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An Examination of the Ignition Delay Period in Gas-Fueled Diesel Engines

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Changes in the physical and chemical processes during the ignition delay period of a gas-fueled diesel engine (dual-fuel engine) due to the increased admission of the gaseous fuels and diluents are examined. The extension to the chemical aspects of the ignition delay with the added gaseous fuels and the diluents into the cylinder charge is evaluated using detailed reaction kinetics for the oxidation of dual-fuel mixtures at an adiabatic constant volume process while employing n-heptane as a representative of the main components of the diesel fuel. In the examination of the physical aspects of the delay period, the relative contributions of changes in charge temperature, pressure, physical properties, pre-ignition energy release, heat transfer, and the residual gas effects due to the admission of the gaseous fuels are discussed and evaluated. It is shown that the introduction of gaseous fuels and diluents into the diesel engine can substantially affect both the physical and chemical processes within the ignition delay period. The major extension of the delay is due to the chemical factors, which strongly depend on the type of gaseous fuel used and its concentration in the cylinder charge.

Introduction

The ignition delay period in a compression ignition engine is a very important performance parameter that influences subsequent combustion processes, engine performance, and exhaust emissions. In gas-fueled diesel engines (dual-fuel engines), the control of the ignition delay period is equally important and can display trends significantly different from those observed in the corresponding diesel engine operation. The injection of a small quantity of liquid diesel fuel is maintained in dual-fuel engine operation to ensure ignition of the charge. The length of the ignition delay, however, increases significantly with the increased admission of the gaseous fuel up to a detectable maximum value and then drops gradually, as shown typically in Fig. 1. Changes in the type of gaseous fuel used in a dual-fuel engine for the same injected quantities of liquid pilot fuel and total equivalence ratio also produce significant changes in ignition delay. For example, as shown in Fig. 1, the admission of propane increases the length of the ignition delay in dual-fuel engine operation to an extent much longer than the corresponding values observed with methane or with other gaseous fuels. For the admission of the diluents nitrogen and carbon dioxide into the intake air, however, the observed experimental values of the ignition delay in the operation of a diesel engine display yet different trends from those observed for the admission of gaseous fuel in the cylinder charge [1, 2]. Neither nitrogen nor carbon dioxide addition could produce comparable trends in increasing the ignition delay of the diesel fuel.

Some research has been carried out in the past to examine the changes in the ignition delay period during the operation of dual fuel engines. Moore and Mitchel [3] indicated that the increase in ignition delay observed in dual-fuel engines was caused by the presence of the gaseous fuels. The length of the ignition delay could be improved by increasing the pilot quantity and preheating the intake charge. Karim and Burn [2] indicated that the observed variations of the ignition delay in dual-fuel engines cannot be explained wholly on the basis of the reduction of the partial pressure of oxygen in the intake charge

as a result of gaseous fuel admission. The gaseous fuel must affect in an unknown manner the pre-ignition processes of the diesel pilot fuel to bring about the observed specific variations in the length of the ignition delay. In our previous work [5], the effects of changes due to gaseous fuel admission, in mean charge temperature, external heat transfer to the surroundings, and the extent of pre-ignition energy release during the compression process on the length of the ignition delay of a dual-fuel engine have been examined while using detailed reaction kinetics for the oxidation of the gaseous fuel and air and employing an experimentally based formulation for the ignition delay of the liquid pilot. The effects of any chemical interaction between the pilot and gaseous fuels during the preignition processes could not be accounted for.

The present contribution examines further the observed changes in the physical and chemical processes during the ignition delay period of a gas-fueled diesel engine (dual-fuel engine) due to the increased admission of the gaseous fuels and diluents. In the examination of the chemical aspects of the ignition delay, the environment of the mixture of diesel pilot with the gaseous fuel is simulated by an adiabatic constant volume process while employing n-heptane as a representative of the main components of the diesel fuel. The effects of changes in the concentrations of the added gaseous fuels, such as methane, propane, and hydrogen, and the diluents carbon dioxide and nitrogen to the cylinder charge as well as the changes in intake charge temperature on the ignition delay of the fuel mixture in air are evaluated through using detailed reaction kinetics for the oxidation of the n-heptane and gaseous fuels mixture.

In the examination of the physical aspects of the delay period, the relative contributions to the ignition delay, resulting from changes in charge temperature, pressure, physical properties, pre-ignition energy release, heat transfer, and the effects of the residual gases due to the admission of gaseous fuels are discussed and evaluated. It is shown that the introduction of gaseous fuels and diluents into the diesel engine will change both the physical and chemical processes of the ignition delay period. The extension to the chemical process of the delay period with the admission of the gaseous fuel is the main rate controlling processes. Its extent, which depends on the type of the gaseous fuel used and its concentration in the cylinder charge, will be decreased with the improvement of combustion performance.
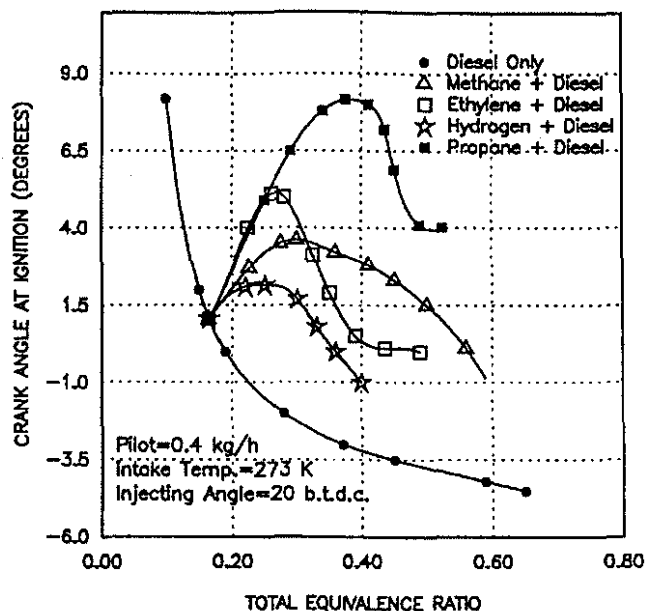
Fig. 1 Variations of ignition delay with various gaseous fuels admission over a range of equivalence ratio in a dual fuel engine operation

Analytical Considerations

The ignition delay in a diesel engine is defined as the time interval between the start of fuel injection and the commencement of rapid energy release due to combustion. The pre-ignition processes can be viewed as being initially predominantly physical, followed by overlapping somewhat later chemical processes. In the physical part of the delay process, the fuel is injected, atomized, vaporized, and mixed with the air. The associated chemical processes are controlled by the precombustion reactions of the local mixtures of the fuel, air, and residual gases. A convenient approach based on experimental observation of the delay in diesel engines is to consider the length of the ignition delay period to be a function of the charge pressure and equivalence ratio of the fuel vapour and air, and exponentially dependent on the inverse of the mean charge temperature [6, 7].

In dual-fuel engine operation, the admission of a gaseous fuel with the air will influence profoundly both the physical and chemical ignition processes of the mixture. This admission will bring about variations in the physical properties of the mixture, such as the specific heat ratio and heat transfer parameters. These can lead to significant changes in the charge temperature and pressure levels at the time of fuel injection and extend the physical ignition delay period of the mixture. The presence of the gaseous fuel–air charge during the pre-ignition reaction results in changes to the energy release and the associated production of active species. Moreover, any chemical interactions that may take place between the diesel vapor and gaseous fuel will produce further changes in the chemical ignition processes of the mixture.

Some of the major effects of the introduction of the gaseous fuel on the ignition period of the dual-fuel–air engine can be expressed conveniently as a modification to the compression mean charge temperature, ΔT, and can be written as:

$$\Delta T = \Delta T_{th} + \Delta T_{re} + \Delta T_{ht} + \Delta T_{ri} + \ldots \quad (1)$$

where ΔT_{th} is the temperature change due to any variations in the thermodynamic and physical properties of the mixture, ΔT_{re} is the change due to the contribution of residual gases, ΔT_{ht} is the change due to the heat transfer, and ΔT_{ri} is the change due to the contribution of pre-ignition energy release. Changes in the thermodynamic and physical properties of the mixture could

normally bring about a decrease in the charge temperature while other changes, such as the contribution of the residual gases, could result in an increase in the charge temperature. The effects of any chemical interaction between the diesel and gaseous fuels during the preignition reactions can be accounted for empirically through a modification to the effective overall activation energy term of the mixture, which will be strongly dependent on the types and concentration of gaseous fuels involved.

Hence, when accounting for the effects of these changes, a *modified value* for the ignition delay in dual fuel engines can be produced [5]. This modified value, $\tau + \Delta\tau(s)$, in order to be compared to the corresponding value under diesel operation [6, 7], can be written as:

$$\tau + \Delta\tau = A(P + \Delta P)^a(\phi + \Delta\phi)^b \exp\left(\frac{c + \Delta c}{T_s + \Delta T}\right) \quad (2)$$

where P and T_s represent, respectively, the mean cylinder pressure (atm) and charge temperature (K) during the ignition delay period. ϕ is the equivalence ratio of the fuel vapor–air mixture. A, a, b, and c are constants to be established experimentally for the relevant operating conditions. The values of these constants as obtained, for example, by Hiroyasu [6, 7] in a constant volume vessel are:

$$A = 4.0 \times 10^{-3}, \quad a = -2.5, \quad b = -1.04, \quad c = 6000 \quad (3)$$

In the present work, the equivalent modifications to the charge temperature in accordance with Eq. (1) can be correlated from the results of analysis and experiment. The corresponding chemical effects on the ignition delay period of the dual-fuel–air mixture are examined on the basis of adiabatic constant volume reaction conditions while employing detailed reaction kinetics for the oxidation of the dual-fuel–air mixture. In these kinetic considerations, n-heptane is chosen to represent the oxidation of the diesel fuel since the chemical kinetics of the diesel fuel oxidation are currently unavailable. Moreover, the adiabatic constant volume conditions tend to be close to the environment of the diesel pilot fuel in dual-fuel engines during the delay period (for example, a charge mean temperature of 780 K and a charge pressure of 28 atm). The concentrations of the mixtures of n-heptane vapor and the gaseous fuel are considered in terms of their corresponding stoichiometric value, which tends to be associated with the peak value of the reaction rates for the oxidation of the mixture. The chemical reaction mechanism of the mixtures of n-heptane and the other gaseous fuels was based on those schemes reported by Westbrook et al. [8]. This detailed kinetic scheme consisted of 1966 elementary reaction steps and 380 chemical species. The corresponding thermochemical data were obtained mainly from JANAF tables [10].

The residual gases from the previous cycle, which were assumed to fill the clearance volume when a new cycle began, were considered to have the same composition as that for the exhaust gases at the end of expansion to atmospheric pressure. These residual gases, when the inlet valve was opened, mixed completely and adiabatically with the fresh charge at the same pressure. For heat transfer, the mean wall temperature T_w was assumed to remain constant over the cycle, while convective and radiative heat transfer was accounted for by a formulation recommended by Annand [11] following his analysis of a wide range of experimental data in engines.

Results and Discussion

When the pilot diesel fuel is injected into the combustion chamber under high injection pressures, the pilot fuel is atomized and distributed within its spray cone. The resulting axial and radial fuel concentration profiles could be calculated approximately by employing established theoretical procedures for the flow of jets [12]. Increasingly more surrounding fuel along with the air are entrained into the spray cone as the jet
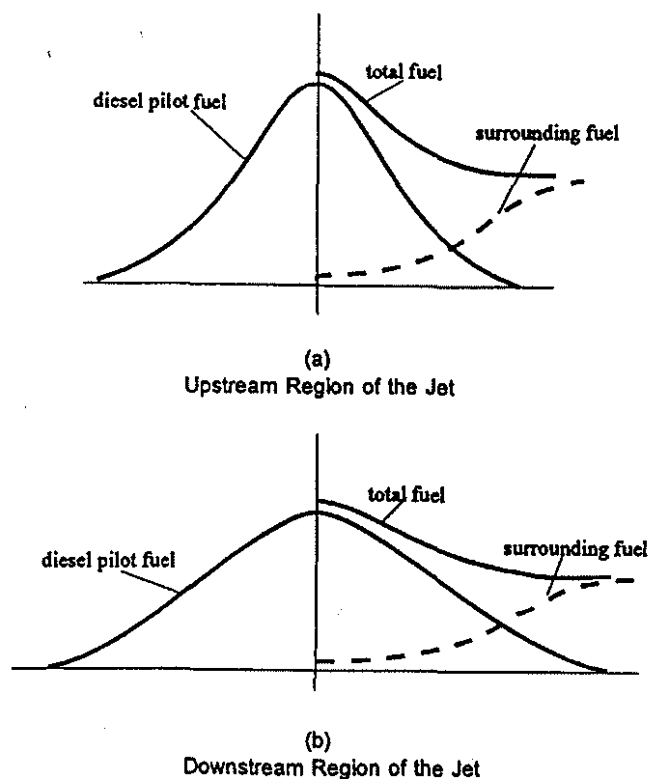
(a)
Upstream Region of the Jet

(b)
Downstream Region of the Jet

Fig. 2 Schematic representation of fuel concentration profile within a diesel fuel jet issuing in an atmosphere of gaseous fuel and air mixture
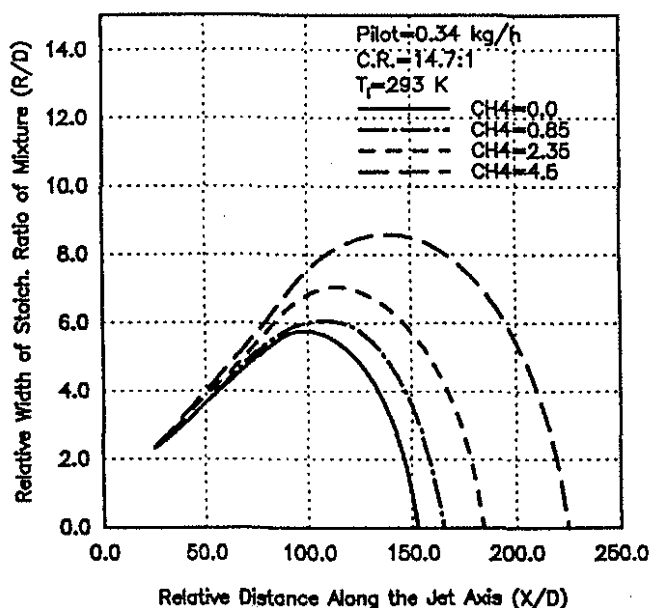

Fig. 3 Calculated relative width of the stoichiometric ratio envelopes in jet fuel mixture with changes in methane concentration in the surrounding charge

of diesel fuel moves downstream. The downstream radial fuel concentration profiles become increasingly flatter. Consequently, for the same overall fuel–air ratio in the cylinder charge, the relative concentration of the gaseous fuel at a downstream jet location, as shown schematically in Fig. 2(a) and 2(b), has a much higher value than that at an upstream jet location due to the entrainment of the surrounding gaseous fuel. The induction of more gaseous fuel into the engine cylinder will further change the local fuel composition and increase the concentration of the total fuel at any point while the concentration of the air reduced by the same amount. However, this change in the local fuel composition is not uniform for the mixture within the jet spray cone. As shown in Fig. 3, the overall size of the stoichiometric region at every section downstream of the nozzle is increased, both in width and length, as the concentration of the gaseous fuels in the surroundings is increased. However, the increase of gaseous fuel in the local fuel composition for the same stoichiometric zone tends to be prominent only at regions away from the discharge point of the jet. These changes in local fuel composition with the admission of the gaseous fuels play an important role in modifying the ignition and combustion characteristics of the engine from those of normal diesel operation.

It is expected that the most probable location for first ignition encountered will be along a stoichiometric mixture envelope of the fuel jet for the same temperature level. In the operation of a dual-fuel engine, the ignition delay period will depend not only on the concentration of the mixture but also on the local fuel composition for the same values of the stoichiometric mixture, since the admission of the gaseous fuel changes the local fuel composition, as shown in Figs. 2 and 3. It has been confirmed in Fig. 4 that for stoichiometric mixtures at mean temperature and pressure values similar to those during the delay period in engines, the calculated ignition delay period of heptane and gaseous fuel mixtures in air is gradually extended as the percentage of the gaseous fuel in the mixture is increased. For methane admission, the extension to the ignition delay period

of the fuel mixture tends to be initially very slow until the percentage of the methane in the fuel mixture is substantially increased to beyond around 70 percent. The increased percentage of hydrogen in the mixture does not increase the ignition delay significantly. However, for propane admission, the ignition delay extends more rapidly with increasing the percentage of propane in the fuel mixture. These changes in the ignition delay period, which depend on the type of the gaseous fuel and its concentration in the cylinder charge, are consistent with those observed experimentally in Fig. 1 for dual-fuel engine operation. Figure 5 shows similarly the corresponding variations of the ignition delay period with increasing concentrations of gaseous fuel and the diluents carbon dioxide and nitrogen in the local stoichiometric mixture for n-heptane and the added gas. It can be seen that unlike with the admission of gaseous fuels, neither the presence of small amounts of nitrogen nor
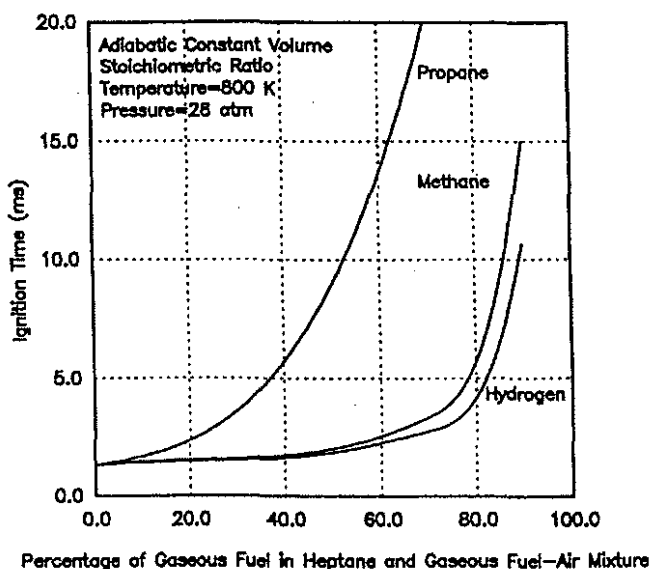

Fig. 4 Calculated ignition times of the stoichiometric dual-fuel mixture with changes in the percentage of gaseous fuel in the total mixture for an adiabatic constant volume process
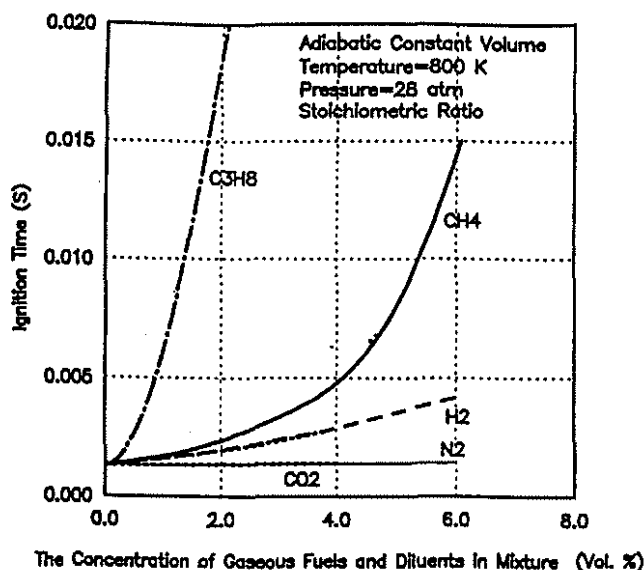
Fig. 5 Variations of calculated ignition times with changes in the concentration of gaseous fuel and diluent in the mixture for an adiabatic constant-volume process

Fig. 7 Variations of calculated maximum temperatures with equivalence ratios for propane, methane, hydrogen, carbon dioxide, and nitrogen in a motored engine operation

carbon dioxide with n-heptane can produce significant increases in the ignition delay period. The small changes observed are associated mainly with the reduction of the partial pressure of oxygen in the surroundings. Figure 6 shows that the decrease in the mixture temperature extends the ignition delay period of the mixture without significantly changing the trends of ignition delay period with the increased admission of gaseous fuels.

Accordingly, on the basis of these trends, the admission of the gaseous fuel with the intake air in dual-fuel applications will result in an extension to the ignition delay period due to the chemical interactions between the diesel and gaseous fuels. This extension will be further increased, but not proportionally, with the increase of the concentration of the gaseous fuel in the cylinder charge. It can be anticipated that ignition in the dual-fuel engine will first take place within the region of the diesel

pilot jet where sufficient amounts of diesel fuel vapor and air but with small concentration of gaseous fuel form the most reactive ignition elements. Those regions that are close to or far away from the discharge point of the fuel jet will tend to produce a later ignition due to either the lack of vaporized diesel fuel or a relatively high concentrations of the gaseous fuel in the local mixture.

Another major effect of the introduction of a gaseous fuel or a diluent in the engine cylinder with the intake air is the resulting variations in the charge temperature during compression. These are due to the changes in the physical properties of the mixture, such as the specific heat ratio and heat transfer parameters, as well as any energy release arising from the pre ignition reactions of the gaseous fuels. As shown in Fig. 7, the addition of hydrogen to the engine intake air reduces the maximum temperature level of the charge at the end of compression only relatively little. However, the corresponding values of temperature observed with the addition of methane or propane decrease markedly. With propane addition, for the typical case shown, a drop in temperature of around 90 K was observed for the stoichiometric mixture. Similarly, the mean value of the charge temperature at the end of compression decreases essentially linearly with increasing the concentrations of carbon dioxide in the cylinder charge. The addition of nitrogen to the intake air hardly changes the charge temperature.

The effect of changes in the physical properties of the mixture and heat transfer arising from the admission of the gaseous fuel on the charge temperature at the end of compression can be correlated on the basis of the type and concentration of the gaseous fuel. As shown in Fig. 8, this temperature is markedly reduced with the increased addition of methane into the air while following similar trends for wide working conditions. The values predicted by the correlated formulation agree very well with the corresponding individually calculated values according to the following relationship:

$$\Delta T_{g\max} = (T_{a\max} - T_{g\max}) = T_{a\max}\left(1 - \exp\left(-\frac{\varphi}{a}\right)\right) \quad (4)$$

where $T_{g\max}$ is the charge temperature at the end of compression with the admission of gaseous fuel, $T_{a\max}$ is the charge temperature at the end of compression with pure air admission, φ is the equivalence ratio of the gaseous fuel, a is a constant having the following values 16.61, 8.90, 55.31, and 13.56 for the addi-
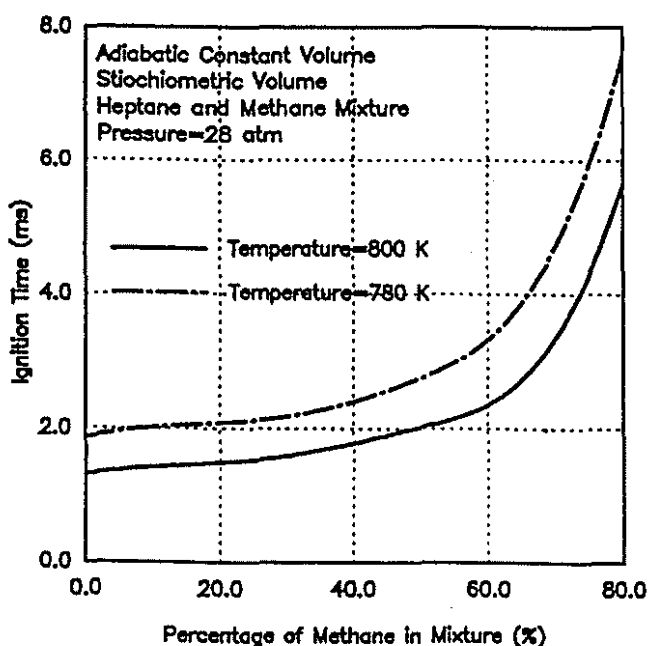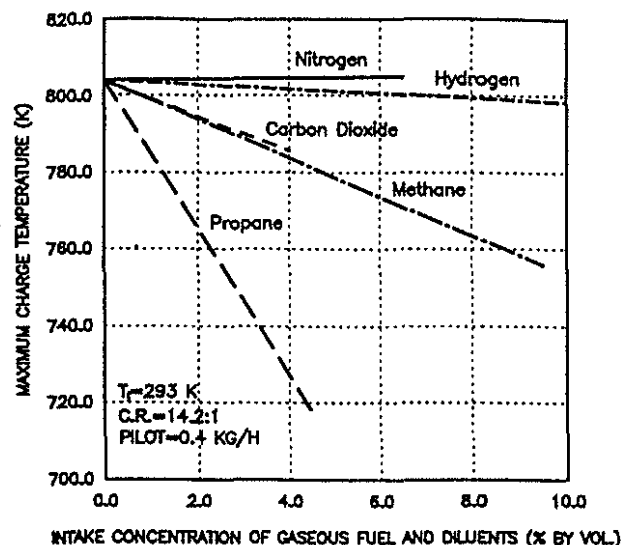

Fig. 6 Variations of calculated ignition times with changes in intake temperatures for methane admission for an adiabatic constant volume process
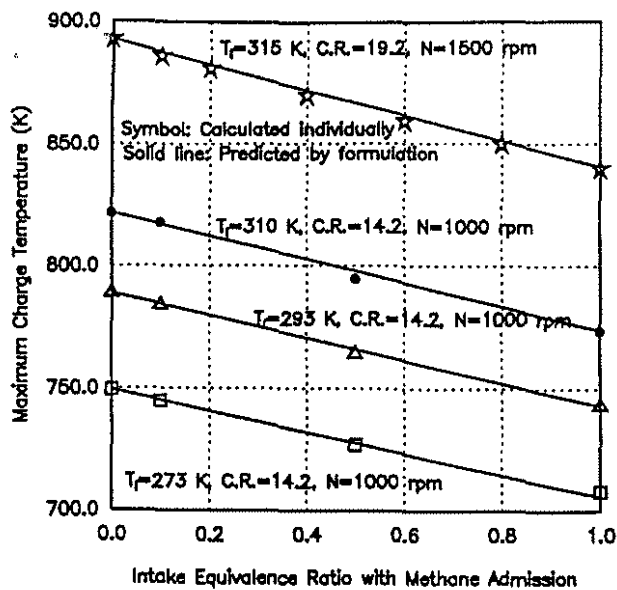
Fig. 8 Comparison of maximum charge temperatures predicted by full calculation and by the correlated formulation for methane admission of Eq. (4)

Fig. 10 Variations of experimental ignition delay, exhaust temperature and calculated maximum charge temperature with methane admission

tion of methane, propane, hydrogen, and ethylene, respectively. On this basis when the charge temperature at the end of compression for pure diesel operation is known, the charge temperatures at the end of compression with the admission of different gaseous fuels can be evaluated.

With the consideration of both the physical and chemical effects of the admission of the gaseous fuels or the presence of the diluents on the ignition delay period of the mixture, the observed changes in the experimental values of the ignition delay during the operation of dual fuel engines can be diagnosed. As shown in Fig. 9, the observed experimental values of the ignition delay increase almost linearly with the extent of carbon dioxide admission to the cylinder charge. A higher intake temperature results in a relatively shorter ignition delay, while an essentially linear trend is maintained. The increase in the
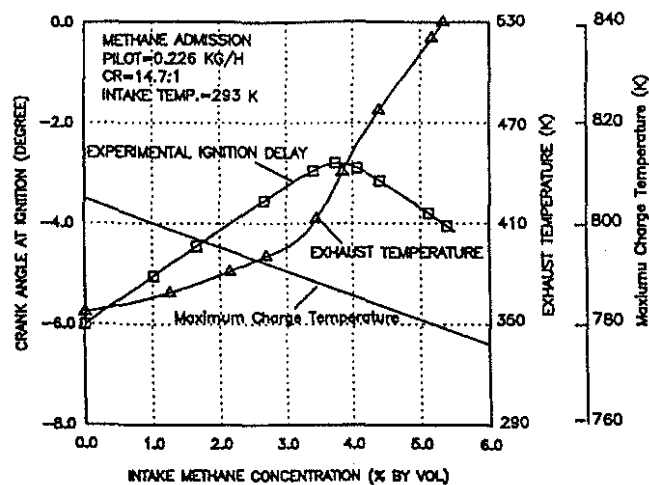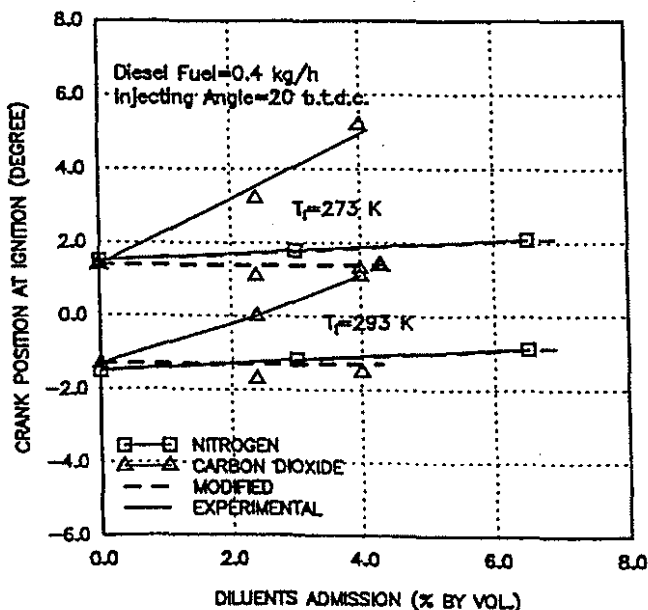

Fig. 9 Variations of experimental and modified ignition delay values with the intake concentration of carbon dioxide and nitrogen for two intake temperatures
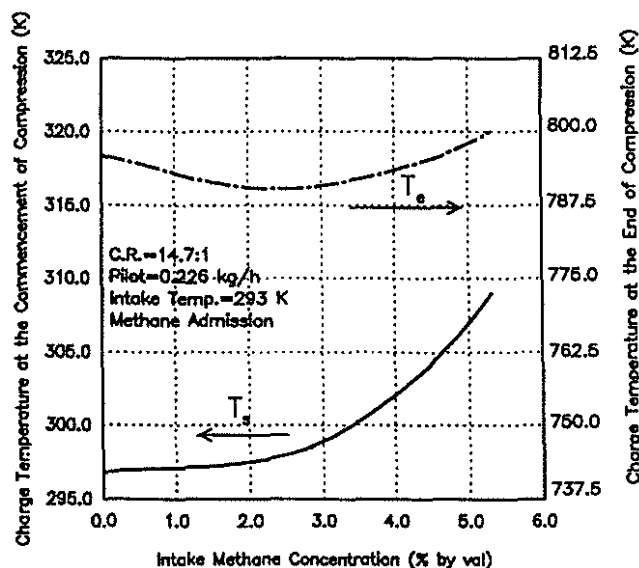
ignition delay period with the admission of carbon dioxide is mainly attributable to the decrease in the charge temperature due to the variations of the physical properties of the charge and the heat transfer during compression. The addition of a small amount of carbon dioxide does not significantly affect the pre-ignition reaction processes. Meanwhile, as shown in Fig. 5, the admission of a small amount of carbon dioxide into the intake air does not produce a significant extension to the chemical part of the ignition delay period of the mixture. Hence, when these factors that affect the ignition delay period due to the addition of carbon dioxide have been excluded, the modified ignition delay calculated by Eq. (2) remains, as shown in Fig. 9, at almost the same value as observed in pure diesel operation and will not change with the increased carbon dioxide concentrations.

As shown in Fig. 6, the addition of nitrogen will not change the mean charge temperature and no extension to the physical process of the ignition delay period is expected with the admission of small amounts of nitrogen. The corresponding changes in the ignition delay for nitrogen admission, as show in Fig. 9, are far less evident than those observed with carbon dioxide admission. The very small increase observed in the value of the ignition delay resulted from the small extension to the chemical process of the delay period.

Unlike with the admission of the diluents, Fig. 10 shows that the ignition delay period, measured in a direct-injection single-cylinder dual-fuel engine, initially increases significantly up to a maximum value as the methane concentration in the cylinder charge is increased. The admission of the gaseous fuel influences the length of the ignition delay not only through a possible modification of the nature of the chemical reactions of the mixture but also through changes in the charge temperature levels, heat transfer, the extent of pre-ignition energy release during compression, and the associated changes in the contribution of residual gases from previous cycles. As shown typically in Fig. 10, the increased admission of methane reduces the calculated values of the maximum charge temperature at the end of compression. The corresponding measured exhaust temperature, which is consistent with the state of the residual gases, is initially increased slowly but with a continued increase in methane concentration in the cylinder charge its value is enhanced very significantly. The marked reduction in the length of the ignition delay is accompanied by the significant increase in the exhaust temperature.

Figure 11 shows typically the variations of the charge temperatures at the commencement and end of the compression stroke with methane admission, when the effects of the changes in physical properties of the mixture, heat transfer, the extent of

Fig. 11 Variations of calculated charge temperatures at the commencement and end of the compression stroke for methane admission

pre-ignition energy release during compression, and the associated contribution of residual gases from previous cycles on the charge temperature have been considered on the basis of the results in Fig. 10. It can be seen that at light load, which involves very lean gaseous fuel–air mixtures, the charge temperature at the commencement of the compression stroke is not increased significantly with the consideration of the contribution of the residual gases, since the combustion of the mixture at light load is confined to around the pilot fuel and cannot produce sufficiently hot residual gases. The values of the corresponding charge temperature at the end of the compression stroke are lower than the value observed for pure diesel operation due to the variations of the physical properties of the charge and external heat transfer effects. With the continued increase in the gaseous fuel concentration, the combustion process can extend gradually further into regions of the mixture made up of the gaseous fuel and air to produce higher residual gas temperatures. The values of the charge temperature at the commencement of the compression stroke, as shown in Fig. 11, is then significantly elevated through the increased contribution of the hotter residual gases. These increases in the charge mean temperature at the commencement of compression will contribute to counteracting the corresponding reduction in the charge temperature due to the admission of methane to produce eventually a higher charge temperature at the end of compression.

These changes in the charge temperature with the admission of methane influence significantly the ignition characteristics of the pilot fuel. As shown in Fig. 12, the changes in the ignition delay period of the dual-fuel engine can be considered in terms of physical and chemical extensions calculated in accordance with Eqs. (1) and (2). At light load, the decrease in the charge temperature, as shown in Fig. 11, extends the physical process of the ignition delay period. Meanwhile, the increased presence of methane with the diesel fuel charge will result in some extension to the chemical processes of the delay, as displayed in Figs. 4 and 5. Both of these extensions to the ignition period lead to the observed increase in the delay period in dual-fuel engines as the methane concentrations in the cylinder mixture are increased.

At relatively high loads, the charge temperature at the end of compression can reach high values mainly due to the increased contribution of the hotter residual gases. Hence, as shown in Fig. 12, the extension to the physical process of the ignition delay is reduced gradually as the charge temperature at the

end of compression continues to increase. The corresponding extension to the chemical processes of the ignition delay is also reduced under the increased charge temperatures. Thus, the ignition delay period at relatively high load is decreased with the increased methane concentration in the cylinder charge.

These changes in the ignition delay period of the dual-fuel engine show that the extension to the chemical processes of the ignition delay with the admission of the gaseous fuel is the main rate controlling processes during the delay period of the dual fuel engine. The extent of this extension, which depends on the type of gaseous fuel used and its concentration in the cylinder charge, will be decreased with the improvement of combustion performance.

These analytical results can be used further to explain other changes in the ignition delay period observed in dual fuel engine operation. For example, the admission of propane into the dual-fuel engine results in a significant decrease in the charge temperature and a longer extension to the chemical part of the ignition delay period. The value of the delay for propane admission is higher than those values observed for methane or hydrogen admission. Moreover, an increase in the size of the pilot fuel, which improves the combustion characteristics of the dual fuel engine, reduces the relative concentration of the gaseous fuel in the fuel mixture for the same overall equivalence ratio, resulting in higher charge temperatures at the end of the compression and a shorter chemical extension to the ignition delay period. Hence, the observed values of the ignition delay are lower than those observed for small pilots [1, 2].

Conclusion

The introduction of gaseous fuels or diluents with the intake air into a diesel engine will change both the physical and chemical processes of the ignition delay period. The corresponding extension to the physical process of the delay period is related to changes in the charge temperature, pressure, pre-ignition energy release, heat transfer, and the effects of the residual gases. The extension to the chemical process of the ignition delay, which results from the chemical interactions between the diesel and gaseous fuels, is the main rate-controlling process during the delay period of the dual-fuel engine. The extent of the extension to the ignition delay period depends strongly on the type of the gaseous fuel used and its concentration in the cylinder charge.
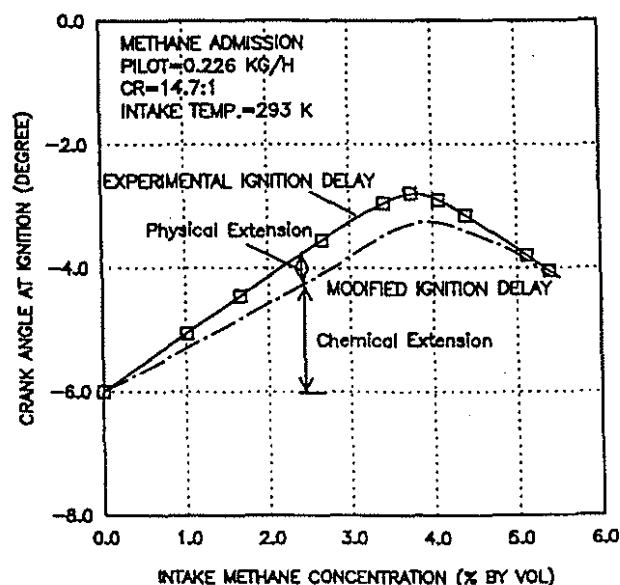

Fig. 12 Variations of experimental and modified ignition delay values with intake concentration for methane admission

Acknowledgments

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