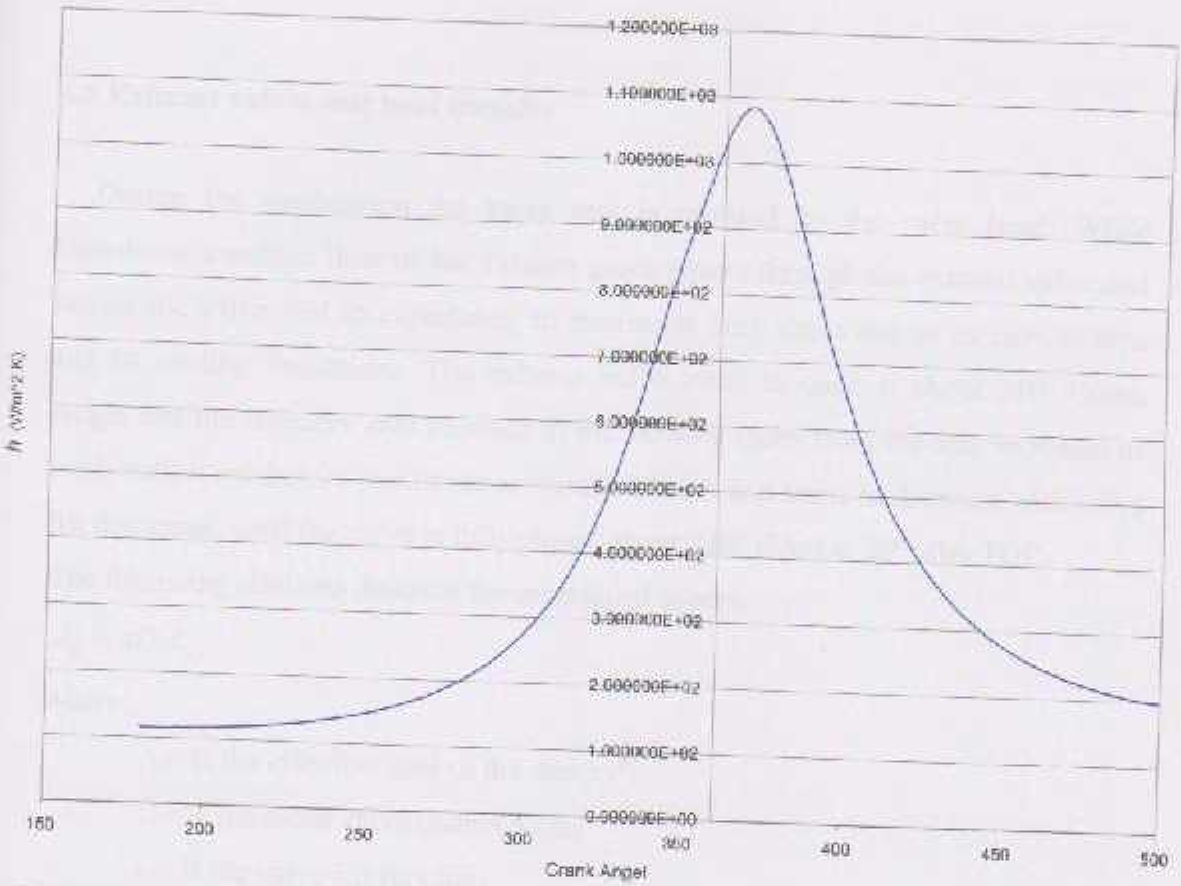

Figure 4.4: thermal convection coefficient heat transfer crank angle diagram

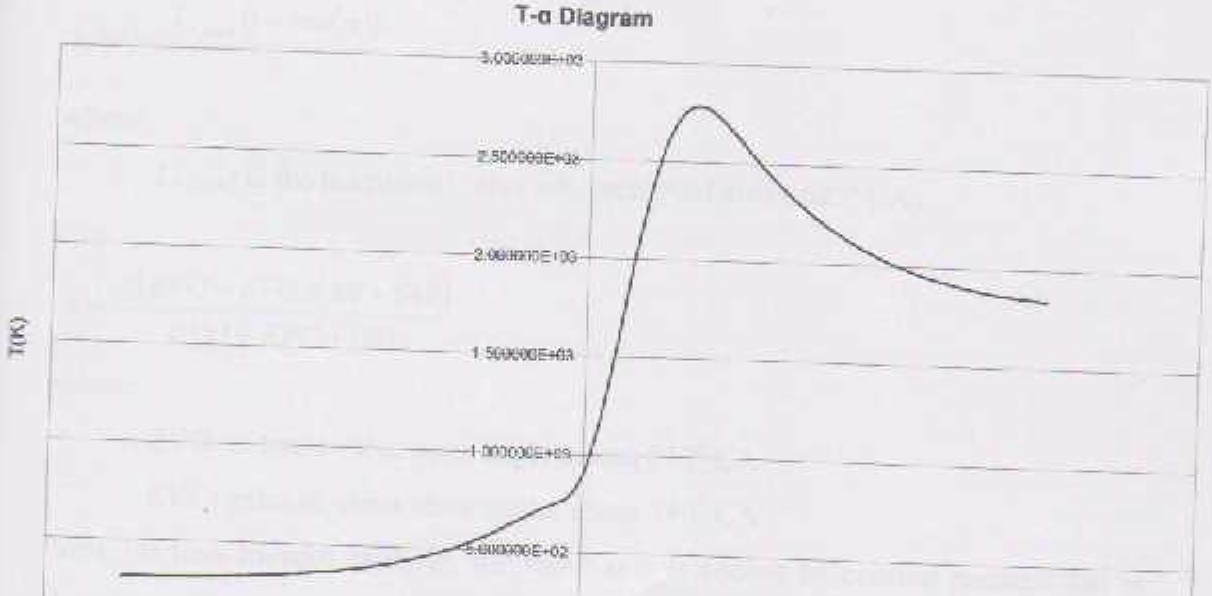

Figure 4.5: Temperature Crank angel diagram

4.5 Exhaust valves seat heat transfer

During the combustion the valve seat is covered by the valve head. While blowdown a sudden flow of hot exhaust gases passes through the exhaust valve and causes the valve seat to experience an enormous heat stress due to its narrow area and its cooling limitations. The exhaust valve starts to open at about 510° Crank Angel and the effective area exposed to the flowing gases from the seat increases as well, until it reaches its maximum at about 625° CA and starts to decrease with valve lift decreases, until the valve is fully closed about 740° CA; i.e. 20° after TDC.

The following relations describe the mentioned events.

$$A_R = \pi D_v L_v$$

where:

A_R: is the effective area of the seat(m^2)

D_v: is the mean valve diameter (m)

L_v: is the valve lift function

$$L_v(\theta) = \frac{L_{v,max}\left(1+\cos(\varphi)\right)}{2}$$

where:

$L_{v,max}$: is the maximum valve lift. (achieved about 625° CA)

$$\varphi = \frac{\pi\left(EVO - EVC + 2\theta + 540\right)}{EVO + EVC + 180}$$

where:

EVO: exhaust valve open angle; about 510° CA

EVC: exhaust valve close angle; about 740° CA

Now for heat transfer analysis, the valve seat is cooled by cooling passage that is 6mm away from the seat.

For minimum valve lifts and higher exhaust gases temperature and pressure, Eichelberg's formula of h_g by Ganesan modification can predict the heat transfer coefficient value for a certain P_a and T_a.

Fig(4.6) shows the measured cylinder pressure and calculated exhaust gas temperature Vs. CA for a certain SI IC engine. [2]

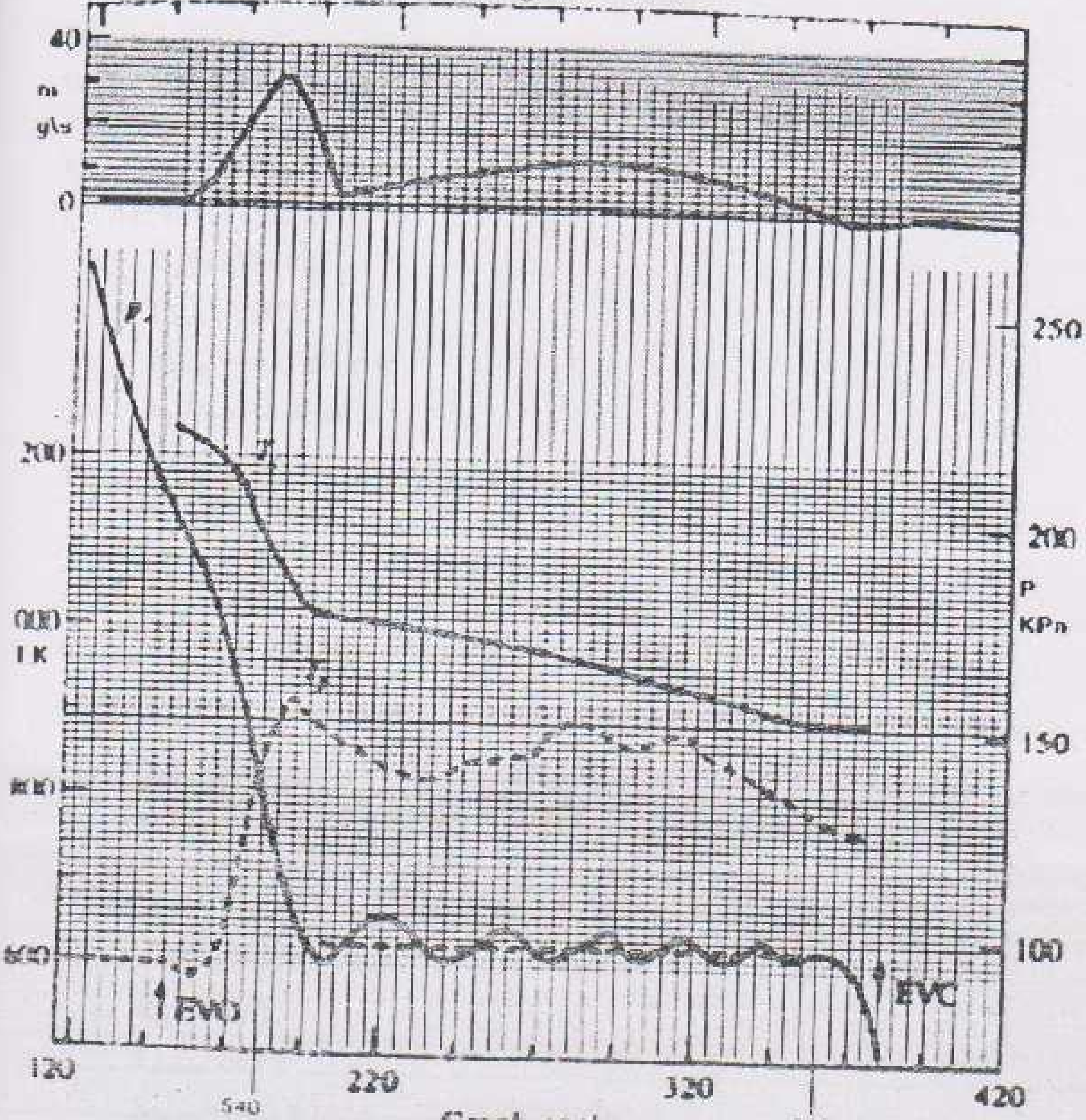

Figure 4.6 Measured cylinder pressure, calculated cylinder gas temperature and exhaust gas mass flow rate Vs. CA

$$R_{h,g} = \frac{1}{h_g} = \frac{1}{71.3988} = 0.014005 m^2K/W$$

$$R_{c,head} = \frac{w}{K} = \frac{6*10^{-3}}{221} = 27.15*10^{-6} K/W$$

$$R_{h,coolant} = \frac{1}{1462} = 6.84*10^{-4} m^2K/W$$

Substituting:

$$Q_{seat} = 0.000113097*\frac{(980.1-350)}{(0.014005+0.02715*10^{-3}+0.684*10^{-1})} = 4.88kJ$$

And finally, for A_R=0.0000520321m^2:

$T_{c,g}$=905.54^{o}k

$T_{coolant}$=350^{o}k

$h_{coolant}$=1462 W/m^2.K

And h_g 69.71584 W/m^2.K

$$R_{h,g} = \frac{1}{h_g} = \frac{1}{69.71584} = 0.014394 m^2K/W$$

$$R_{c,head} = \frac{w}{K} = \frac{6*10^{-3}}{221} = 27.15*10^{-6} K/W$$

$$R_{h,coolant} = \frac{1}{1462} = 6.84*10^{-4} m^2K/W$$

Substituting:

$$Q_{seat} = 0.0000052032l*\frac{(90554-350)}{(0.014394+0.02715*10^{-3}+0.684*10^{-1})} = 4.88kJ$$

Now, and after showing the actual heat transfer on both the engine head and exhaust valve seat, it will be easier to understand and illustrate the thermal stress representation on the next chapter.

Chapter Five

Thermal Loading

5.1 Introduction

5.2 Heat Equation

5.3 **Piston and Cylinder Wall Thermal Loading**

5.1 Introduction

Internal combustion engines at best can transfer about 25 - 35 % of chemical energy in the fuel into mechanical energy, about 35% of the heat generated is lost to the cooling medium, remainder is being dissipated through exhaust and lubricating oil

During the process of combustion, the cylinder gas temperature often reaches quite high value, a considerable amount of heat is transferred to the walls of the combustion chamber; Excessive thermal loading on critical regions may result in material deformation or even destruction; abnormal combustion for instance will result in a burned exhaust valves due to excessive heat rejection on the blowdown process. Further more; an erratic blowdown process will directly lead to serious damages in exhaust valve seat which will be sensed immediately as lake in engine's power.

5.2 Heat Equation

Nomenclature:

α : thermal Diffusivity
t : time
u : unknown (Temp)
x : lengthe in catesian system
k : coefficient of thermal conductivity
v : unokown 2
n : unit normal
i, j, k : unit vectors in a cartesian coordinate system
δ : central - difference operaters
G : amplefier vactor
h : convection heat transfer coefficient

The one dimension heat equation

$$\frac{\partial u}{\partial t} = \alpha \frac{\partial^2 u}{\partial x^2} \qquad 4\text{-}1$$

is a parabolic PDE. In its form, it is the governing equation for heat conduction or diffusion in a 1-D isotropic medium. It can be used to "model" in a simple fashion the parabolic boundary – layer equation for the initial condition

$$u(x,0) = f(x)$$

And boundary conditions

$$u(0,t) = u(1,t) = 0$$

Is

$$u(x,t) = \sum_{n=1}^{\infty} A_n e^{-\alpha k^2 t} \sin(kx) \qquad 4\text{-}2$$

Where

$$A_n = 2\int_0^1 f(x)\sin(kx)dx$$

And $k = n\pi$. Let us now examine some of the most important finite-difference algorithms that can be used to solve the heat equation.

5.2.1 Richardson's Method

Richardson (1910) proposed the following explicit one-step three time level scheme for solving the heat equation.

$$\frac{u_j^{n+1} - u_j^n}{\Delta t} = \alpha \frac{u_{j+1}^n - 2u_j^n + u_{j-1}^n}{(\Delta x)^2} \qquad 4\text{-}3$$

This scheme is second order accurate with T.E of $O[(\Delta t)^2, (\Delta x)^2]$.

Unfortunately this method was proved to be unconditionally unstable and cannot be used to solve the heat equation. It is presented here for historic purposes only.

5.2.2 Keller Box and Modified Box Method

The Keller box method, (Keller, 1970) for parabolic PDEs, is an implicit scheme with second-order accuracy in both space and time. This formulation allows for the spatial and temporal steps to vary without causing deterioration in the formal second-order accuracy. The scheme considerably differs from others, so far, system of first-order equations result for the 1-D heat equation

$$\frac{\partial u}{\partial t} = \alpha \frac{\partial^2 u}{\partial x^2}$$

We can define

$$v = \frac{\partial u}{\partial x}$$

so that the second-order heat equation can be written as a system of two first-order equation:

$$\frac{\partial u}{\partial x} = v$$

$$\frac{\partial u}{\partial t} = \alpha \frac{\partial v}{\partial x}$$

Now we attempt to approximate these equations using only central differences, making use of the four points at the corners of a "box" about $(n+\frac{1}{2}, j-\frac{1}{2})$ (see fig 5.1). The resulting difference equations are

$$\frac{u_j^{n+1} - u_{j-1}^{n+1}}{\Delta x_j} = v_{j-\frac{1}{2}}^{n+1} \qquad 4\text{-}4$$

$$\frac{u_{j-\frac{1}{2}}^{n+1} - u_{j-\frac{1}{2}}^{n}}{\Delta t_{n+1}} = \frac{\alpha(v_j^{n+\frac{1}{2}} - v_{j-1}^{n+\frac{1}{2}})}{\Delta x_j} \qquad 4\text{-}5$$

Where the difference molecules are shown in fig 5.2 and fig 5.3. The mesh functions that contain a subscript or superscript $\frac{1}{2}$ are defined as averages.

After substituting the averaged expressions into equations (5-4) and (5-5) the new difference equations become

$$\frac{u_j^{n+1} - u_{j-1}^{n+1}}{\Delta x_j} = \frac{v_j^{n+1} + v_{j-1}^{n+1}}{2} \qquad \text{4-6}$$

$$\frac{u_j^{n+1} + u_{j-1}^{n+1}}{\Delta t_{n+1}} = \alpha \frac{v_j^{n+1} - v_{j-1}^{n+1}}{\Delta x_j} + \frac{u_j^{n} + u_{j-1}^{n}}{\Delta t_{n+1}} + \alpha \frac{v_j^{n} - v_{j-1}^{n}}{\Delta x_j} \qquad \text{4-7}$$

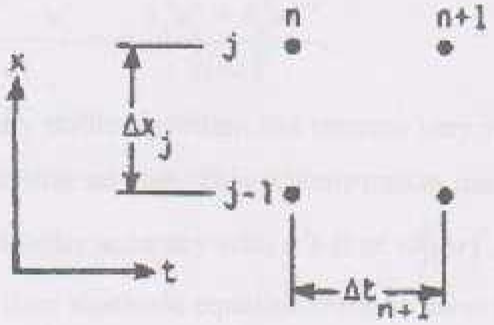

Figure 4-1: Grid box scheme

Figure 4-2: Difference molecule for evaluation of $v_{j-\frac{1}{2}}^{n+1}$

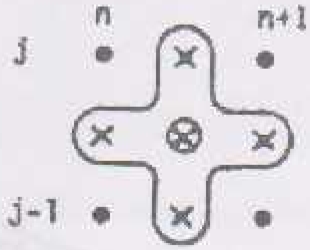

Figure 4-3: Difference molecule for Eq (5.5)

5.2.3 Crank-Nicolson Method

Crank and Nicolson (1947) used the following implicit algorithm to solve the heat equation

$$\frac{u_j^{n+1}-u_j^n}{\Delta t}=\alpha\,\frac{\delta_x^2 u_j^n+\delta_x^2 u_j^{n+1}}{2(\Delta x)^2} \qquad \text{5-8}$$

This unconditionally stable algorithm has become very well known and is referred to as the Crank-Nicolson scheme. This scheme makes use of trapezoidal differencing to achieve second-order accuracy with a T.E of $O\left[(\Delta t)^2,(\Delta x)^2\right]$. Once again, a tridiagonal system of liner algebraic equation must be solve at each time level $n+1$. The modified equation for the Crank-Nicolson method is

$$u_t-\alpha u_{xx}=\frac{\alpha(\Delta x)^2}{12}u_{xxxx}+\left[\frac{1}{12}\alpha^3(\Delta t)^2+\frac{1}{360}\alpha(\Delta x)^4\right]u_{xxxxxx}+\ldots \qquad \text{4-9}$$

The amplification factor

$$G=\frac{1-r(1-\cos\beta)}{1+r(1-\cos\beta)} \qquad \text{4-10}$$

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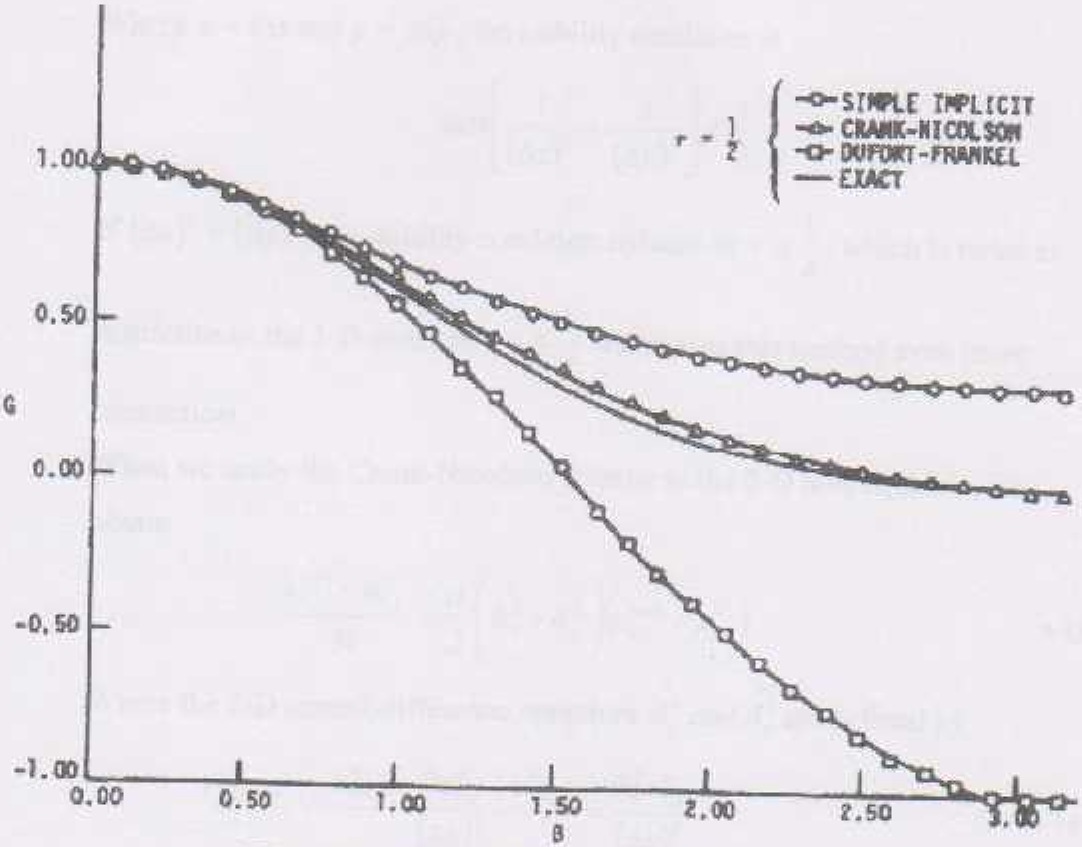

Figure 4-4: Amplification factor for several methods

5.2.4 Methods for the Two Dimensions Heat Equation

The 2-D heat equation is given

$$\frac{\partial u}{\partial t}=\alpha\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \qquad \text{4-11}$$

Since this PDE is different from the 1-D equation, caution must be exercised when attempting to apply the previous finite-difference methods in this equation. The following two examples illustrate some of the difficulties. If we apply the simple explicit method to the 2-D heat equation, the following algorithm results:

$$\frac{u_{i,j}^{n+1}-u_{i,j}^{n}}{\Delta t}=\alpha\left[\frac{u_{i+1,j}^{n}-2u_{i,j}^{n}+u_{i-1,j}^{n}}{(\Delta x)^2}+\frac{u_{i,j+1}^{n}-2u_{i,j}^{n}+u_{i,j-1}^{n}}{(\Delta y)^2}\right] \qquad \text{4-12}$$

Where $x = i\Delta x$ and $y = j\Delta y$, the stability condition is

$$\alpha\Delta t\left[\frac{1}{(\Delta x)^2}+\frac{1}{(\Delta y)^2}\right]\le\frac{1}{2}$$

If $(\Delta x)^2 = (\Delta y)^2$, the stability condition reduces to $r \le \frac{1}{4}$, which is twice as restrictive as the 1-D constraint $r \le \frac{1}{2}$ and makes this method even more impractical.

When we apply the Crank-Nicolson scheme to the 2-D heat equation, we obtain

$$\frac{u^{n+1}_{i,j}-u^{n}_{i,j}}{\Delta t}=\frac{\alpha}{2}\left(\hat{\delta}^2_x+\hat{\delta}^2_y\right)\left(u^{n-1}_{i,j}+u^{n}_{i,j}\right) \qquad 4\text{-}13$$

Where the 2-D central-difference operators $\hat{\delta}^2_x$ *and* $\hat{\delta}^2_y$ are defined by

$$\hat{\delta}^2_x u^n_{i,j}=\frac{u^n_{i+1,j}-2u^n_{i,j}+u^n_{i-1,j}}{(\Delta x)^2}=\frac{\delta^2_x u^n_{i,j}}{(\Delta x)^2} \qquad 4\text{-}14$$

$$\hat{\delta}^2_y u^n_{i,j}=\frac{u^n_{i,j+1}-2u^n_{i,j}+u^n_{i,j-1}}{(\Delta y)^2}=\frac{\delta^2_y u^n_{i,j}}{(\Delta y)^2}$$

As with the 1-Dcase, the Crank-Nicolson scheme is unconditionally stable when applied to the 2-D heat equation with periodic boundary conditions. Unfortunately, the resulting system of linear algebraic equation is no longer tridiagonal because of the five unknowns $u^{n+1}_{i,j}$, $u^{n+1}_{i+1,j}$, $u^{n+1}_{i-1,j}$, $u^{n+1}_{i,j+1}$ and $u^{n+1}_{i,j-1}$. The same is true for all the implicit schemes we have studied previously. In order to examine this further, let us rewrite Equation.(5-13) as

$$au^{n-1}_{i,j-1}+bu^{n+1}_{i-1,j}+cu^{n+1}_{i,j}+bu^{n+1}_{i+1,j}+au^{n+1}_{i,j+1}=d^n_{i,j} \qquad 4\text{-}15$$

Where

$$a = -\frac{\alpha\Delta t}{2(\Delta y)^2} = -\frac{1}{2}r_y$$

$$b = -\frac{\alpha\Delta t}{2(\Delta x)^2} = -\frac{1}{2}r_x$$

$$c = 1 + r_x + r_y$$

$$d_{i,j}^{n} = u_{i,j}^{n} + \frac{\alpha\Delta t}{2}\left(\hat{\delta}_x^2 + \hat{\delta}_y^2\right)u_{i,j}^{n}$$

If we apply Eq.(5-15)to the 2-D (6×6) computational mesh shown in fig.(5-4), the following system of 16 linear algebraic equation must be solved at each (n+1)time level:

$$\left[\begin{array}{cccccccccccccccc}
c & b & 0 & 0 & a & 0 & & & & & & & & & & 0\\
b & c & b & & & a & & & & & & & & & & \\
0 & b & c & b & & & a & & & & & & & & & \\
0 & & b & c & 0 & & & a & & & & & & & & \\
a & & & 0 & c & b & & & a & & & & & & & \\
0 & a & & & b & c & b & & & a & & & & & & \\
 & & a & & & b & c & b & & & a & & & & & \\
 & & & a & & & b & c & 0 & & & a & & & & \\
 & & & & a & & & 0 & c & b & & & a & & & \\
 & & & & & a & & & b & c & b & & & a & & \\
 & & & & & & a & & & b & c & b & & & a & 0\\
 & & & & & & & a & & & b & c & 0 & & & a\\
 & & & & & & & & a & & & 0 & c & b & & 0\\
 & & & & & & & & & a & & & b & c & b & 0\\
 & & & & & & & & & & a & & & b & c & b\\
0 & & & & & & & & & & 0 & a & 0 & 0 & b & c
\end{array}\right]
\begin{bmatrix}
u_{2,2}^{n+1}\\ u_{3,2}^{n+1}\\ u_{4,2}^{n+1}\\ u_{5,2}^{n+1}\\ u_{2,3}^{n+1}\\ u_{3,3}^{n+1}\\ u_{4,3}^{n+1}\\ u_{5,3}^{n+1}\\ u_{2,4}^{n+1}\\ u_{3,4}^{n+1}\\ u_{4,4}^{n+1}\\ u_{5,4}^{n+1}\\ u_{2,5}^{n+1}\\ u_{3,5}^{n+1}\\ u_{5,5}^{n+1}\\ u_{5,5}^{n+1}
\end{bmatrix}
=
\begin{bmatrix}
d_{2,2}^{''}\\ d_{3,2}^{'}\\ d_{4,2}^{'}\\ d_{5,2}^{''}\\ d_{2,3}^{'}\\ d_{3,3}\\ d_{4,3}\\ d_{5,3}^{'}\\ d_{2,4}^{''}\\ d_{3,4}\\ d_{4,4}\\ d_{5,4}^{''}\\ d_{2,5}^{''}\\ d_{3,5}^{'}\\ d_{4,5}^{'}\\ d_{5,5}^{''}
\end{bmatrix}
\qquad \text{4-16}$$

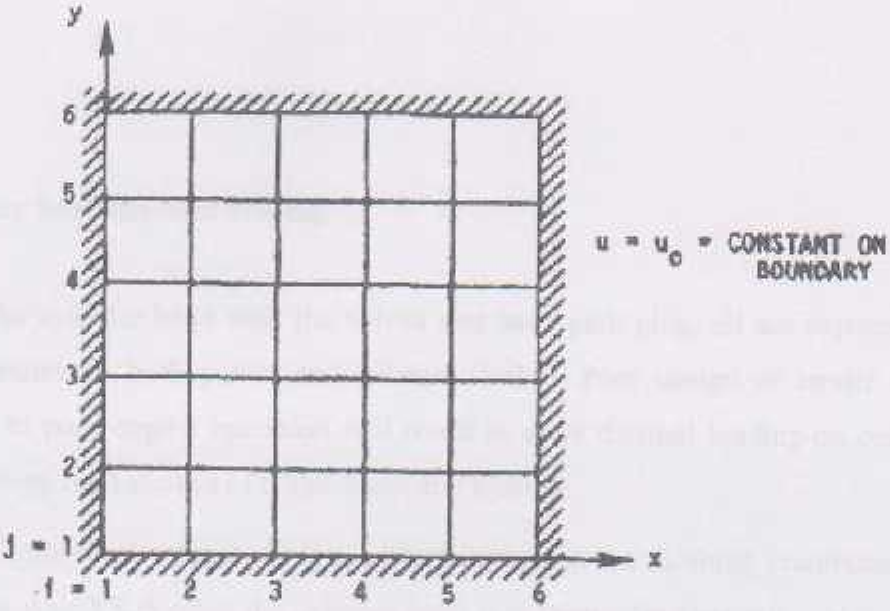

Figure 4-5: Two-dimensional computational mesh

Where $d' = d - au_0$

$d'' = d - bu_0$

$d''' = d - (a+b)u_0$

A system of equation like Eq(5-16) requires substantially more computer time to solve than dose a tridiagonal system. In fact, equations of this type are often solved by iterative methods.

5.2.5 Additional Comment

The selection of a best method for solving the heat equation is made difficult by the large variety of acceptable method. In general, implicit methods are considered more suitable than explicit method. For the 1-D heat equation, the Crank-Nicolson method is highly recommended because of its second-order temporal and spatial accuracy. For the 2-D and 3-D heat equation, both the ADI schemes of Douglas and Gunn and the modified Keeler box method give excellent result.

5.3 Cylinder head thermal loading

The cylinder head with the valves seat and spark plug, all are exposed to high temperature in both power and exhaust strokes. Poor design or erratic heat release due to poor engine operation will result in extra thermal loading on certain locations during both strokes of combustion and exhaust.

Finite element analysis is used in this project, the meshing preprocessing procedure in ANSYS divided the cylinder head into triangular elements, see fig (5-6); because the triangular element has more accuracy than rectangular element in the thermal analysis, the rectangular element is divided into tow triangular elements. Recalling that a triangular element is defined to have three nodes, on the other hand, this will represent the variation of a dependent variable. Considering the nodal tempertures as shown in fig (5-6), the following condition must be satisfied:

$$\begin{aligned} T &= T_i \quad \text{at } X = X_i \quad \text{and } Y = Y_i \\ T &= T_j \quad \text{at } X = X_j \quad \text{and } Y = Y_j \\ T &= T_k \quad \text{at } X = X_k \quad \text{and } Y = Y_k \end{aligned} \qquad \text{4-17}$$

The temperature nodal values gives by equations:

$$\begin{aligned} T_i &= a_1 + a_2 X_i + a_3 Y_i \\ T_j &= a_1 + a_2 X_j + a_3 Y_j \\ T_k &= a_1 + a_2 X_k + a_3 Y_k \end{aligned} \qquad \text{4-18}$$

Solving for a_1, a_2 and a_3, we get

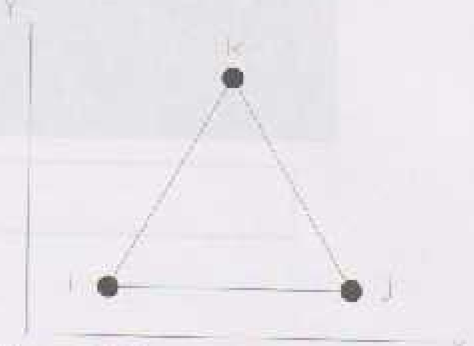

Figure 4-6 Triangular element

$$
\begin{aligned}
a_1 &= \frac{1}{2A}\left[(X_jY_k - X_kY_j)T_i + (X_kY_i - X_iY_k)T_j + (X_iY_j - X_jY_i)T_k\right] \\
a_2 &= \frac{1}{2A}\left[(Y_j - Y_k)T_i + (Y_k - Y_i)T_j + (Y_i - Y_j)T_k\right] \\
a_3 &= \frac{1}{2A}\left[(X_k - X_j)T_i + (X_i - X_k)T_j + (X_j - X_i)T_k\right]
\end{aligned}
\qquad \textbf{5-19}
$$

Where A is the area of the triangular element

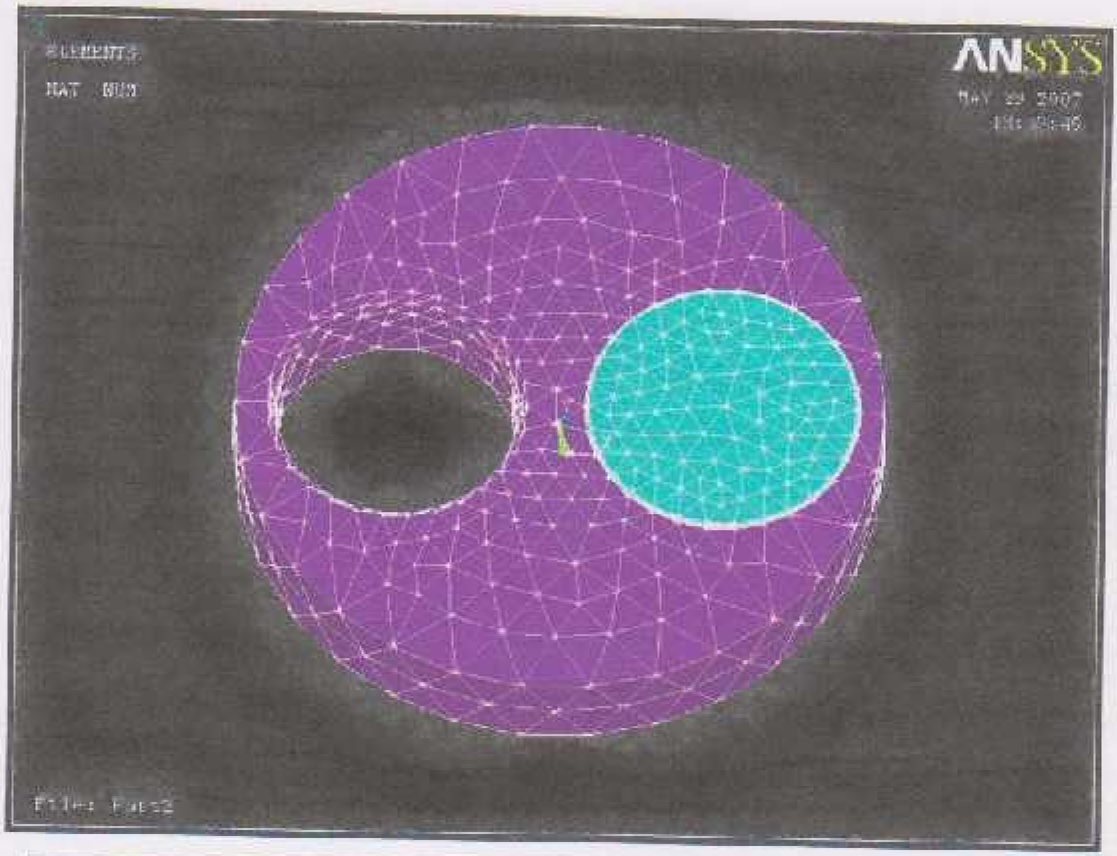

Figure 4-7 Cylinder head 3-D mesh (6250 Nodes)

Fig (5-7) shows a cylinder head mesh, this part was used to calculate the cylinder head thermal loading.

Employing the Galerkin approach, the three residual equation for a triangular element, in matrix form, are given by

$$\iint_A [S]^T \left(k_x \frac{\partial^2 T}{\partial X^2} + k_y \frac{\partial^2 T}{\partial Y^2} + \dot{q} \right) dA = 0 \qquad \text{5-20}$$

Where

$[S]^T = \begin{Bmatrix} S_i \\ S_j \\ S_k \end{Bmatrix}$ Where the shape functions S_i, Sj and S_k

As explained earlier, the convection boundary condition contributes to both the conductance matrix and the load matrix. The convective boundary condition contributes to the conductance matrices of elements (56, 1033, 1032, 1031, 1030, 1029……) according to the relationship

$$[\mathrm{K}]^{56}_{convection} = \frac{hl_{4,81}}{6} \begin{array}{c} \begin{bmatrix} 0 & 0 & 0 \\ 0 & 2 & 1 \\ 0 & 1 & 2 \end{bmatrix} \end{array} \begin{array}{c} 2287 \\ 4 \\ 81 \end{array}$$

The conductance matrix due to conduction in triangular element is given:

$$[\mathrm{K}]^{56}_{conduction} = \frac{k}{4A} \begin{bmatrix} \beta_{2287}^2 & \beta_{2287}\beta_4 & \beta_{2287}\beta_{81} \\ \beta_{2287}\beta_4 & \beta_4^2 & \beta_4\beta_{81} \\ \beta_{2287}\beta_{81} & \beta_4\beta_{81} & \beta_{81}^2 \end{bmatrix} + \frac{k}{4A} \begin{bmatrix} \delta_{2287}^2 & \delta_{2287}\delta_4 & \delta_{2287}\delta_{81} \\ \delta_{2287}\delta_4 & \delta_4^2 & \delta_4\delta_{81} \\ \delta_{2287}\delta_{81} & \delta_4\delta_{81} & \delta_{81}^2 \end{bmatrix}$$

Where the $\beta\ and\ \delta$ terms are given by the relation of equation (5-21). Because the $\beta\ and\ \delta$ terms are calculated from the difference of the coordinates of the involved nodes, it dose not matter where we place the origin of the coordinate system X, Y.

For using ANSYS to calculate the temperature on the (625) crank angel, (1000 rpm) motor speed and lambda (1), study on the 625 crank angel; because at this position the combustion chamber have maximum temperature, the output of ANSYS (temperatures on nodes) gives: (nodes from 425 to 6201 are eliminated to shorten the table)

```
PRINT TEMP NODAL SOLUTION PER
NODE

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****
 LOAD STEP=   1 SUBSTEP=   1
  TIME=  0.45455E-01 LOAD CASE=  0

  NODE    TEMP
    1  409.49
    2  405.12
    3  410.30
    4  398.33
    5  409.49
    6  406.89
    7  414.40
    8  411.48
    9  419.64
   10  404.36
   11  421.32
   12  415.16
   13  415.08
   14  405.67
   15  409.21
   16  394.64
   17  412.87
   18  404.05
   19  413.15
   20  409.99
   21  420.19
   22  409.24
   23  410.23
   24  396.21
   25  407.67
   26  380.21
   27  417.61
   28  385.40
   29  416.71
   30  386.04
   31  406.60
   32  412.47
   33  409.73
   34  420.61
   35  415.75
   36  421.94
37  415.04
   38  416.82
   39  378.40

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=   1 SUBSTEP=   1
  TIME=  0.45455E-01 LOAD CASE=  0

  NODE    TEMP
   40  417.65
   41  411.94
   42  411.61
   43  399.77
   44  417.85
   45  384.63
   46  414.36
   47  409.38
   48  416.30
   49  377.71
   50  417.36
   51  392.08
   52  421.82
   53  418.56
   54  413.59
   55  401.70
   56  413.46
   57  405.85
   58  408.46
   59  400.79
   60  413.37
   61  387.99
   62  369.41
   63  384.77
   64  386.82
   65  433.98
   66  382.05
   67  395.16
   68  429.61
   69  429.33
   70  420.30
```

```
  71  431.99
  72  430.70
  73  432.43
  74  387.21
  75  435.61
  76  389.31
  77  374.06
  78  431.47

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=   1  SUBSTEP=   1
  TIME=  0.45455E-01  LOAD CASE=  0

  NODE    TEMP
  79  393.28
  80  433.60
  81  385.02
  82  432.14
  83  375.98
  84  386.54
  85  373.26
  86  386.18
  87  430.57
  88  439.72
  89  435.83
  90  391.17
  91  435.95
  92  423.75
  93  423.27
  94  371.45
  95  428.53
  96  435.76
  97  434.40
  98  376.40
  99  429.52
 100  433.52
 101  440.38
 102  432.76
 103  382.65
 104  388.19
 105  433.72
 106  390.71
 107  435.52
 108  428.96
 109  381.17
 110  433.65
 111  432.95
 112  375.74
 113  431.79
 114  426.61
 115  386.54
 116  431.61
 117  379.92

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=   1  SUBSTEP=   1
  TIME=  0.45455E-01  LOAD CASE=  0

  NODE    TEMP
 118  376.51
 119  387.75
 120  388.37
 121  431.01
 122  385.32
 123  435.13
 124  431.56
 125  396.72
 126  419.32
 127  371.04
 128  428.10
 129  442.71
 130  438.01
 131  387.06
 132  423.70
 133  425.05
 134  384.74
 135  380.87
 136  425.24
 137  385.03
 138  386.69
 139  432.12
 140  388.71
 141  429.25
 142  432.18
 143  397.52
 144  429.95
 145  395.46
 146  389.67
 147  430.50
 148  387.16
 149  436.46
 150  433.46
 151  391.14
 152  432.06
 153  392.65
 154  430.23
 155  423.66
 156  383.85

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****
```

```
 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.45455E-01  LOAD CASE=  0

  NODE     TEMP
   157   421.49
   158   435.98
   159   426.65
   160   425.91
   161   405.03
   162   428.51
   163   385.45
   164   437.50
   165   421.27
   166   427.60
   167   391.54
   168   382.18
   169   427.49
   170   431.70
   171   434.35
   172   386.74
   173   425.60
   174   388.76
   175   395.69
   176   426.52
   177   390.05
   178   427.23
   179   392.88
   180   423.91
   181   393.79
   182   427.78
   183   431.27
   184   431.71
   185   427.22
   186   398.36
   187   430.00
   188   429.89
   189   395.92
   190   389.89
   191   426.86
   192   391.51
   193   426.45
   194   386.60
   195   400.06

 *****  POST1  NODAL  DEGREE  OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.45455E-01  LOAD CASE=  0

  NODE     TEMP
   196   434.31
   197   438.55
   198   439.36
   199   421.44
   200   420.86
   201   418.07
   202   420.71
   203   377.50
   204   391.25
   205   384.89
   206   387.07
   207   426.59
   208   429.56
   209   430.24
   210   398.73
   211   391.87
   212   429.75
   213   428.86
   214   386.95
   215   396.47
   216   385.50
   217   385.68
   218   427.64
   219   393.51
   220   394.89
   221   394.34
   222   395.09
   223   431.01
   224   434.98
   225   426.83
   226   386.80
   227   385.28
   228   428.61
   229   423.25
   230   423.31
   231   435.87
   232   436.42
   233   432.84
   234   429.14

 *****  POST1  NODAL  DEGREE  OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.45455E-01  LOAD CASE=  0

  NODE     TEMP
   235   429.25
   236   432.20
   237   432.47
   238   431.03
   239   426.31
   240   430.23
   241   434.17
   242   430.61
```

```
 243  428.79
 244  426.47
 245  428.47
 246  433.08
 247  430.07
 248  429.31
 249  435.19
 250  439.58
 251  439.74
 252  432.84
 253  430.00
 254  430.63
 255  429.58
 256  389.92
 257  432.30
 258  393.47
 259  432.74
 260  399.80
 261  427.95
 262  405.65
 263  426.73
 264  412.82
 265  431.21
 266  436.84
 267  433.41
 268  430.80
 269  382.53
 270  426.70
 271  437.57
 272  435.43
 273  400.64

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1 SUBSTEP=    1
  TIME=  0.45455E-01  LOAD CASE=  0

  NODE    TEMP
 274  435.09
 275  392.97
 276  430.53
 277  434.03
 278  439.89
 279  430.96
 280  385.37
 281  434.99
 282  404.56
 283  437.81
 284  432.08
 285  425.95
 286  434.48
 287  433.77
```

```
 288  428.90
 289  427.96
 290  433.80
 291  437.66
 292  438.92
 293  364.17
 294  442.96
 295  375.61
 296  383.05
 297  379.77
 298  446.58
 299  395.21
 300  384.46
 301  385.31
 302  397.30
 303  381.32
 304  400.10
 305  379.91
 306  380.12
 307  385.10
 308  379.84
 309  381.10
 310  447.00
 311  379.78
 312  389.65

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1 SUBSTEP=    1
  TIME=  0.45455E-01  LOAD CASE=  0

  NODE    TEMP
 313  383.94
 314  426.93
 315  394.75
 316  377.31
 317  383.44
 318  377.93
 319  383.83
 320  367.59
 321  438.04
 322  369.03
 323  444.57
 324  388.94
 325  382.01
 326  381.48
 327  393.04
 328  403.00
 329  405.06
 330  393.00
 331  385.79
 332  391.66
```

```
 333  373.21
 334  443.19
 335  380.47
 336  445.42
 337  386.17
 338  385.40
 339  384.99
 340  449.95
 341  378.98
 342  379.53
 343  376.86
 344  384.16
 345  373.30
 346  366.20
 347  375.38
 348  390.91
 349  371.23
 350  447.74
 351  368.48

 *****  POST1  NODAL  DEGREE  OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.45455E-01  LOAD CASE=   0

  NODE     TEMP
 352  369.85
 353  368.55
 354  391.63
 355  374.89
 356  454.05
 357  375.39
 358  371.20
 359  376.74
 360  263.89
 361  269.58
 362  260.35
 363  264.13
 364  270.16
 365  280.81
 366  271.11
 367  274.82
 368  274.14
 369  270.12
 370  271.61
 371  272.19
 372  268.70
 373  267.26
 374  271.40
 375  273.94
 376  274.95
 377  281.30
```

```
 378  275.37
 379  274.99
 380  277.18
 381  275.22
 382  275.10
 383  273.72
 384  269.97
 385  270.44
 386  268.10
 387  270.62
 388  270.90
 389  272.44
 390  274.46

 *****  POST1  NODAL  DEGREE  OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.45455E-01  LOAD CASE=   0

  NODE     TEMP
 391  269.55
 392  270.57
 393  266.98
 394  268.97
 395  269.12
 396  270.51
 397  274.61
 398  282.06
 399  278.03
 400  271.42
 401  269.21
 402  269.06
 403  270.40
 404  268.13
 405  278.21
 406  269.07
 407  275.75
 408  266.74
 409  275.86
 410  268.48
 411  279.99
 412  279.11
 413  276.85
 414  271.45
 415  266.54
 416  268.28
 417  264.65
 418  260.38
 419  261.94
 420   114.79
 421   164.42
 422   118.07
```

```
  423  143.94
  424  146.40


 *****  POST1  NODAL  DEGREE  OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.45455E-01  LOAD CASE=  0

  NODE     TEMP
  6202  207.87
  6203  201.29
  6204  295.81
  6205  267.39
  6206  232.71
  6207  301.02
  6208  206.70
  6209  297.89
  6210  328.56
  6211  309.41
  6212  274.64
  6213  326.30
  6214  329.86
  6215  304.84
  6216  102.17
  6217  254.00
  6218  65.598
  6219  76.803
  6220  68.209
  6221  231.26
  6222  383.88
  6223  373.65
  6224  373.01
  6225  151.06
  6226  249.27
  6227  250.31
  6228  147.18
  6229  322.03
  6230  297.57
  6231  349.18
  6232  346.46
  6233  348.09
  6234  343.02
  6235  287.49
  6236  278.28
  6237  375.79
  6238  102.01
  6239  288.00
  6240  290.62

 *****  POST1  NODAL  DEGREE  OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.45455E-01  LOAD CASE=  0

  NODE     TEMP
  6241  388.91
  6242  275.86
  6243  101.35
  6244  322.91
  6245  192.10
  6246  112.30
  6247  102.08
  6248  289.38
  6249  139.40
  6250  319.17

 MAXIMUM ABSOLUTE VALUES
 NODE       356
 VALUE    454.05
```

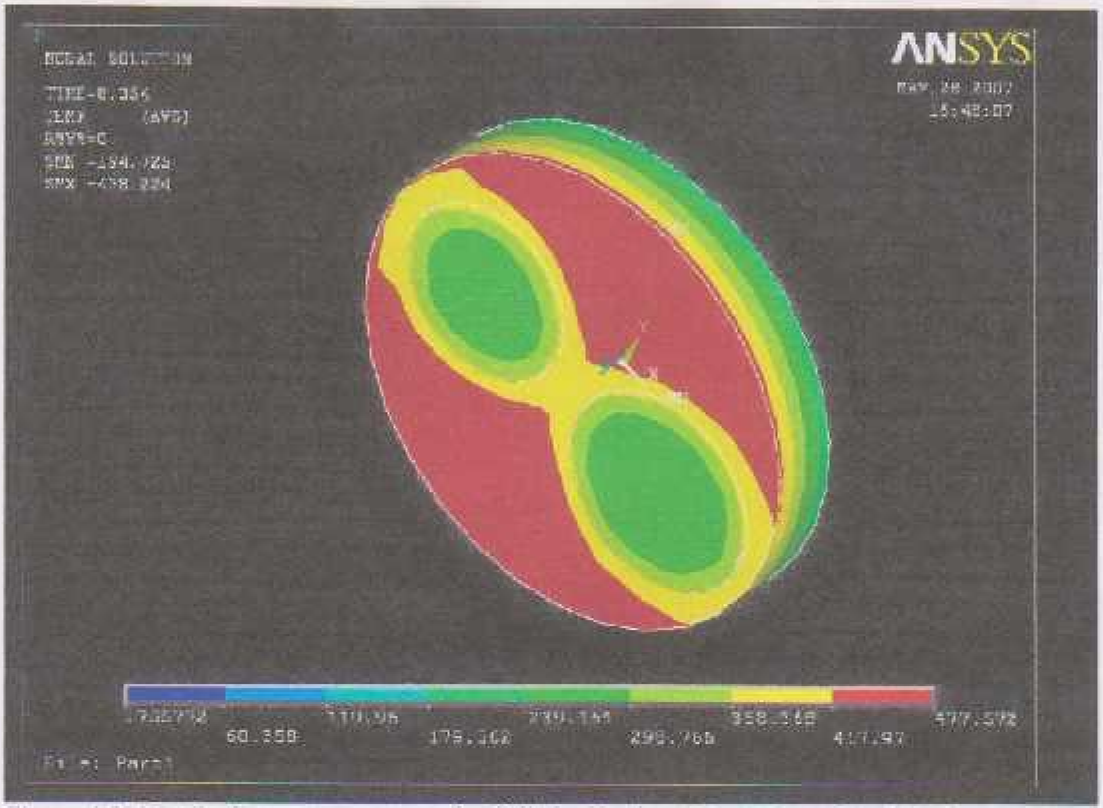

Figure 4-9: Distributions temperature on the Cylinder Head at 625 crank angel and 1000 rpm

In figure (5-9) we see the maximum temperature on the cylinder head, the valves which are made of cast iron experiences an extra loading due to decreased conductivity. In this figure the cylinder head is under combustion phase temperature.

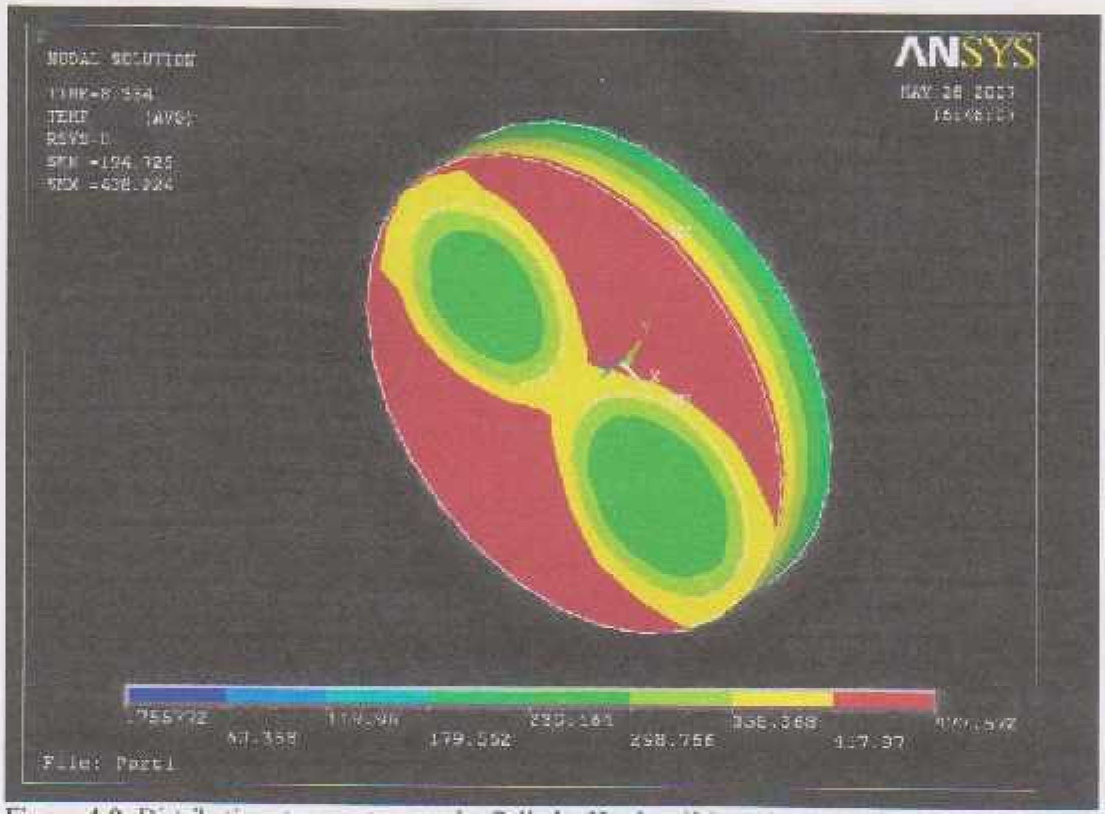

Figure 4-9: Distributions temperature on the Cylinder Head at 625 crank angel and 1000 rpm

In figure (5-9) we see the maximum temperature on the cylinder head, the valves which are made of cast iron experiences an extra loading due to decreased conductivity. In this figure the cylinder head is under combustion phase temperature.

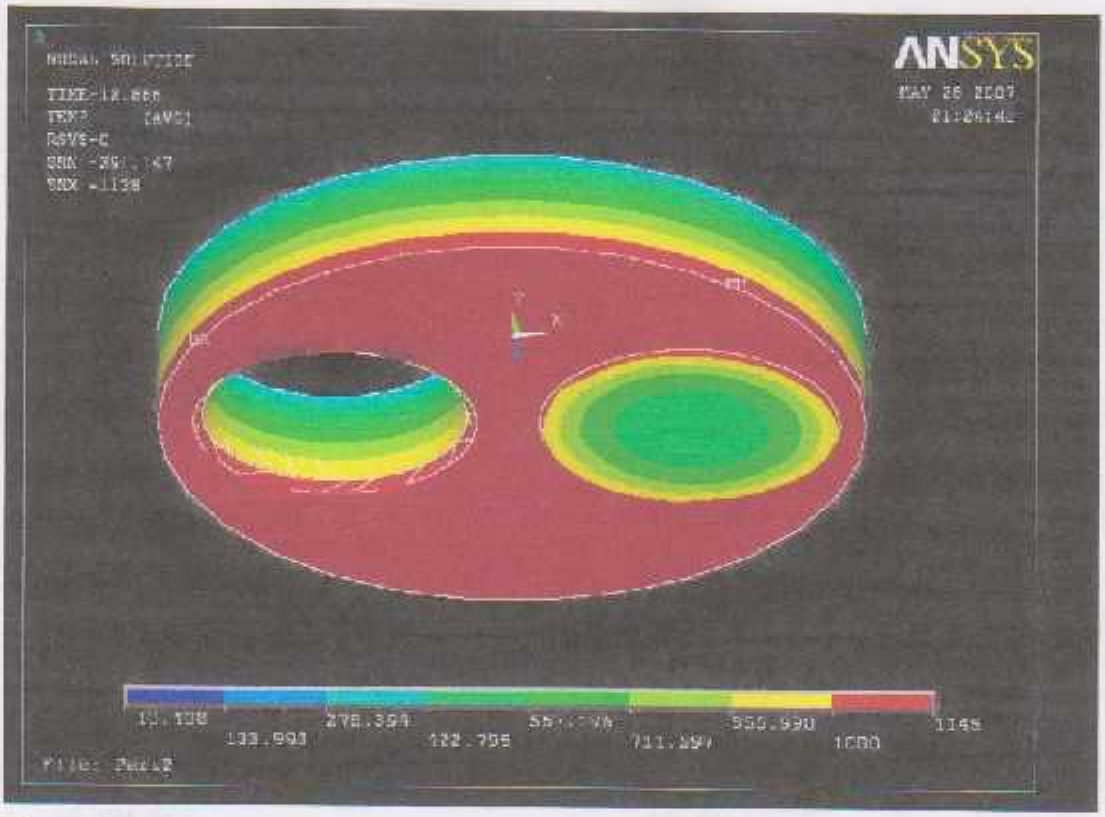

Figure 4-10: Distributions temperature on the cylinder head at 700 crank angel and 1000 rpm with the exhaust vale open

In the exhaust phase the nodal temperature tables indicates after solving in ANSYS that the node number 1259 experiences the maximum temperature loaded on it as shown in Figure 4-10 above and the following tables illustrates that:

(Nodes from 1270 to 4800 are eliminated to shorten the table).

```
PRINT TEMP NODAL SOLUTION PER
NODE

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=   0

  NODE     TEMP
    1  921.95
    2  898.88
    3  903.12
    4  916.75
    5  904.58
    6  908.45
    7  862.88
    8  874.82
    9  858.94
   10  882.46
   11  874.34
   12  899.41
   13  910.66
   14  915.55
   15  913.23
   16  915.29
   17  914.37
   18  952.38
   19  935.62
   20  947.99
   21  952.86
   22  949.10
   23  922.65
   24  927.61
   25  906.99
   26  878.90
   27  873.12
   28  880.18
   29  872.51
   30  883.21
   31  891.83
   32  903.04
   33  918.20
   34  904.84
   35  933.16
   36  946.78
   37  953.80
   38  934.39
   39  945.35

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=  0

  NODE     TEMP
   40  932.82
   41  938.96
   42  935.06
   43  941.55
   44  938.58
   45  935.05
   46  927.07
   47  922.50
   48  925.18
   49  917.66
   50  913.62
   51  918.87
   52  923.47
   53  938.16
   54  934.08
   55  917.34
   56  903.28
   57  909.23
   58  928.89
   59  924.05
   60  916.96
   61  295.73
   62  540.37
   63  309.95
   64  445.97
   65  433.35
   66  425.34
   67  436.92
   68  438.80
   69  446.41
   70  514.38
   71  456.12
   72  441.76
   73  433.19
   74  444.24
   75  446.67
   76  456.62
   77  510.06
   78  201.31

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=  0

  NODE     TEMP
```

```
PRINT TEMP NODAL SOLUTION PER
NODE

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=   0

  NODE     TEMP
     1  921.95
     2  898.88
     3  903.12
     4  916.75
     5  904.58
     6  908.45
     7  862.88
     8  874.82
     9  858.94
    10  882.46
    11  874.34
    12  899.41
    13  910.66
    14  915.55
    15  913.23
    16  915.29
    17  914.37
    18  952.38
    19  935.62
    20  947.99
    21  952.86
    22  949.10
    23  922.65
    24  927.61
    25  906.99
    26  878.90
    27  873.12
    28  880.18
    29  872.51
    30  883.21
    31  891.83
    32  903.04
    33  918.20
    34  904.84
    35  933.16
    36  946.78
    37  953.80
    38  934.39
    39  945.35

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****
```

```
 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=   0

  NODE     TEMP
    40  932.82
    41  938.96
    42  935.06
    43  941.55
    44  938.58
    45  935.05
    46  927.07
    47  922.50
    48  925.18
    49  917.66
    50  913.62
    51  918.87
    52  923.47
    53  938.16
    54  934.08
    55  917.34
    56  903.28
    57  909.23
    58  928.89
    59  924.05
    60  916.96
    61  295.73
    62  540.37
    63  309.95
    64  445.97
    65  433.35
    66  425.34
    67  436.92
    68  438.80
    69  446.41
    70  514.38
    71  456.12
    72  441.76
    73  433.19
    74  444.24
    75  446.67
    76  456.62
    77  510.06
    78  201.31

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=   0

  NODE     TEMP
```

```
  79  202.19
  80  205.21
  81  206.03
  82  207.67
  83  209.96
  84  203.83
  85  222.83
  86  221.28
  87  225.04
  88  227.22
  89  229.06
  90  234.19
  91  229.92
  92  257.27
  93  258.30
  94  281.19
  95  256.77
  96  255.00
  97  275.27
  98  253.57
  99  256.39
 100  277.51
 101  259.57
 102  258.91
 103  282.00
 104  260.23
 105  262.09
 106  287.06
 107  266.57
 108  269.25
 109  297.97
 110  266.63
 111  259.26
 112  271.11
 113  309.06
 114  322.08
 115  322.06
 116  316.82
 117  314.35

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=  0

  NODE     TEMP
  118  312.54
  119  313.80
  120  318.74
  121  319.02
  122  321.94
  123  324.96
  124  333.72
  125  358.31
  126  372.01
  127  394.99
  128  370.53
  129  355.93
  130  364.28
  131  395.65
  132  380.33
  133  349.11
  134  358.42
  135  384.53
  136  370.88
  137  342.64
  138  353.90
  139  378.93
  140  368.02
  141  344.11
  142  354.05
  143  381.82
  144  377.66
  145  350.01
  146  359.35
  147  385.69
  148  381.85
  149  354.95
  150  363.85
  151  398.38
  152  363.49
  153  328.77
  154  367.87
  155  434.74
  156  449.12

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=  0

  NODE     TEMP
  157  446.75
  158  430.26
  159  419.41
  160  414.59
  161  410.55
  162  421.31
  163  422.49
  164  403.26
  165  510.44
  166  511.69
  167  524.85
  168  542.30
```

```
  79  202.19
  80  205.21
  81  206.03
  82  207.67
  83  209.96
  84  203.83
  85  222.83
  86  221.28
  87  225.04
  88  227.22
  89  229.06
  90  234.19
  91  229.92
  92  257.27
  93  258.30
  94  281.19
  95  256.77
  96  255.00
  97  275.27
  98  253.57
  99  256.39
 100  277.51
 101  259.57
 102  258.91
 103  282.00
 104  260.23
 105  262.09
 106  287.06
 107  266.57
 108  269.25
 109  297.97
 110  266.63
 111  259.26
 112  271.11
 113  309.06
 114  322.08
 115  322.86
 116  316.82
 117  314.35

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
 TIME=  0.64935E-01  LOAD CASE=  0

  NODE     TEMP
  118  312.54
  119  313.80
  120  318.74
  121  319.02
  122  321.94
  123  324.96
```

```
 124  333.72
 125  358.31
 126  372.01
 127  394.99
 128  370.53
 129  355.93
 130  364.28
 131  395.65
 132  380.33
 133  349.11
 134  358.42
 135  384.53
 136  370.88
 137  342.64
 138  353.90
 139  378.93
 140  368.02
 141  344.11
 142  354.05
 143  381.82
 144  377.66
 145  350.01
 146  359.35
 147  385.69
 148  381.85
 149  354.95
 150  363.85
 151  398.38
 152  363.49
 153  328.77
 154  367.87
 155  434.74
 156  449.12

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
 TIME=  0.64935E-01  LOAD CASE=  0

  NODE     TEMP
  157  446.75
  158  430.26
  159  419.41
  160  414.59
  161  410.55
  162  421.31
  163  422.49
  164  403.26
  165  510.44
  166  511.69
  167  524.85
  168  542.30
```

```
  169  505.98
  170  478.55
  171  493.98
  172  505.44
  173  524.49
  174  491.94
  175  467.43
  176  487.16
  177  500.69
  178  520.75
  179  487.21
  180  459.86
  181  479.97
  182  492.77
  183  515.90
  184  488.57
  185  474.77
  186  496.78
  187  508.15
  188  530.21
  189  497.11
  190  474.87
  191  493.66
  192  503.32
  193  524.71
  194  492.95
  195  441.99

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=  0

  NODE     TEMP
   196  459.17
   197  510.31
   198  542.37
   199  523.62
   200  542.98
   201  567.23
   202  639.08
   203  608.29
   204  632.57
   205  612.75
   206  566.25
   207  572.61
   208  612.39
   209  596.63
   210  549.82
   211  564.78
   212  606.90
   213  590.22
```

```
   214  538.05
   215  552.55
   216  601.00
   217  595.96
   218  557.38
   219  567.26
   220  619.82
   221  608.66
   222  554.48
   223  564.51
   224  610.29
   225  596.32
   226  548.24
   227  558.31
   228  615.57
   229  625.52
   230  608.94
   231  646.28
   232  798.93
   233  787.89
   234  746.43

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=  0

  NODE     TEMP
   235  742.04
   236  734.92
   237  727.53
   238  740.26
   239  749.46
   240  720.71
   241  717.59
   242  708.21
   243  707.82
   244  733.69
   245  734.41
   246  763.14
   247  767.91
   248  719.51
   249  719.68
   250  709.00
   251  706.80
   252  732.26
   253  732.69
   254  763.99
   255  750.98
   256  700.98
   257  697.40
   258  678.36
```

```
 259  682.71
 260  725.41
 261  727.31
 262  751.90
 263  753.81
 264  719.69
 265  725.82
 266  714.51
 267  715.92
 268  745.48
 269  743.16
 270  778.39
 271  777.84
 272  727.21
 273  724.55

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=     1  SUBSTEP=     1
  TIME=  0.64935E-01  LOAD CASE=   0

  NODE      TEMP
  274  705.63
  275  705.08
  276  737.18
  277  735.05
  278  757.04
  279  754.88
  280  713.04
  281  712.86
  282  695.68
  283  706.07
  284  735.09
  285  741.14
  286  781.90
  287  779.40
  288  750.54
  289  740.28
  290  751.94
  291  762.95
  292  623.77
  293  610.76
  294  655.86
  295  585.08
  296  545.48
  297  567.99
  298  637.98
  299  592.11
  300  550.54
  301  575.46
  302  650.47
  303  598.28
```

```
 304  551.67
 305  573.27
 306  629.51
 307  582.29
 308  533.87
 309  558.01
 310  634.34
 311  590.83
 312  547.35

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=     1  SUBSTEP=     1
  TIME=  0.64935E-01  LOAD CASE=   0

  NODE      TEMP
  313  568.24
  314  638.50
  315  596.81
  316  561.20
  317  582.69
  318  667.87
  319  630.88
  320  614.77
  321  674.43
  322  479.88
  323  453.44
  324  366.94
  325  436.37
  326  416.04
  327  435.33
  328  414.67
  329  427.42
  330  402.50
  331  432.24
  332  404.31
  333  435.15
  334  412.34
  335  447.29
  336  426.62
  337  430.56
  338  304.66
  339  372.88
  340  308.62
  341  357.90
  342  302.04
  343  353.23
  344  298.88
  345  344.93
  346  295.55
  347  349.94
  348  299.96
```

```
 259  682.71
 260  725.41
 261  727.31
 262  751.90
 263  753.81
 264  719.69
 265  725.82
 266  714.51
 267  715.92
 268  745.48
 269  743.16
 270  778.39
 271  777.84
 272  727.21
 273  724.55

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=   0.64935E-01  LOAD CASE=   0

  NODE     TEMP
  274  705.63
  275  705.08
  276  737.18
  277  735.05
  278  757.04
  279  754.88
  280  713.04
  281  712.86
  282  695.68
  283  706.07
  284  735.09
  285  741.14
  286  781.90
  287  779.40
  288  750.54
  289  740.28
  290  751.94
  291  762.95
  292  623.77
  293  610.76
  294  655.86
  295  585.08
  296  545.48
  297  567.99
  298  637.98
  299  592.11
  300  550.54
  301  575.46
  302  650.47
  303  598.28
  304  551.67
  305  573.27
  306  629.51
  307  582.29
  308  533.87
  309  558.01
  310  634.34
  311  590.83
  312  547.35

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=   0.64935E-01  LOAD CASE=   0

  NODE     TEMP
  313  568.24
  314  638.50
  315  596.81
  316  561.20
  317  582.69
  318  667.87
  319  630.88
  320  614.77
  321  674.43
  322  479.88
  323  453.44
  324  366.94
  325  436.37
  326  416.04
  327  435.33
  328  414.67
  329  427.42
  330  402.50
  331  432.24
  332  404.31
  333  435.15
  334  412.34
  335  447.29
  336  426.62
  337  430.56
  338  304.66
  339  372.88
  340  308.62
  341  357.90
  342  302.04
  343  353.23
  344  298.88
  345  344.93
  346  295.55
  347  349.94
  348  299.96
```

```
  349  360.43
  350  302.42
  351  328.98

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=  0

  NODE     TEMP
  352  231.14
  353  247.58
  354  238.56
  355  234.19
  356  233.65
  357  227.85
  358  229.42
  359  195.55
  360  985.57
  361  968.67
  362  955.63
  363  945.70
  364  937.12
  365  929.28
  366  970.55
  367  996.24
  368  963.03
  369  1011.8
  370  948.57
  371  997.43
  372  985.89
  373  972.60
  374  930.18
  375  1004.0
  376  1015.2
  377  1027.8
  378  1020.0
  379  1026.9
  380  1002.4
  381  1033.3
  382  1027.4
  383  1046.5
  384  1032.8
  385  1059.0
  386  1024.5
  387  1029.7
  388  1019.4
  389  990.13
  390  960.37

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=  0

  NODE     TEMP
  391  953.66
  392  951.00
  393  967.41
  394  972.58
  395  960.41
  396  951.81
  397  937.51
  398  926.54
  399  917.11
  400  908.03
  401  940.96
  402  943.61
  403  920.57
  404  944.84
  405  929.98
  406  953.92
  407  943.63
  408  947.46
  409  908.99
  410  958.93
  411  912.24
  412  909.03
  413  918.14
  414  937.98
  415  945.02
  416  993.60
  417  968.23
  418  945.32
  419  1001.5
  420  988.40
  421  969.10
  422  998.04
  423  928.47
  424  949.38
  425  978.38
  426  986.71
  427  940.26
  428  948.74
  429  1018.4

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=  0

  NODE     TEMP
  430  960.66
```

```
 431  1019.0
 432  990.36
 433  960.70
 434  1009.0
 435  998.76
 436  972.82
 437  978.61
 438  928.02
 439  984.66
 440  928.73
 441  951.37
 442  996.71
 443  941.76
 444  949.67
 445  1028.1
 446  968.34
 447  1002.7
 448  986.42
 449  975.24
 450  996.31
 451  975.66
 452  963.19
 453  982.27
 454  927.95
 455  977.79
 456  918.23
 457  941.55
 458  977.21
 459  915.09
 460  922.02
 461  1004.2
 462  951.39
 463  1000.9
 464  971.67
 465  942.66
 466  991.78
 467  957.59
 468  951.93

 ***** POST1 NODAL DEGREE OF FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=   0.64935E-01  LOAD CASE=   0

  NODE     TEMP
  469  964.08
  470  896.55
  471  900.40
  472  877.75
  473  886.99
  474  913.96
  475  893.62
  476  895.29
  477  980.01
  478  935.82
  479  956.23
  480  931.46
  481  908.15
  482  934.66
  483  912.42
  484  899.32
  485  920.44
  486  877.08
  487  937.34
  488  877.13
  489  900.07
  490  952.85
  491  896.01
  492  904.10
  493  936.62
  494  889.70
  495  931.54
  496  911.48
  497  890.99
  498  930.68
  499  911.93
  500  900.12
  501  948.69
  502  876.54
  503  903.94
  504  883.00
  505  891.76
  506  935.01
  507  917.59

 ***** POST1 NODAL DEGREE OF FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=   0.64935E-01  LOAD CASE=   0

  NODE     TEMP
  508  930.41
  509  933.78
  510  889.52
  511  940.50
  512  915.53
  513  891.59
  514  951.27
  515  919.29
  516  905.67
  517  941.65
  518  921.96
  519  929.34
  520  984.78
```

```
 521  925.28
 522  942.81
 523  900.22
 524  944.41
 525  930.84
 526  922.19
 527  907.58
 528  917.61
 529  953.34
 530  966.12
 531  927.69
 532  918.17
 533  919.22
 534  951.08
 535  920.83
 536  924.99
 537  939.05
 538  915.91
 539  932.25
 540  927.68
 541  904.25
 542  925.46
 543  880.80
 544  915.43
 545  903.77
 546  919.13

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=  0

  NODE     TEMP
  547  887.48
  548  916.12
  549  937.81
  550  902.87
  551  889.92
  552  971.43
  553  963.98
  554  931.52
  555  938.15
  556  977.35
  557  988.35
  558  967.41
  559  943.14
  560  991.15
  561  979.15
  562  963.42
  563  949.25
  564  983.76
  565  945.45
```

```
 566  1021.3
 567  1014.3
 568  982.97
 569  953.04
 570  977.37
 571  983.95
 572  1007.8
 573  981.87
 574  1011.3
 575  1027.7
 576  1030.5
 577  1032.9
 578  1053.5
 579  1033.4
 580  1014.6
 581  1010.3
 582  1023.3
 583  1018.4
 584  1029.3
 585  1015.7

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=  0

  NODE     TEMP
  586  1015.6
  587  1019.8
  588  1002.6
  589  994.04
  590  976.00
  591  968.89
  592  1013.3
  593  1009.9
  594  1005.8
  595  972.12
  596  924.71
  597  946.23
  598  927.53
  599  911.56
  600  938.75
  601  964.00
  602  977.76
  603  928.79
  604  941.82
  605  933.68
  606  930.42
  607  938.63
  608  920.10
  609  961.85
  610  988.36
```

```
  611  962.88
  612  937.44
  613  984.65
  614  959.40
  615  946.21
  616  995.51
  617  956.56
  618  978.95
  619  1007.8
  620  1002.6
  621  959.99
  622  985.37
  623  977.77
  624  941.61

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=   0

  NODE     TEMP
  625  979.64
  626  959.92
  627  942.49
  628  986.60
  629  957.40
  630  942.41
  631  1021.7
  632  958.61
  633  1022.3
  634  961.99
  635  987.80
  636  1005.2
  637  965.94
  638  980.06
  639  986.65
  640  929.78
  641  985.75
  642  957.55
  643  930.29
  644  985.95
  645  965.88
  646  943.89
  647  1012.6
  648  955.78
  649  1011.9
  650  953.56
  651  978.21
  652  999.69
  653  961.46
  654  969.20
  655  993.03
```

```
  656  939.76
  657  996.63
  658  972.90
  659  948.90
  660  995.95
  661  963.66
  662  960.33
  663  996.65

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=   0

  NODE     TEMP
  664  949.28
  665  981.53
  666  948.48
  667  962.87
  668  971.42
  669  955.75
  670  964.86
  671  980.28
  672  947.23
  673  968.33
  674  949.78
  675  934.76
  676  975.97
  677  934.62
  678  936.57
  679  974.09
  680  957.72
  681  995.95
  682  952.70
  683  970.73
  684  973.06
  685  960.52
  686  958.53
  687  955.63
  688  916.61
  689  925.23
  690  916.83
  691  910.00
  692  950.10
  693  950.93
  694  923.66
  695  965.84
  696  954.20
  697  950.80
  698  942.34
  699  945.61
  700  945.90
```

```
 701  937.26
 702  930.51

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=   0.64935E-01  LOAD CASE=   0

  NODE      TEMP
   703  965.19
   704  937.90
   705  979.30
   706  961.80
   707  945.22
   708  984.04
   709  954.13
   710  946.48
   711  936.76
   712  926.03
   713  921.97
   714  973.14
   715  921.36
   716  980.00
   717  932.69
   718  982.18
   719  921.18
   720  911.91
   721  935.29
   722  949.17
   723  951.60
   724  943.51
   725  947.19
   726  938.45
   727  939.76
   728  947.41
   729  933.11
   730  924.52
   731  923.01
   732  942.70
   733  925.68
   734  964.88
   735  955.59
   736  940.98
   737  950.99
   738  936.23
   739  914.14
   740  966.05
   741  960.97

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=   0.64935E-01  LOAD CASE=   0

  NODE      TEMP
   742  955.40
   743  949.32
   744  963.47
   745  960.15
   746  978.01
   747  961.55
   748  979.34
   749  971.16
   750  964.22
   751  944.91
   752  984.71
   753  982.40
   754  963.44
   755  955.76
   756  980.00
   757  974.65
   758  965.19
   759  952.45
   760  904.40
   761  922.59
   762  905.41
   763  911.07
   764  914.68
   765  920.17
   766  919.54
   767  919.90
   768  922.48
   769  924.53
   770  927.94
   771  929.01
   772  930.94
   773  932.05
   774  929.64
   775  929.08
   776  927.77
   777  929.57
   778  932.29
   779  929.36
   780  928.13

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=   0.64935E-01  LOAD CASE=   0

  NODE      TEMP
   781  926.30
   782  930.85
```

```
 783  934.40
 784  934.03
 785  929.13
 786  931.05
 787  929.38
 788  928.65
 789  925.02
 790  922.77
 791  1028.5
 792  941.77
 793  967.09
 794  996.15
 795  1018.0
 796  1027.6
 797  1021.2
 798  1027.4
 799  1025.3
 800  1032.8
 801  1028.3
 802  1035.6
 803  1032.4
 804  1038.2
 805  1033.6
 806  1041.2
 807  1036.9
 808  1041.3
 809  1037.1
 810  1043.4
 811  1035.7
 812  1046.5
 813  1039.9
 814  1046.6
 815  1040.2
 816  1045.3
 817  1038.2
 818  1049.5
 819  1044.3

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=  0

  NODE      TEMP
  820  1044.1
  821  1032.1
  822  1040.6
  823  1033.0
  824  1041.2
  825  922.56
  826  946.60
  827  979.59
```

```
 828  960.56
 829  922.38
 830  938.13
 831  967.54
 832  976.89
 833  971.85
 834  974.54
 835  977.12
 836  974.17
 837  976.42
 838  925.63
 839  946.36
 840  984.65
 841  981.13
 842  940.22
 843  994.33
 844  962.48
 845  990.74
 846  965.00
 847  980.18
 848  974.63
 849  974.92
 850  975.57
 851  970.49
 852  957.70
 853  966.51
 854  963.81
 855  971.32
 856  973.10
 857  978.59
 858  974.60

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=  0

  NODE      TEMP
  859  974.50
  860  979.40
  861  972.22
  862  984.51
  863  977.56
  864  974.41
  865  959.99
  866  948.47
  867  925.73
  868  928.73
  869  929.65
  870  926.80
  871  928.87
  872  926.96
```

```
 873  928.85
 874  930.45
 875  932.39
 876  933.98
 877  934.86
 878  935.77
 879  933.23
 880  930.81
 881  928.87
 882  928.71
 883  929.84
 884  928.87
 885  927.93
 886  927.88
 887  927.69
 888  925.20
 889  923.01
 890  920.57
 891  919.55
 892  916.53
 893  912.62
 894  909.68
 895  904.15
 896  1042.4
 897  1039.1

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=  0

  NODE     TEMP
  898  1041.4
  899  1031.5
  900  1043.3
  901  1041.3
  902  1051.9
  903  1041.7
  904  1044.8
  905  1040.0
  906  1045.7
  907  1042.5
  908  1048.1
  909  1038.4
  910  1042.2
  911  1033.7
  912  1039.9
  913  1040.0
  914  1041.0
  915  1035.0
  916  1037.6
  917  1032.5
```

```
  918  1035.5
  919  1031.2
  920  1032.6
  921  1025.1
  922  1028.2
  923  1019.9
  924  1027.4
  925  976.49
  926  920.10
  927  941.57
  928  975.72
  929  981.62
  930  973.58
  931  974.42
  932  966.75
  933  967.12
  934  960.86
  935  923.79
  936  979.98

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=  0

  NODE     TEMP
  937  943.63
  938  977.14
  939  946.07
  940  966.73
  941  1004.2
  942  996.17
  943  972.13
  944  971.48
  945  980.19
  946  976.92
  947  975.24
  948  956.05
  949  976.23
  950  977.66
  951  973.05
  952  978.32
  953  980.03
  954  982.31
  955  979.22
  956  973.82
  957  975.29
  958  974.65
  959  972.64
  960  968.06
  961  962.99
  962  967.97
```

```
  963  943.70
  964  12.631
  965  14.586
  966  13.850
  967  14.275
  968  14.404
  969  14.740
  970  14.795
  971  14.821
  972  14.895
  973  14.687
  974  14.923
  975  14.884

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=  0

  NODE     TEMP
  976  14.920
  977  14.882
  978  14.875
  979  14.829
  980  14.796
  981  14.863
  982  14.723
  983  268.91
  984  522.27
  985  646.45
  986  767.50
  987  824.78
  988  878.60
  989  902.16
  990  251.61
  991  497.99
  992  623.29
  993  747.14
  994  806.79
  995  861.53
  996  884.38
  997  860.19
  998  881.16
  999  609.14
  1000   626.64
  1001   200.78
  1002   204.66
  1003   224.44
  1004   225.05
  1005   213.48
  1006   211.01
  1007   201.07
```

```
  1008  197.78
  1009  197.32
  1010  196.91
  1011  196.43
  1012  450.90
  1013  441.53
  1014  383.49

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=  0

  NODE     TEMP
  1015  452.51
  1016  559.69
  1017  201.44
  1018  210.61
  1019  223.31
  1020  265.50
  1021  657.91
  1022  269.65
  1023  213.69
  1024  546.60
  1025  396.62
  1026  464.59
  1027  643.38
  1028  422.85
  1029  475.87
  1030  626.09
  1031  658.37
  1032  467.16
  1033  775.94
  1034  557.19
  1035  586.26
  1036  553.65
  1037  554.74
  1038  544.17
  1039  865.85
  1040  572.54
  1041  585.42
  1042  721.76
  1043  766.93
  1044  867.11
  1045  840.57
  1046  836.96
  1047  562.05
  1048  719.17
  1049  828.01
  1050  825.20
  1051  571.88
  1052  759.30
```

```
 1053  838.07

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=   0.64935E-01  LOAD CASE=   0

  NODE       TEMP
  1054   838.79
  1055   867.50
  1056   866.93
  1057   851.72
  1058   854.57
  1059   715.36
  1060   735.00
  1061   852.58
  1062   826.00
  1063   828.19
  1064   838.67
  1065   837.88
  1066   725.93
  1067   834.55
  1068   861.40
  1069   749.43
  1070   623.47
  1071   834.91
  1072   815.75
  1073   597.16
  1074   778.47
  1075   832.41
  1076   814.76
  1077   755.03
  1078   678.91
  1079   880.77
  1080   862.01
  1081   654.68
  1082   799.67
  1083   856.42
  1084   835.14
  1085   777.46
  1086   806.97
  1087   830.37
  1088   700.12
  1089   724.88
  1090   796.52
  1091   726.69
  1092   702.83

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=   0.64935E-01  LOAD CASE=   0

  NODE       TEMP
  1093   760.82
  1094   789.41
  1095   728.97
  1096   411.41
  1097   708.66
  1098   733.65
  1099   433.43
  1100   388.31
  1101   379.55
  1102   405.92
  1103   522.43
  1104   515.90
  1105   387.02
  1106   14.729
  1107   14.843
  1108   14.806
  1109   14.980
  1110   14.880
  1111   14.521
  1112   14.915
  1113   14.759
  1114   14.924
  1115   15.101
  1116   14.910
  1117   14.734
  1118   14.781
  1119   14.870
  1120   14.385
  1121   14.046
  1122   13.835
  1123   860.95
  1124   879.57
  1125   619.83
  1126   626.55
  1127   210.05
  1128   210.60
  1129   224.78
  1130   225.37
  1131   213.55

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=   0.64935E-01  LOAD CASE=   0

  NODE       TEMP
  1132   210.79
  1133   198.83
  1134   192.49
```

```
 1135  188.93
 1136  209.63
 1137  184.93
 1138  429.81
 1139  463.56
 1140  375.85
 1141  463.61
 1142  554.12
 1143  200.57
 1144  210.11
 1145  224.65
 1146  269.12
 1147  663.95
 1148  269.82
 1149  213.69
 1150  545.36
 1151  395.23
 1152  464.52
 1153  643.91
 1154  423.19
 1155  478.49
 1156  629.40
 1157  658.44
 1158  467.16
 1159  775.57
 1160  556.22
 1161  586.07
 1162  535.09
 1163  543.89
 1164  562.13
 1165  871.41
 1166  573.19
 1167  585.95
 1168  722.31
 1169  769.11
 1170  873.00

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=   0

  NODE      TEMP
 1171  841.15
 1172  837.91
 1173  561.95
 1174  719.75
 1175  830.87
 1176  827.88
 1177  572.06
 1178  759.24
 1179  837.07
 1180  836.62
 1181  865.45
 1182  865.83
 1183  850.32
 1184  854.87
 1185  713.88
 1186  734.23
 1187  852.22
 1188  824.18
 1189  824.79
 1190  835.44
 1191  829.53
 1192  714.04
 1193  825.37
 1194  870.42
 1195  759.16
 1196  600.02
 1197  817.61
 1198  829.12
 1199  619.14
 1200  830.50
 1201  771.24
 1202  757.31
 1203  815.30
 1204  882.22
 1205  677.01
 1206  654.43
 1207  862.38
 1208  853.50
 1209  796.92

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=   0

  NODE      TEMP
 1210  777.56
 1211  835.63
 1212  807.65
 1213  826.03
 1214  706.37
 1215  716.08
 1216  801.92
 1217  722.32
 1218  704.28
 1219  762.26
 1220  788.80
 1221  729.63
 1222  411.56
 1223  709.48
 1224  733.81
```

```
 1225  434.25
 1226  404.94
 1227  365.53
 1228  405.21
 1229  522.64
 1230  522.12
 1231  384.07
 1232  1051.5
 1233  1094.2
 1234  1069.7
 1235  1076.2
 1236  1073.0
 1237  1087.0
 1238  1088.1
 1239  1092.5
 1240  1096.9
 1241  1099.9
 1242  1100.5
 1243  1101.4
 1244  1101.9
 1245  1102.3
 1246  1102.4
 1247  1102.5
 1248  1102.6

 ***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=   0

  NODE     TEMP
 1249  1102.6
 1250  1102.6
 1251  1102.6
 1252  1102.5
 1253  1102.5
 1254  1102.3
 1255  1102.1
 1256  1101.5
 1257  1101.2
 1258  1099.7
 1259  1103.1
 1260  1096.4
 1261  1099.2
 1262  1088.3
 1263  1090.3
 1264  1101.0
 1265  1094.7
 1266  1098.3
 1267  1099.7
 1268  1100.9
 1269  1101.5
```

```
 *****  POST1  NODAL  DEGREE  OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=   0

  NODE     TEMP
  4798  714.54
  4799  846.39
  4800  269.14
  4801  824.45
  4802  659.33
  4803  869.60
  4804  895.99
  4805  869.56
  4806  935.10
  4807  284.28
  4808  831.89
  4809  288.25
  4810  253.41
  4811  298.60
  4812  832.32
  4813  731.22
  4814  575.74
  4815  832.40
  4816  533.85
  4817  679.53
  4818  803.99
  4819  925.62
  4820  877.65
  4821  759.43
  4822  897.25
  4823  872.09
  4824  999.74
  4825  860.42
  4826  864.36
  4827  1020.0
  4828  294.46
  4829  491.71
  4830  925.57
  4831  823.28
  4832  202.22
  4833  288.72
  4834  209.61
  4835  760.94
  4836  656.64

 *****  POST1  NODAL  DEGREE  OF
FREEDOM LISTING *****

 LOAD STEP=    1  SUBSTEP=    1
  TIME=  0.64935E-01  LOAD CASE=   0
```

```
NODE    TEMP
4837  928.88
4838  890.97
4839  840.95
4840  809.80
4841  859.80
4842  921.56
4843  305.39
4844  842.91
4845  843.21
4846  869.03
4847  849.51
4848  838.01
4849  746.43
4850  930.61
4851  890.10
4852  213.95
4853  900.24
4854  905.13
4855  190.49
4856  641.89
4857  945.29
4858  918.09
4859  884.37
4860  921.38
4861  919.93
4862  896.74
4863  1051.3
4864  988.24
4865  853.81
4866  816.39
4867  694.43
4868  955.60
4869  875.85
4870  1015.1
4871  875.75
4872  301.58
4873  575.63
4874  832.33
4875  719.83

***** POST1 NODAL DEGREE OF
FREEDOM LISTING *****

LOAD STEP=    1  SUBSTEP=    1
 TIME=  0.64935E-01  LOAD CASE=  0

NODE    TEMP
4876  899.08
4877  629.65
4878  892.24
4879  845.05
4880  1013.0
4881  890.50
4882  884.93
4883  903.90
4884  876.81
4885  955.37
4886  921.89
4887  690.33
4888  912.81
4889  831.11
4890  832.07
4891  831.60
4892  868.20
4893  878.61
4894  269.09
4895  210.29
4896  281.37
4897  319.83
4898  886.18

MAXIMUM ABSOLUTE VALUES
NODE      1259
VALUE    1103.1
```

In figure 5.11 below it is obvious that the maximum heat stress is found to be in a region somewhere around the exhaust valve where a sufficient cooling is needed.

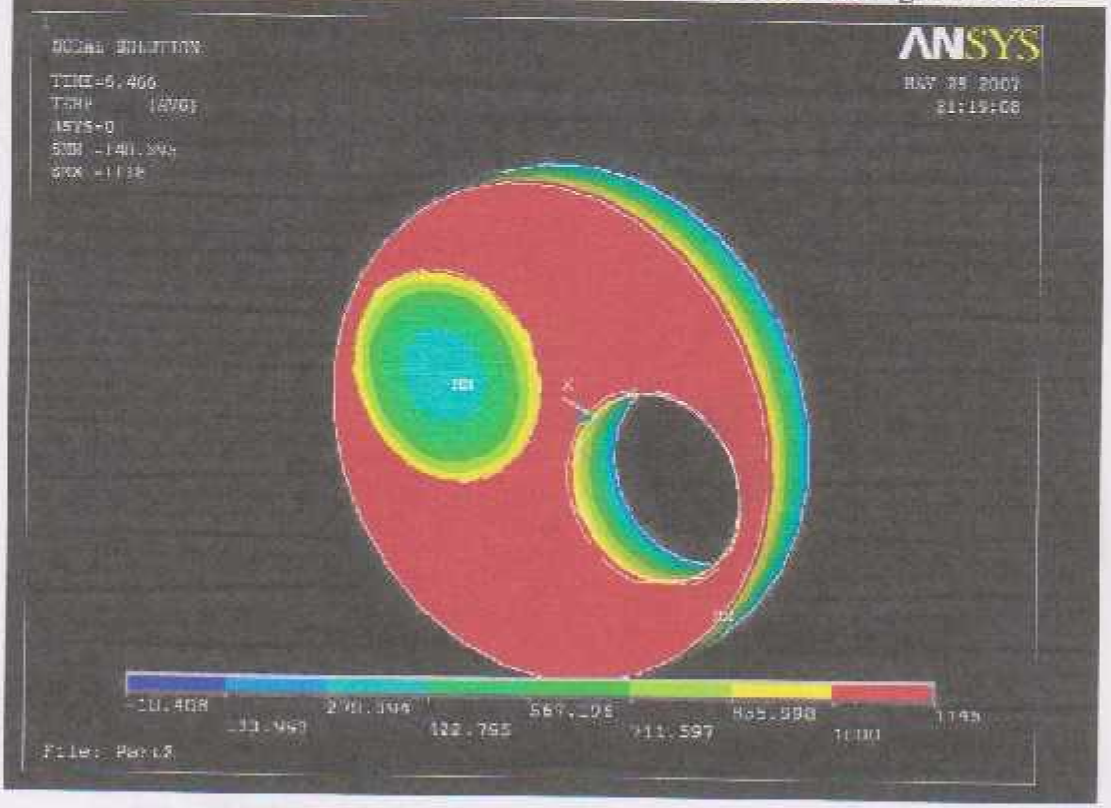

figure 5.11: exhaust stroke thermal stesses around exhaust valve seat

Appendix

Values of h_E,Ganesan, T and P Vs. crank angel in the combustion phase:

α °	$h_{E,Ganesan}$ W/m^2K	T K	P, MPa
180	53.68887	520.93679	0.1
181	53.69089	520.94522	0.100006
182	53.69693	520.97052	0.100024
183	53.70689	521.01272	0.100053
184	53.7211	521.07182	0.100094
185	53.73925	521.14787	0.100147
186	53.76147	521.24091	0.100212
187	53.78776	521.35099	0.100288
188	53.81814	521.47818	0.100378
189	53.85264	521.62256	0.100479
190	53.89129	521.7842	0.100592
191	53.9341	521.9632	0.100717
192	53.98112	522.15966	0.100855
193	54.03236	522.37371	0.101005
194	54.08788	522.60545	0.101168
195	54.14771	522.85503	0.101343
196	54.21189	523.12258	0.101532
197	54.28046	523.40826	0.101733
198	54.35349	523.71224	0.101948
199	54.43101	524.03469	0.102176
200	54.51309	524.37578	0.102418
201	54.59978	524.73571	0.102673
202	54.69115	525.11469	0.102943
203	54.78725	525.51293	0.103227
204	54.88816	525.93065	0.103525
205	54.99396	526.36808	0.103838
206	55.1047	526.82548	0.104166
207	55.22048	527.30308	0.10451
208	55.34138	527.80115	0.104869
209	55.46747	528.31998	0.105244
210	55.59886	528.85983	0.105635
211	55.73563	529.42102	0.106043
212	55.87789	530.00383	0.106468
213	56.02572	530.60859	0.10691
214	56.17924	531.23563	0.10737
215	56.33856	531.88527	0.107847
216	56.50379	532.55787	0.108344
217	56.67504	533.25378	0.108859
218	56.85244	533.97338	0.109394
219	57.03612	534.71704	0.109949
220	57.2262	535.48515	0.110525
221	57.42282	536.27812	0.111121
222	57.62613	537.09635	0.111739
223	57.83626	537.94028	0.112378

224	58.05337	538.81033	0.113041
225	58.27761	539.70697	0.113727
226	58.50914	540.63064	0.114436
227	58.74814	541.58182	0.11517
228	58.99476	542.56099	0.11593
229	59.2492	543.56865	0.116715
230	59.51164	544.6053	0.117527
231	59.78226	545.67148	0.118367
232	60.06126	546.76771	0.119235
233	60.34885	547.89454	0.120132
234	60.64523	549.05254	0.121059
235	60.95063	550.24227	0.122017
236	61.26527	551.46433	0.123006
237	61.58938	552.71932	0.124029
238	61.9232	554.00786	0.125086
239	62.26699	555.33058	0.126177
240	62.621	556.68812	0.127305
241	62.98549	558.08116	0.12847
242	63.36074	559.51036	0.129673
243	63.74704	560.97643	0.130916
244	64.14468	562.48007	0.1322
245	64.55397	564.02202	0.133526
246	64.97521	565.60301	0.134896
247	65.40875	567.22382	0.136312
248	65.85491	568.88521	0.137774
249	66.31404	570.588	0.139285
250	66.78652	572.333	0.140846
251	67.2727	574.12104	0.142459
252	67.77299	575.95298	0.144126
253	68.28778	577.82971	0.145849
254	68.81749	579.75211	0.147629
255	69.36255	581.72112	0.149469
256	69.92341	583.73766	0.151371
257	70.50053	585.80271	0.153338
258	71.0944	587.91724	0.155371
259	71.7055	590.08228	0.157474
260	72.33437	592.29885	0.159649
261	72.98153	594.56802	0.161898
262	73.64754	596.89086	0.164225
263	74.33298	599.26849	0.166632
264	75.03844	601.70204	0.169123
265	75.76454	604.19268	0.171701
266	76.51194	606.7416	0.17437
267	77.28129	609.35001	0.177133
268	78.0733	612.01916	0.179993
269	78.88868	614.75034	0.182956
270	79.72818	617.54484	0.186025
271	80.59258	620.40402	0.189205
272	81.48269	623.32922	0.1925
273	82.39934	626.32187	0.195914

274	83.34341	629.38338	0.199454
275	84.3158	632.51523	0.203125
276	85.31745	635.71892	0.206932
277	86.34934	638.99597	0.21088
278	87.41249	642.34797	0.214978
279	88.50795	645.7765	0.219229
280	89.63681	649.28321	0.223643
281	90.80023	652.86977	0.228225
282	91.99938	656.53788	0.232984
283	93.23549	660.28829	0.237928
284	94.50985	664.12577	0.243064
285	95.82378	668.04913	0.248402
286	97.17867	672.06123	0.253951
287	98.57595	676.16394	0.259721
288	100.0171	680.35917	0.265722
289	101.5037	684.64887	0.271965
290	103.0373	689.03501	0.278461
291	104.6197	693.5196	0.285223
292	106.2525	698.10466	0.292263
293	107.9375	702.79227	0.299595
294	109.6767	707.58448	0.307232
295	111.4716	712.48342	0.31519
296	113.325	717.49118	0.323483
297	115.2384	722.6099	0.332129
298	117.2139	727.84172	0.341144
299	119.254	733.18877	0.350547
300	121.3608	738.65318	0.360357
301	123.5367	744.23707	0.370593
302	125.7842	749.94256	0.381277
303	128.1058	755.77172	0.392431
304	130.504	761.72658	0.404078
305	132.9815	767.80913	0.416242
306	135.541	774.02131	0.428948
307	138.1853	780.36497	0.442224
308	140.9172	786.84186	0.456097
309	143.7396	793.45365	0.470596
310	146.6555	800.20185	0.485751
311	149.6676	807.08784	0.501593
312	152.7791	814.11282	0.518155
313	155.993	821.27778	0.535472
314	159.3121	828.58349	0.553576
315	162.7394	836.03046	0.572506
316	166.2778	843.61888	0.592296
317	169.9302	851.34862	0.612985
318	173.6992	859.21916	0.634612
319	177.5874	867.22956	0.657214
320	181.5971	875.37838	0.68083
321	185.7306	883.66366	0.705499
322	189.9897	892.08285	0.731259
323	194.376	900.63272	0.758148

324	198.8906	909.30933	0.7862
325	203.5342	918.10793	0.81545
326	208.307	927.02289	0.845929
327	213.2088	936.0476	0.877663
328	218.2376	945.17444	0.910676
329	223.3922	954.39462	0.944984
330	228.6694	963.69812	0.9806
331	234.0653	973.07362	1.017524
332	239.5746	982.50838	1.055751
333	245.1909	991.98814	1.095264
334	250.9065	1001.4971	1.136032
335	256.7118	1011.0176	1.178011
336	262.5958	1020.5306	1.221141
337	268.5455	1030.0148	1.265344
338	274.5462	1039.4475	1.310523
339	280.5809	1048.8039	1.356558
340	286.6306	1058.0572	1.403306
341	292.6743	1067.1791	1.450602
342	298.6886	1076.1392	1.498253
343	304.6479	1084.9056	1.54604
344	310.5246	1093.4448	1.593718
345	316.2891	1101.722	1.641016
346	321.9101	1109.7014	1.687639
347	327.3545	1117.3461	1.733266
348	332.5881	1124.6189	1.777561
349	337.5759	1131.4826	1.820168
350	342.2824	1137.9	1.860722
351	346.6722	1143.8351	1.898852
352	351.3873	1151.4897	1.937921
353	356.9665	1162.5941	1.980812
354	363.7484	1178.3152	2.02935
355	371.9797	1199.4367	2.084863
356	381.8321	1226.5266	2.148248
357	393.4049	1259.9359	2.219972
358	406.724	1299.8031	2.300056
359	421.7416	1346.0574	2.388063
360	438.3381	1398.4247	2.483109
361	456.3261	1456.4395	2.583894
362	475.4584	1519.4634	2.688754
363	495.4375	1586.7099	2.795739
364	515.929	1657.2745	2.902698
365	536.5751	1730.1694	3.007383
366	557.0096	1804.3598	3.107554
367	576.8725	1878.7998	3.201074
368	595.8231	1952.4676	3.285998
369	613.5516	2024.3959	3.360649
370	629.7883	2093.6985	3.423666
371	644.3102	2159.5907	3.474041
372	656.9448	2221.4042	3.511128
373	667.5716	2278.5958	3.534637

374	676.121	2330.7515	3.544617
375	682.5715	2377.5845	3.541415
376	686.9458	2418.9305	3.525641
377	689.3051	2454.7388	3.498115
378	689.7431	2485.0618	3.459823
379	688.3801	2510.0419	3.411866
380	685.3564	2529.898	3.355416
381	680.8265	2544.9113	3.291673
382	674.9532	2555.4114	3.221832
383	667.9028	2561.7624	3.147053
384	659.8405	2564.3497	3.068436
385	650.9267	2563.5689	2.987003
386	641.314	2559.8146	2.903684
387	631.1447	2553.4715	2.819313
388	620.5495	2544.9072	2.734622
389	609.6461	2534.4661	2.650242
390	598.5388	2522.4652	2.566704
391	587.3188	2509.1915	2.484451
392	576.0642	2494.9006	2.403837
393	564.8411	2479.8166	2.325141
394	553.704	2464.1335	2.248576
395	542.6976	2448.016	2.174293
396	531.8574	2431.6029	2.102394
397	521.211	2415.0089	2.032941
398	510.7794	2398.3276	1.96596
399	500.578	2381.6353	1.901449
400	490.6173	2364.992	1.839384
401	480.9041	2348.4454	1.779725
402	471.4422	2332.0327	1.722419
403	462.2329	2315.7823	1.667402
404	453.2756	2299.716	1.614607
405	444.5681	2283.8503	1.563959
406	436.1072	2268.1974	1.515382
407	427.8889	2252.7661	1.468799
408	419.9086	2237.563	1.424133
409	412.161	2222.5924	1.381308
410	404.6408	2207.8575	1.340247
411	397.3424	2193.3599	1.300877
412	390.26	2179.1007	1.263127
413	383.3877	2165.0801	1.226927
414	376.7197	2151.2977	1.19221
415	370.2504	2137.7528	1.158911
416	363.9737	2124.4442	1.126967
417	357.8842	2111.3704	1.096319
418	351.9762	2098.5298	1.06691
419	346.2442	2085.9203	1.038685
420	340.6828	2073.5398	1.01159
421	335.2868	2061.3861	0.985576
422	330.051	2049.4567	0.960594
423	324.9704	2037.749	0.936598

424	320.0402	2026.2605	0.913546
425	315.2556	2014.9883	0.891394
426	310.6121	2003.9297	0.870103
427	306.1051	1993.0818	0.849635
428	301.7304	1982.4418	0.829954
429	297.4836	1972.0067	0.811025
430	293.3609	1961.7735	0.792815
431	289.3582	1951.7392	0.775294
432	285.4718	1941.901	0.75843
433	281.6979	1932.2557	0.742197
434	278.033	1922.8005	0.726566
435	274.4737	1913.5323	0.711512
436	271.0166	1904.4481	0.69701
437	267.6585	1895.545	0.683037
438	264.3964	1886.8201	0.669572
439	261.2273	1878.2704	0.656592
440	258.1482	1869.8931	0.644077
441	255.1563	1861.6854	0.632008
442	252.249	1853.6443	0.620368
443	249.4237	1845.7671	0.609137
444	246.6779	1838.051	0.598301
445	244.0092	1830.4934	0.587842
446	241.4151	1823.0914	0.577746
447	238.8935	1815.8425	0.567998
448	236.4422	1808.7441	0.558585
449	234.0591	1801.7935	0.549493
450	231.7421	1794.9882	0.54071
451	229.4894	1788.3258	0.532225
452	227.2989	1781.8037	0.524024
453	225.169	1775.4195	0.516098
454	223.0978	1769.1709	0.508437
455	221.0836	1763.0555	0.50103
456	219.1248	1757.071	0.493867
457	217.2199	1751.2151	0.486941
458	215.3672	1745.4857	0.480241
459	213.5654	1739.8804	0.47376
460	211.8129	1734.3972	0.46749
461	210.1084	1729.034	0.461424
462	208.4506	1723.7886	0.455553
463	206.8382	1718.659	0.449871
464	205.2699	1713.6433	0.444372
465	203.7446	1708.7394	0.439049
466	202.261	1703.9454	0.433895
467	200.8181	1699.2595	0.428906
468	199.4147	1694.6797	0.424076
469	198.0499	1690.2042	0.419398
470	196.7225	1685.8313	0.414869
471	195.4317	1681.5591	0.410482
472	194.1764	1677.386	0.406234
473	192.9558	1673.3102	0.40212

474	191.7689	1669.3301	0.398135
475	190.6149	1665.444	0.394276
476	189.493	1661.6503	0.390538
477	188.4023	1657.9476	0.386917
478	187.3421	1654.3341	0.38341
479	186.3116	1650.8084	0.380014
480	185.31	1647.369	0.376724
481	184.3368	1644.0145	0.373538
482	183.3911	1640.7434	0.370452
483	182.4723	1637.5543	0.367464
484	181.5798	1634.4459	0.36457
485	180.7129	1631.4168	0.361768
486	179.8711	1628.4657	0.359055
487	179.0537	1625.5912	0.356428
488	178.2602	1622.7922	0.353885
489	177.4901	1620.0674	0.351424
490	176.7428	1617.4155	0.349042
491	176.0177	1614.8355	0.346738
492	175.3145	1612.326	0.344508
493	174.6325	1609.8861	0.342351
494	173.9714	1607.5145	0.340265
495	173.3307	1605.2102	0.338248
496	172.71	1602.9721	0.336299
497	172.1088	1600.7992	0.334415
498	171.5267	1598.6905	0.332595
499	170.9633	1596.6449	0.330837
500	170.4182	1594.6615	0.329139
501	169.8911	1592.7394	0.327501
502	169.3816	1590.8776	0.325921
503	168.8894	1589.0753	0.324397
504	168.4141	1587.3315	0.322928
505	167.9554	1585.6454	0.321513
506	167.5129	1584.0163	0.32015
507	167.0865	1582.4432	0.318839
508	166.6757	1580.9254	0.317577
509	166.2804	1579.4622	0.316366

Values of h_E,Ganesan, T, P, valve lift and seat area Vs. crank angel in the exhaust phase, where:

EVO: exhaust valve open

EVC: exhaust valve closed

	α	T, K	P,MPa	h,Ganesan $W/m^2.K$	Lv, m	Ac, m^2
EVO	510	1271.56	0.2	118.6247	0	0
	511	1266.71	0.1995	118.2502	0.000163904	1.54476E-06
	512	1259.31	0.199	117.7564	0.000327778	3.08923E-06
	513	1255.56	0.1985	117.4332	0.00049159	4.63313E-06
	514	1252.39	0.198	117.137	0.000655311	6.17616E-06
	515	1250.15	0.197	116.7363	0.000818909	7.71804E-06
	516	1244.57	0.194	115.5852	0.000982355	9.25847E-06
	517	1240.36	0.191	114.4939	0.001145617	1.07972E-05
	518	1236.84	0.188	113.4299	0.001308665	1.23339E-05
	519	1229.38	0.187	112.7861	0.00147147	1.38683E-05
	520	1225.79	0.186	112.3198	0.001634	1.54001E-05
	521	1221.45	0.184	111.5164	0.001796225	1.6929E-05
	522	1216.65	0.181	110.386	0.001958115	1.84548E-05
	523	1211.33	0.179	109.5341	0.002119639	1.99771E-05
	524	1207.68	0.178	109.0631	0.002280769	2.14957E-05
	525	1200.5	0.177	108.4325	0.002441472	2.30103E-05
	526	1192.95	0.173	106.8627	0.00260172	2.45206E-05
	527	1186.64	0.169	105.3403	0.002761483	2.60264E-05
	528	1180.75	0.166	104.1417	0.002920731	2.75272E-05
	529	1177.65	0.164	103.3765	0.003079433	2.9023E-05
	530	1170.05	0.163	102.7278	0.003237561	3.05133E-05
	531	1161.6	0.16	101.4098	0.003395085	3.19979E-05
	532	1153.73	0.157	100.1137	0.003551976	3.34766E-05
	533	1146.05	0.154	98.82207	0.003708204	3.4949E-05
	534	1140.36	0.151	97.61156	0.00386374	3.64149E-05
	535	1135.49	0.149	96.7557	0.004018555	3.7874E-05
	536	1128.66	0.145	95.16064	0.004172621	3.9326E-05
	537	1119.03	0.141	93.43772	0.004325908	4.07707E-05
	538	1111.56	0.137	91.79489	0.004478388	4.22078E-05
	539	1106.84	0.134	90.59132	0.004630032	4.3637E-05
	540	1100.54	0.132	89.65648	0.004780813	4.50581E-05
	541	1094.36	0.128	88.03936	0.004930702	4.64708E-05
	542	1087.15	0.124	86.36691	0.005079671	4.78748E-05
	543	1081.95	0.12	84.75904	0.005227692	4.92698E-05
	544	1076.4	0.118	83.83389	0.005374737	5.06557E-05
	545	1070.63	0.116	82.89732	0.00552078	5.20321E-05
	546	1066.31	0.113	81.65311	0.005665793	5.33988E-05
	547	1058.88	0.11	80.28077	0.005809749	5.47556E-05
	548	1050.64	0.108	79.23748	0.005952621	5.61021E-05
	549	1044.11	0.107	78.6243	0.006094383	5.74382E-05
	550	1037.33	0.105	77.63274	0.006235007	5.87636E-05
	551	1033.69	0.104	77.1265	0.006374469	6.0078E-05
	552	1029.4	0.102	76.22263	0.006512741	6.13811E-05
	553	1025.7	0.101	75.71164	0.006649797	6.26729E-05

554	1022.77	0.099	74.85113	0.006785614	6.39529E-05
555	1020.35	0.098	74.38398	0.006920164	6.5221E-05
556	1019.21	0.097	73.96214	0.007053423	6.64769E-05
557	1018.81	0.096	73.56547	0.007185366	6.77205E-05
558	1017.33	0.095	73.12814	0.007315969	6.89514E-05
559	1016.85	0.094	72.72507	0.007445207	7.01694E-05
560	1015.46	0.093	72.28774	0.007573055	7.13744E-05
561	1014.3	0.092	71.85697	0.007699491	7.2566E-05
562	1013.63	0.091	71.44177	0.00782449	7.37441E-05
563	1012.84	0.092	71.80524	0.00794803	7.49084E-05
564	1011.39	0.093	72.14273	0.008070087	7.60588E-05
565	1010.9	0.094	72.51199	0.008190638	7.71949E-05
566	1010.64	0.095	72.88729	0.008309661	7.83167E-05
567	1010.3	0.096	73.25758	0.008427133	7.94239E-05
568	1009.89	0.097	73.6232	0.008543034	8.05162E-05
569	1009.26	0.098	73.97864	0.00865734	8.15935E-05
570	1009.56	0.096	73.23075	0.008770032	8.26556E-05
571	1008.73	0.094	72.43412	0.008881087	8.37023E-05
572	1008.3	0.098	73.94345	0.008990485	8.47333E-05
573	1007.85	0.1	74.67749	0.009098206	8.57486E-05
574	1007.1	0.102	75.3925	0.009204229	8.67478E-05
575	1007.61	0.103	75.78036	0.009308535	8.77309E-05
576	1006.78	0.101	75.0101	0.009411105	8.86976E-05
577	1006.3	0.099	74.24601	0.009511919	8.96477E-05
578	1006.1	0.102	75.35507	0.009610958	9.05811E-05
579	1005.6	0.103	75.70473	0.009708204	9.14977E-05
580	1005.1	0.104	76.05243	0.009803639	9.23971E-05
581	1004.6	0.105	76.39818	0.009897244	9.32793E-05
582	1003.6	0.103	75.62941	0.009989004	9.41441E-05
583	1002.94	0.1	74.49537	0.010078899	9.49914E-05
584	1002.64	0.102	75.22538	0.010166914	9.58209E-05
585	1002.2	0.103	75.57664	0.010253033	9.66326E-05
586	1001.75	0.102	75.19199	0.010337238	9.74262E-05
587	1001.3	0.101	74.80568	0.010419515	9.82016E-05
588	1000.75	0.1	74.41399	0.010499848	9.89587E-05
589	1000.3	0.099	74.02434	0.010578222	9.96974E-05
590	1000.07	0.098	73.64106	0.010654623	0.000100417
591	999.56	0.097	73.24569	0.010729035	0.000101119
592	999.3	0.096	72.85768	0.010801446	0.000101801
593	998.7	0.095	72.45546	0.010871842	0.000102465
594	998.41	0.094	72.06264	0.010940209	0.000103109
595	998.1	0.093	71.66718	0.011006536	0.000103734
596	997.61	0.092	71.26333	0.011070808	0.00010434
597	996.83	0.093	71.62157	0.011133016	0.000104926
598	996.2	0.094	71.98284	0.011193146	0.000105493
599	995.98	0.095	72.35672	0.011251188	0.00010604
600	995.4	0.092	71.18435	0.011307131	0.000106567
601	995.12	0.09	70.39645	0.011360964	0.000107075
602	994.73	0.094	71.92971	0.011412678	0.000107562
603	994.1	0.095	72.2884	0.011462263	0.000108029

604	993.65	0.092	71.12175	0.011509709	0.000108476
605	993.23	0.09	70.32957	0.011555007	0.000108903
606	992.66	0.091	70.69891	0.01159815	0.00010931
607	992.11	0.092	71.06661	0.011639129	0.000109696
608	991.74	0.093	71.43848	0.011677937	0.000110062
609	991.3	0.094	71.80559	0.011714566	0.000110407
610	990.61	0.095	72.1614	0.011749009	0.000110732
611	989.45	0.093	71.35595	0.01178126	0.000111036
612	988.34	0.091	70.54491	0.011811314	0.000111319
613	987.3	0.094	71.66057	0.011839163	0.000111581
614	986.7	0.096	72.3969	0.011864804	0.000111823
615	986.23	0.097	72.75566	0.011888231	0.000112044
616	984.6	0.095	71.94217	0.011909441	0.000112244
617	983.31	0.096	72.27243	0.011928428	0.000112423
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619	982.1	0.098	72.97644	0.011959723	0.000112718
620	981.41	0.099	73.32205	0.011972025	0.000112834
621	981.23	0.098	72.94411	0.011982094	0.000112929
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623	980.65	0.096	72.17461	0.011995523	0.000113055
624	980.3	0.095	71.7849	0.011998881	0.000113087
625	980.1	0.094	71.3988	0.012	0.000113097
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627	978.31	0.091	70.18604	0.011995523	0.000113055
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631	974.94	0.095	71.58838	0.011959723	0.000112718
632	973.61	0.092	70.4009	0.01194519	0.000112581
633	972.12	0.091	69.96364	0.011928428	0.000112423
634	971.9	0.093	70.72029	0.011909441	0.000112244
635	971.2	0.095	71.45094	0.011888231	0.000112044
636	970.67	0.096	71.80641	0.011864804	0.000111823
637	969.2	0.094	71.00067	0.011839163	0.000111581
638	967.65	0.095	71.32023	0.011811314	0.000111319
639	966.12	0.097	72.01006	0.01178126	0.000111036
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641	964.76	0.095	71.21365	0.011714566	0.000110407
642	964.3	0.093	70.44324	0.011677937	0.000110062
643	963.5	0.091	69.65276	0.011639129	0.000109696
644	963.13	0.094	70.77798	0.01159815	0.00010931
645	962.54	0.096	71.50506	0.011555007	0.000108903
646	961.23	0.095	71.08325	0.011509709	0.000108476
647	960.6	0.092	69.92895	0.011462263	0.000108029
648	959.45	0.094	70.64263	0.011412678	0.000107562
649	958.64	0.096	71.36006	0.011360964	0.000107075
650	957.12	0.097	71.67387	0.011307131	0.000106567
651	956.23	0.095	70.89813	0.011251188	0.00010604
652	955.37	0.093	70.11631	0.011193146	0.000105493
653	954.3	0.095	70.82654	0.011133016	0.000104926

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661	946.31	0.095	70.52942	0.010578222	9.96974E-05
662	945.13	0.093	69.73953	0.010499848	9.89587E-05
663	944.67	0.096	70.83819	0.010419515	9.82016E-05
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669	940.83	0.094	69.9538	0.009897244	9.32793E-05
670	940.31	0.095	70.30547	0.009803639	9.23971E-05
671	939.7	0.093	69.53891	0.009708204	9.14977E-05
672	938.89	0.091	68.75746	0.009610958	9.05811E-05
673	938.2	0.094	69.85595	0.009511919	8.96477E-05
674	937.7	0.096	70.57638	0.009411105	8.86976E-05
675	937.11	0.098	71.28532	0.009308535	8.77309E-05
676	936.64	0.095	70.18814	0.009204229	8.67478E-05
677	935.74	0.094	69.76431	0.009098206	8.57486E-05
678	932.6	0.092	68.90225	0.008990485	8.47333E-05
679	931.1	0.093	69.21997	0.008881087	8.37023E-05
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681	929.46	0.095	69.89868	0.00865734	8.15935E-05
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683	927.34	0.097	70.55002	0.008427133	7.94239E-05
684	926.97	0.098	70.8986	0.008309661	7.83167E-05
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686	924.31	0.097	70.43467	0.008070087	7.60588E-05
687	923.74	0.095	69.68326	0.00794803	7.49084E-05
688	922.37	0.092	68.5233	0.00782449	7.37441E-05
689	921.65	0.094	69.23708	0.007699491	7.2566E-05
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698	913.48	0.097	70.02082	0.006512741	6.13811E-05
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703	908.7	0.095	69.11365	0.005809749	5.47556E-05

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	705	905.54	0.097	69.71584	0.00552078	5.20321E-05
	706	904.64	0.095	68.95908	0.005374737	5.06557E-05
	707	903.49	0.093	68.18596	0.005227692	4.92698E-05
	708	902.67	0.094	68.52045	0.005079671	4.78748E-05
	709	902.1	0.096	69.22369	0.004930702	4.64708E-05
	710	901.64	0.098	69.92322	0.004780813	4.50581E-05
	711	901.13	0.095	68.82517	0.004630032	4.3637E-05
	712	900.56	0.091	67.33933	0.004478388	4.22078E-05
	713	900.2	0.093	68.0617	0.004325908	4.07707E-05
	714	899.8	0.095	68.77436	0.004172621	3.9326E-05
	715	899.4	0.097	69.47909	0.004018555	3.7874E-05
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	719	898.64	0.096	69.09081	0.003395085	3.19979E-05
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	721	897.89	0.097	69.42074	0.003079433	2.9023E-05
	722	897.76	0.095	68.69636	0.002920731	2.75272E-05
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	725	897.61	0.097	69.40991	0.002441472	2.30103E-05
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	733	897.41	0.06	54.58369	0.001145617	1.07972E-05
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	736	897.27	0.042	45.66443	0.000655311	6.17616E-06
	737	897.24	0.03	38.59284	0.00049159	4.63313E-06
	738	897.21	0.02	31.51039	0.000327778	3.08923E-06
	739	897.15	0.015	27.28789	0.000163904	1.54476E-06
EVC	740	897	0.01	22.27861	0	0

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