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An Analysis of the Effect of Heat Transfer on Internal Combustion Engines

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ABSTRACT

In this paper, the temperature and nitric oxide concentrations are predicted using a numerical approach. The main application of this method is for the internal combustion engines. The predictions are made with the help of three correlation models including the Eichelberg, the Hohenberg, and the Woschini correlation models. The experimental results are designed with the help of a multi-zone approach to effectively capture the combustion process. The zones were further divided into burned and unburned zones. The experimental results have shown that under adiabatic conditions, all the three models can predict the temperature and nitric oxide concentration relatively accurately.

Keywords – internal combustion engine, nitric oxide, numerical methods, multi-zonal

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I. INTRODUCTION

Recently, there has been an increased awareness about the effect of greenhouse gasses on the environment. It is being encouraged to reduce the human dependence on fossil fuels as they are a threat to the environment. Nitric oxides and carbon dioxide are two byproducts of the combustion of fossil fuels. The automotive industry has been very active in attempting to reduce the emissions of these oxides.

It has been observed that the heat transfer phenomenon is critical to understand the combustion process in Internal Combustion Engines (ICEs). In particular, it is very closely coupled to the combustion rates as well as to emissions in such engines (Chang et al., 2004). The parameters that effect the heat transfer in ICEs and the still not well-understood, nor are the rates and emissions of such oxides. Hence, in order to improve the performance of ICEs, it is important to understand the heat transfer process associated with it. For this, there are two ways: experimental approach and numerical approach.

In the experimental approach, obtaining accurate data has been a challenge because of the difficulties in measuring and the complication nature of the heat processes. On the other hand, numerical approach is relatively simple. They can be used to predict both the temperature and other byproducts of combustion such as nitrogen and carbon oxides. Numerical methods again can be classified into two methods: ones that are based on solving linear correlations and the ones that are based on computational fluid dynamics (CFD) and heat transfer.

The rest of the paper is organized as follows: in Section II, a literature survey is presented. In Section III the proposed method is discussed while in Section IV, the results obtained for the proposed method are presented and discussed. Finally, in Section V, conclusions of this paper are presented.

II. LITERATURE REVIEW

In this section, related literature is reviewed. In terms of related literature on heat transfer, the techniques used to measure heat flux have been studied before by Childs et al. (1999). Measuring techniques are generally based on non-intrusive methods. For example, Eichelberg (1939) used surface thermos couples were used to measure the instantaneous surface temperature in an ICE. A faster version of this method was used by Chang et al. (2004). Many experimental and numerical methods have been proposed in the literature to understand he heat transfer processes in Spark Ignition (SI) and Compression Ignition (CI) engines (e.g, Eichelberg ,1939; Annand & Ma, 1971; Sihling & Woschni, 1967l; and Han et al 1997). Chang et al. (2004) proposed an experimental investigation method for heat transfer. This method was based on a Homogeneous Charge Compression Engine

(HCCI). They also presented a global heat transfer model.

Among the numerical approaches, Agarwal et al. (1998) proposed multi-dimensional computational fluid dynamic (CFD) models. Another important work in this regard is that of Caton (2003). He investigated the effect of different burn rate parameters on emissions of nitric oxide. An SI based engine was used for this study. The engine is based on a 3-zone thermodynamics simulation. Understanding and reducing nitric oxide emissions from HCCI and SI engines are critical to reducing the atmospheric pollution. Caton (2003) used a thermodynamic engine cycle simulation which included three different layers for the combustion process. These included the unburned, the adiabatic core, and the boundary layers. It is found that the heat transfer and the rate of generation of pollutants like Nitric oxides are very related. Hence, it is important to understand the process of heat transfer. In a previous study by Caton (2000), it was observed that varying the burn rate can increase power and thermal efficiency by around 8%. To further understand the production mechanism and the parameters that are important to its rate of production, its kinetics are studied.

The literature points to four different mechanisms which are responsible for the formation of nitric oxides in a combustion process. These mechanisms include: thermal, prompt, nitrous oxide, and fuel nitrogen. The thermal mechanism is also called the Zeldovich mechanism. Caton (2003) only studied the Zeldovich mechanism. Zeldovich mechanism was enhanced by Lavoie et al. (1970) by including an additional reaction. This enhanced Zeldovich mechanism is important for many combustion conditions.

III. METHODOLOGY

In the proposed method, we investigate the correlation between temperature and the emission rate of nitric oxides in an ICE. The literature in the previous sections suggests that the design and operating parameters of an ICE have a major influence on the overall combustion process. In this work, the nitric oxide emissions are estimated from three temperature related correlations. The first correlation is based on Eichelberg (1939), the second correlation is based on Hohenberg (1979) and the third correlation is based on Woschini (1967). The performance of each correlation method is evaluated by comparing their results with those obtained experimentally. Adiabatic boundary conditions are considered for the simulations.

The specifications of the engine used for the simulations are as follows: Bore: 100mm, Stroke: 88.4mm, Conrod length: 180mm, Inlet valve diameter, 50mm, no. of cylinders: 2. compression ratio: 8.1, speed, 1400rpm, ignition angle: 60 degrees, residual fraction: 0. The fuel type which was used for simulations was ISOCTANE. A computer program has been developed based on the relevant system of equations. The three temperature correlation models are included in the program and heat transfer, temperature field, pressure values, and nitric oxide distributions can be predicted by this program.

IV. RESULTS AND DISCUSSION

In this section, the results of the proposed method are presented and discussed. This is done by first presenting the results for the engine specification data only in the next sub-section.

A. Preliminary Results

In this sub-section, the preliminary results of the simulations are presented. For the preliminary results, engine specifications were chosen to be the same as that of Caton (2003). While there are many similarities between the simulations performed as part of this research and those of Caton (2003) but there are some major differences as well. One of these is the difference in the amount of fuel used in both the simulations. This is an important difference as the burning of different amounts of fuel results in producing different amounts of nitric oxide and other pollutants. Another major difference is the difference in inlet temperatures for the two simulations. Similarly, another difference is different mathematical approaches used in both the simulations where Caton (2003) used a more specific approach while the proposed simulations address a more general problem. Hence, with all the difference, different results are expected from both the simulations. Moreover, since many of the engine specifications were similar, the general behaviors of the related parameters are expected to have some degree of similarity. The preliminary results are shown in Fig. 1.

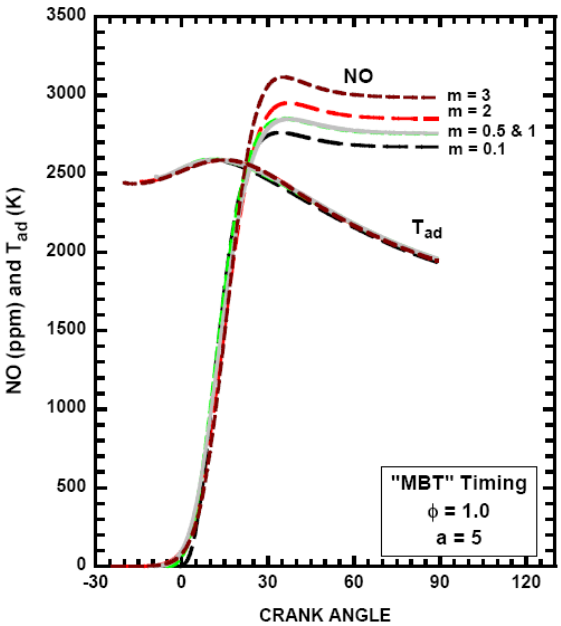

Figure 1 Preliminary results showing temperature and nitric oxide distributions as functions of the crank angle.

The preliminary results shown in Fig. 1 present the temperature distribution as a function of the crank angle for both Caton (2003) and the proposed simulations. For interpreting the results, it needs to be taken into consideration that Caton (2003) was based on a modified version of the heat transfer model used in Woshini (1967) while in the proposed simulations, the exact model of Woshini (1967) was used. Another aspect that needs to be taken into consideration is that while both the simulations used multi-zone criteria for modeling burned region, the simulations of Caton (2003) were based on fine tuning of the model parameters while the proposed simulations are based on observing the values of temperature and nitric oxide distribution in different zones.

Fig. 2 and Fig. 3 present the temperature distribution and nitric oxide distribution as functions of the crank angle in different burning zones. The burning area is divided into 20 zones. The results are shown for different zones in such a way that all the zones are covered. Zones 5 and 10 represent the intermediate zones.

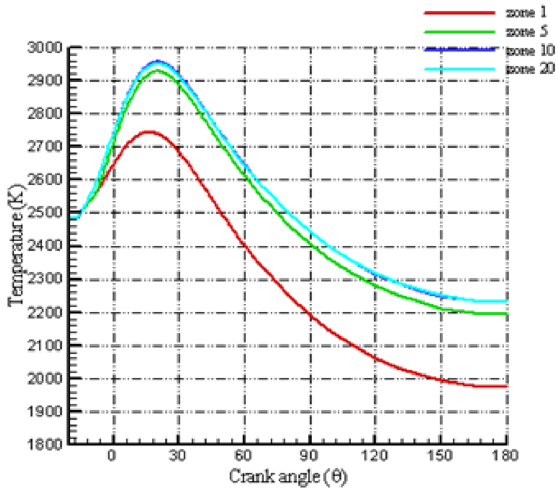

Figure 2 Temperature distribution as a function of the crank angle for different burning zones.

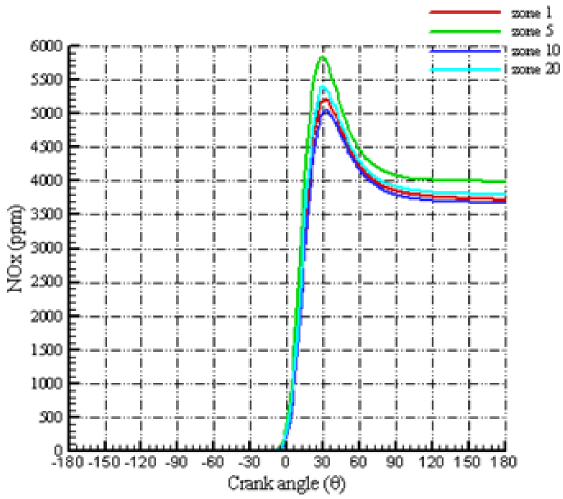

Figure 3 Nitric oxide distribution as a function of the crank angle for different burning zones.

From the results shown in Fig. 2, it can be seen that the temperature distributions for different zones obtained using Caton (2003) and the proposed simulations produced similar results. In both the cases, the temperature initially increases as the crank angle increases, reaches the maximum when crank angle is between 15^o and 20^o, and then starts decreasing monotonically as the crank angle increases further. It can also be observed that the behavior in zone 1 is slightly different in that it produces a significantly lower profile compared to the profiles obtained for all other zones. The same behavior was observed by Caton (2003) (See. Fig. 1). Hence, it can be observed that the proposed simulations produced similar results to that of Caton (2003).

Similarly, the results in Fig. 3 show the distribution of nitric oxide as a function of the crank angle for different zones. It can be seen that the behavior in Fig. 3 is very similar to that of Caton

(2003) in that when the crank angle is zero, the concentration of nitric oxide is zero. The maximum nitric oxide concentration is reached at a crank angle of approximately 30^o. When the crank angle is increased further, the nitric oxide concentration starts decreasing and at about 90^o, the nitric oxide concentration becomes stable. The slight differences between the results obtained for the proposed simulations and those of Caton (2003) can be attributed to the different mathematical foundations and the different molar values used in both the simulations.

The results shown in Fig. 2 and Fig. 3 were obtained by considering adiabatic conditions. The preliminary results show that the developed computer program produces good quality results. The developed program and the underlying assumed models can accurately predict the parameters of the combustion process.

B. Overall Results

The overall results of the proposed method are presented in this sub-section. The developed program is used to assess the performance of the three heater transfer correlation models. In total, there are three different simulation scenarios. In all the simulations, adiabatic boundary conditions are assumed. Again, the burned region was divided into 20 different zones. The simulation results are shown for four zones representing different burn regions. In particular, the results of temperature distribution, pressure distribution, and nitric oxide distribution are presented and discussed in this sub-section.

1) Temperature Field

Heat transfer rates are affected by the temperature field. Hence, it is important to study the temperature field/distribution. For this purpose, first, the unburned temperature distributions are shown for three different prediction models. These are Eichelberg, Hogenberg, and Woschini. These results are shown in Fig. 4, Fig. 5, and Fig 6 respectively. The results in Fig. 4, Fig. 5, and Fig. 6 show that before the start of the combustion process, temperature exists only for the unburned zone. After the start of the combustion process, temperature starts showing in the burned zones as well. The results show that in the case of unburned temperature, all the three models showed similar temperature variations when temperature was plotted against the crank angle.

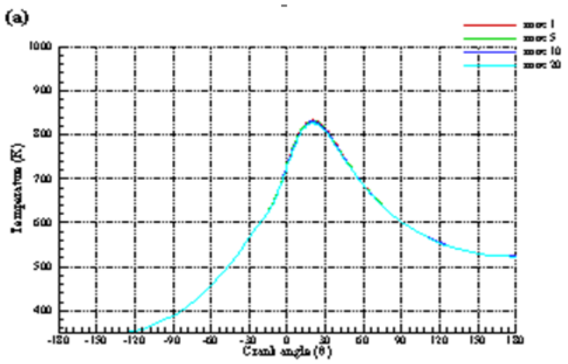

Figure 4 Unburned temperature distributions for the Eichelberg model

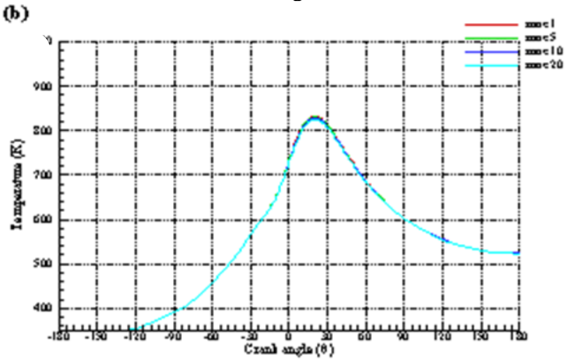

Figure 5 Unburned temperature distributions for the Hohenberg model

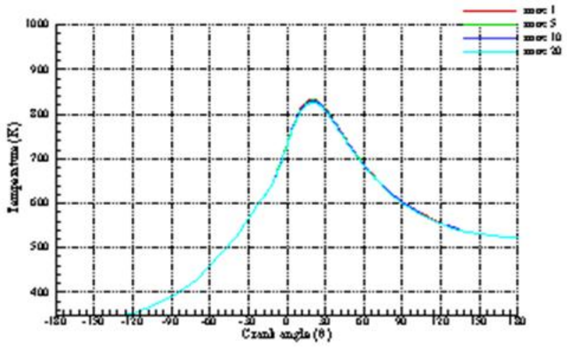

Figure 6 Unburned temperature distributions for Woschini model

In all the three cases, the unburned temperature showed a gradual increase with an increase in the crank angle. In all the three cases, the maximum temperature of around 830K is reached at the crank angle of around 20^o. Moreover, for all the three models, no variation between temperatures were observed for the four different zones. Hence, the results show that all the three models can predict unburned temperature accurately.

Next, the distribution of burned temperature is shown for all the three cases. These results are shown in Fig. 7, Fig. 8, and Fig. 9.

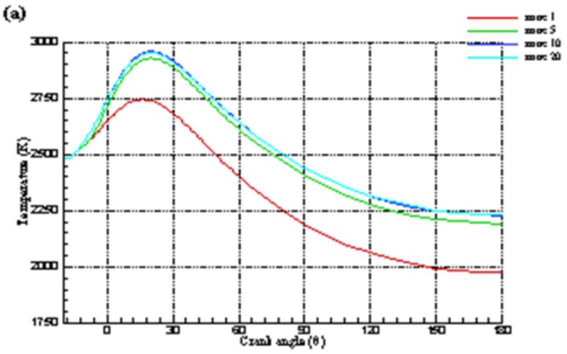

Figure 7 Burned temperature distribution as a function of crank angle for the Eichelberg model

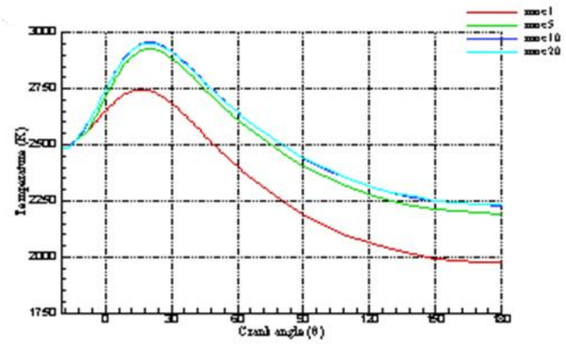

Figure 8 Burned temperature distribution as a function of crank angle for the Hohenberg model

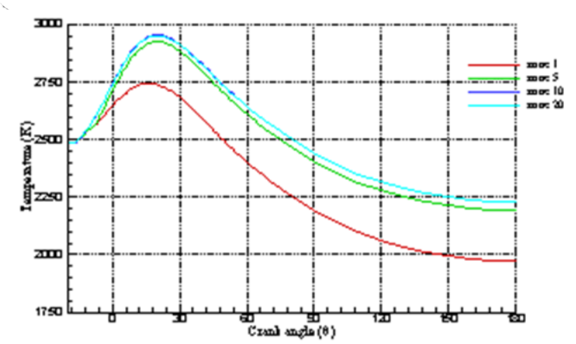

Figure 9 Burned temperature distribution as a function of crank angle for the Woschini model

It can be seen from the results in Figs. 7 – 9 that the burned zone temperature starts rising when the combustion starts. Moreover, all the three models predict similar temperature profiles. It can also be observed from these results that zone 1 has the lowest profile, followed by zone 5 and then by zone 10 and zone 20 respectively with the difference between the profiles quite evident for inner zones than for the outer zones. In terms of the effect of the crank angle, it can be seen that the temperatures start increasing from the initial 2500K when the crank angle increases until the crank angle of around 15^o – 20^o when the temperature is maximum. When the crank angle is increased further, the temperatures start decreasing and around 150^o, somewhat stable profiles are observed.

2) Nitric oxide distribution

The nitric oxide distributions for the three cases are shown in Fig. 10, Fig. 11, and Fig. 12.

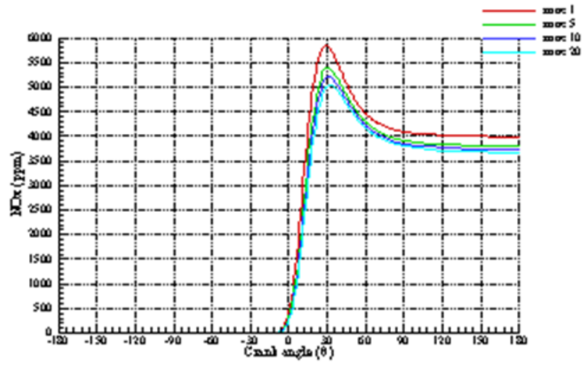

Figure 10 Nitric oxide distribution as a function of crank angle for the Eichelberg model.

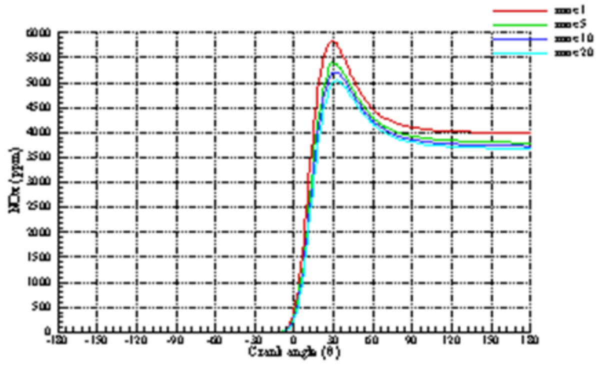

Figure 11 Nitric oxide distribution as a function of crank angle for the Hohenberg model.

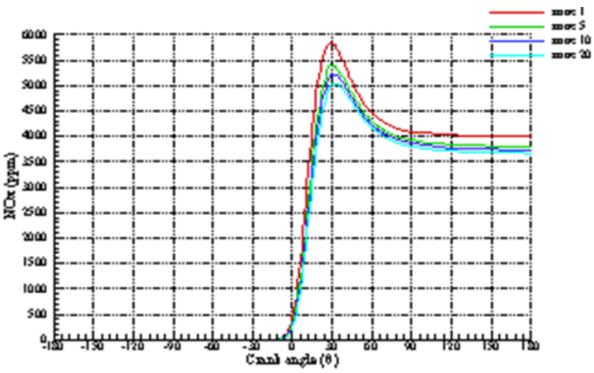

Figure 12 Nitric oxide distribution as a function of crank angle for the Woschini model.

It can be seen from Figs. 10 – 12, that all the three correlation models predicted similar values of nitric oxide concentrations. In all the three cases, the concentration of nitric oxide sees a sudden rise as the crank angle increases from 0^o and reaches a maximum concentration of around 5000ppm at around 30^o. When the crank angle is further increased, the concentration of nitric oxide starts decreasing. When the crank angle reaches around 90^o, the concentration becomes relatively stable around 4000ppm.

V. CONCLUSIONS

In this paper, numerical approach was used to simulate the combustion process for an internal combustion engine. A multiple zone method was used in which the entire region was divided into 20 different zones. The simulations were conducted under the assumption of adiabatic heat transfer conditions. Three different correlation models were used including the Eichelberg correlation model, the Hohenberg correlation model, and the Woschini correlation model. The effects of each model on the temperature and nitric oxide concentrations were examined. The experimental results concluded that all the three models are able to accurately predict temperature and nitric oxide concentrations under adiabatic conditions. Moreover, it remains to be seen how the three models behave under non-adiabatic conditions. This can be examined in a future study.

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