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REDUCING SOOT IN DIESEL EXHAUST

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Reducing Soot in Diesel Exhaust

Electrically charged fuel improves oxidation.

A proposed fuel-injection system would reduce the amount of soot formed in diesel engines. A spray injector electrically charges the fuel droplets as they enter the cylinder. The charged droplets repel each other, creating a dilute fuel mist that is easily penetrated by the oxygen in the cylinder. This encourages more complete combustion and hinders soot formation.

A mathematical model describes the expansion of the cloud of identically charged droplets. The required electrical power has been computed in terms of the fuel, spray, and engine characteristics. Despite the high voltage needed to charge the droplets, sparking will not occur before compression-induced ignition if the droplet-expansion time is properly chosen.

This work was done by Josette Bellan of Caltech for **NASA's Jet Propulsion Laboratory.**

NPO-15715

NEW TECHNOLOGY REPORT

5178 CASE NO.

15715 IR NO.

TITLE: Soot Reduction In Diesel Engines Trough Electrostatic Spray Dispersion

I. NOVELTY

This new injection system will electrically charge the drops of the fuel spray as they are injected in the power system of a diesel engine thus reducing soot formation.

II. PROBLEM

To reduce soot formation in a diesel engine.

III. SOLUTION

A spray injector electrically charges the diesel fuel droplets thus creating a mechanism for dispersing the spray. When effectively dispersed, the non-dilute spray injected in a diesel engine becomes dilute thereby precluding soot formation.

IV. DeSCRIPTION AND EXPLANATION

A high voltage system will allow electrical charging of injected fuel droplets in a diesel engine thus providing an effective way to disperse the non-dilute spray configuration. In contrast to a non-dilute spray, a dilute spray can easily be penetrated by oxygen which hinders soot formation. This concept is shown to be workable by mathematical equations set forth in the attached manuscript authored by the innovator.

A NEW APPROACH TO SOOT CONTROL IN DIESEL ENGINES BY FUEL-DROP CHARGING

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ABSTRACT

Using the observation that the evaporation time of a spray can be optimized by balancing heat losses and fuel-vapour pressure effects, and that this optimum evaporation time is obtained for heavy hydrocarbons in the lean mixture regime,an idea is presented, which, if implemented, would both minimize the evaporation time of real sprays and reduce soot production in Diesel engines. By electrically charging the drops of the spray with identical charges, the dense spray injected in the cylinder of a Diesel engine expands to the configuration of a dilute spray corresponding to that obtained at the optimum evaporation time. A mathematical model has been developed which describes the expansion of a cloud composed of identically charged drops due the repulsive forces between the drops. In particular, the power and voltage needed to achieve this expansion have been computed in terms of the fuel, spray, and engine characteristics so that the spray reaches a desired configuration in a given fraction of the total average combustion time. Parametric calculations show that, despite the high voltage needed for charging the drops, sparking would not occur in the spray prior to compression-induced ignition, if care is taken in choosing this fraction of the total combustion time and the pressure in the cylinder at injection. Feasibility of the concept has been shown by investigating the already existing technology for charging fuel sprays.

I. INTRODUCTION

Particulates, commonly known as soot, have been identified a long time ago as the major pollutant that is exhausted from Diesel engines. Their dangerous effects to health are serious and well-known. Because of this, unless the automotive industry finds a way to control their formation in the very near future, automobiles powered by Diesel engines may be banned from U.S. roads despite the fact that they afford greater fuel economy.

All attempts towards soot control in Diesel engines have so far been unsuccessful. This is shown by the fact that the automotive industry asked and has obtained from the Environmental Protection Agency a delay in the application of more stringent soot exhaust standards (0.6 g/mile).

Unlike many of the previous proposals that suggested treatment of the exhaust in order to remove or chemically transform soot that has already been formed, the idea presented in this paper is directed towards prevention of soot formation during combustion of the charge in the cylinder of the engine. Such a direct approach was possible due to a greater understanding recently achieved on the evaporation of non-dilute sprays as compared to that of dilute sprays(1).

The following considerations of how particulates form show that if the Diesel spray were dilute, the particulate formation problem would be greatly reduced. Particulate formation in both the liquid and the gas phase is greatly enchanced by the non-diluteness of the spray because: (1) Liquid-phase formation is enhanced when the close proximity of the droplets in the non-dilute spray creates such a rate of heat transfer to the individual droplets, that these droplets, instead of evaporating completely during combustion, undergo high temperature pyrolysis, a process by which hydrogen atoms are lost, leaving a carbon-rich cenosphere -- the particulate(2). This particulate is either exhausted from the engine or else burns at a very slow rate (typically 10-30% of the volatile burning rate[3]). (2) Gas-phase particulate formation occurs when evaporation of the close-proximity droplets in the spray creates a fuel-rich vapour that accumulates without burning (because oxygen cannot penetrate inside the spray) and instead undergoes complex chemical reactions[4,5] which, combined with nucleation processes,[5,6,7] form soot. Therefore, if the spray were dilute, particulate formation would be greatly reduced because (i) the droplets could be heated at a rate at which evaporation with no pyrolysis would occur and (ii) oxygen would surround each droplet precluding the formation of fuel-rich vapour that accumulates without burning.

Thus, although the injected spray in a Diesel engine cylinder is non-dilute it is clearly desirable to burn it in a dilute configuration. However, waiting for the drops in the spray to disperse by themselves in the surrounding gas present in the cylinder is not a viable solution since this process takes a long time, and would affect the power output of the engine. On the other hand, dispersion of the drops using turbulent effects is not totally reliable either since pockets of closely spaced drops always survive this process. Several questions then arise: (1) is there a reliable way to dilute a non-dilute spray that is injected in a Diesel engine cylinder, (2) could the above method be easily incorporated into Diesel engine design, and (3) is it possible to optimize spray dilution, and then by how much should the spray be diluted in order to gain maximum benefits from dilution without compromising the power output of the engine.

This paper presents a model showing that all above questions have a positive answer. In the section titled Physical Picture and Associated Model, I show that by electrically charging each drop of the cloud with the same change, the spray expands due to drop repulsion, and thus becomes dilute.

The drop charge, e, is calculated as a function of the drop mass, the initial spray density, the ratio of the desired final to the initial spray density and the time desired to achieve the new spray density. In the following section titled Practical Considerations, I calculate quantities that are pertinent to achieving droplet charging in a self-sufficient Diesel engine. In particular, I develop expressions for the power neeeded for charging, the initial voltage of the cloud and the average current as a function of engine rpm, the injection rate, the duration of injection, the density of the fuel that is injected, the initial nondimensional radius of the drop's sphere of influence as defined by Bellan and Cuffel[1], the ratio of the desired final to the initial drop density, and the fraction of the total combustion time in which it is desired to achieve the cloud expansion. The results of calculations using the model developed in Sections II and III are presented next. Computations are made using one of the conclusions of Ref. 1 to show that cloud expansion can indeed be optimized such as to achieve maximum evaporation rate for a minimum of power used to expand the drop-cloud. This is possible because Bellan and Cuffel[1] have identified for each set of initial spray conditions, namely drop-temperature, surrounding temperature and composition, an equivalence ratio of the two-phase mixture for which an optimum time of evaporation of the spray can be expected. For this equivalence ratio inter-drop spacing is optimized in such a way that both heat losses which are important for very dilute sprays, and fuel-vapour pressure effects that are important in dense sprays, are minimized. The results of Ref. 1 show that for realistic Diesel-spray initial conditions, this optimization occurs for n-decane at an equivalence ratio where the spray is dilute, the overall mixture is lean and thus particulate formation is minimized. Thus, it is desirable to expand the initially-injected spray to a configuration that will correspond to this optimum equivalence ratio.

The significance of the results obtained in Section III is discussed in the next section and in particular the feasibility of implementation of a drop-charging scheme is discussed in terms of known and existing technology. Finally, in the section titled Conclusions, a brief summary of the salient points of the concept and the methods for achieving it is presented.

II. PHYSICAL PICTURE AND ASSOCIATED MODEL

The conical drop-cloud that enters the cylinder of a Diesel engine is approximated here by a spherical cloud of radius R as shown on Figure 1. It is additionally assumed that all quantities in the cloud are spherically symmetric, so that all dependent variables will be spatial functions of $\hat{r}$ only. For reasons of mathematical simplicity it is also assumed that injection, evaporation, ignition and finally combustion of the drops are events that occur sequentially, even though it is well known that there is a certain overlap between them. However, uncoupling of these phenomena is very desirable in a model such as that presented here. Under these conditions, knowing the cloud density n^o at the time of injection t^o, and the desired cloud density $n^f(<n^o)$ at time t^f, at which evaporation starts, one would like to find the needed droplet charge e, such that (1) all drops have the same charge and (2) the expansion of the cloud is entirely achieved through drop repulsion.

The above physical picture is mathematically described by the following equation of motion for a spherical shell of the cloud:

$$M \frac{d^2\hat{R}}{dt^2} = F \tag{1}$$

where

$$M = 4\pi\hat{R}^2 \, d\hat{R} \; nm \tag{2}$$

and

$$F = \frac{q_1 \, q_2}{\hat{R}^2} \tag{3}$$

In Eq. (3) q_1 is the charge of the cloud of radius $\hat{R}$ and q_2 is the charge of the surface of the cloud that is located at $\hat{R} + d\hat{R}$. By definition

$$q_2 = 4\pi\hat{R}^2 \; n \; e \; d\hat{R} \tag{4}$$

and q_1 is calculated using Gauss's theorem which proves that under the above assumptions the surface of radius $\hat{R} + d\hat{R}$ feels the effect of the cloud of radius $\hat{R}$ as if the charge of this cloud were concentrated at its center. It follows that

$$q_1 = \frac{4\pi\hat{R}^3}{3} ne \tag{5}$$

Replacing Eqs. (4) and (5) into Eq. (3), and further Eqs. (2) and (3) into Eq. (1), the final equation of motion for the surface of the cloud is obtained:

$$\frac{d^2\hat{R}}{dt^2} = \frac{\omega^2}{3} \hat{R} \tag{6}$$

where

$$\omega^2 = \frac{4\pi ne^2}{m} \tag{7}$$

Since ω^2 depends upon n, it is a function of time, so that Eq. (6) cannot be solved unless an additional relationship is found that gives ω^2 explicitly as a function of other existing variables. Such a relationship is provided by the statement of conservation of the number of drops, namely:

$$\frac{4\pi\hat{R}^3}{3} n = \frac{4\pi\hat{R}^{o\,3}}{3} n^o \tag{8}$$

yielding

$$n = n^o \frac{\hat{R}^{o\,3}}{\hat{R}^3} \tag{9}$$

and consequently

$$\omega^2 = \omega_o^2 \frac{\hat{R}_o^3}{\hat{R}^3} \tag{10}$$

Replacing Eq. (10) into Eq. (6), a second order ordinary differential equation for $\hat{R}$ is obtained:

$$\frac{d^2\hat{R}}{dt^2} = \frac{\omega_o^2 \hat{R}_o^3}{3} \frac{1}{R^2} \tag{11}$$

By multiplying the above equation by $\frac{d\hat{R}}{dt}$ it can be integrated once to yield

$$\left(\frac{d\hat{R}}{dt}\right)^2 = \frac{2}{3} \omega_o^2 \hat{R}_o^3 \left(\frac{1}{\hat{R}_o} - \frac{1}{\hat{R}}\right) + \left.\frac{d\hat{R}}{dt}\right)_{t=t_o} \tag{12}$$

Knowing that $\frac{d\hat{R}}{dt} > 0$, then

$$\frac{d\hat{R}}{dt} = \sqrt{\frac{2}{3} \omega_o^2 \hat{R}_o^3 \left(\frac{1}{\hat{R}_o} - \frac{1}{\hat{R}}\right) + \left.\frac{d\hat{R}}{dt}\right)_{t=t_o}} \tag{13}$$

Eq. (13) can be written as

$$\frac{-\,dy}{y^2 \sqrt{a + by}} = dt \tag{14}$$

where

$$a = \left(\frac{d\hat{R}}{dt}\right)^2_{t=t_o} + \frac{2}{3} \omega_o^2 \hat{R}_o^2 \;, \tag{15}$$

$$b = -\frac{2}{3} \omega_o^2 \hat{R}_o^3 \tag{16}$$

and

$$y = \frac{1}{\hat{R}} \tag{17}$$

Since a > 0, Eq. (14) is integrated[8] to give

$$t^o - t = \left[- \frac{\sqrt{a+by}}{ay} - \frac{b}{2a} \frac{1}{\sqrt{a}} \ln \frac{\sqrt{a+by} - \sqrt{a}}{\sqrt{a+by} + \sqrt{a}} \right]_{1/y^o}^{1/y} \tag{18}$$

or, going back to $\hat{R}$ as a dependent variable

$$t^o - t = \frac{\sqrt{a+b/\hat{R}^o}}{a/\hat{R}^o} - \frac{\sqrt{a+b/\hat{R}}}{a/\hat{R}} + \frac{b}{2a\sqrt{a}} \times$$

$$\ln \left(\frac{\sqrt{a+b/\hat{R}o} - \sqrt{a}}{\sqrt{a+b/\hat{R}o} + \sqrt{a}} \times \frac{\sqrt{a+b/\hat{R}} + \sqrt{a}}{\sqrt{a+b/\hat{R}} - \sqrt{a}} \right) \tag{19}$$

Eq. (19) can be greatly simplified if one realizes that since $\hat{R}$ (t) give the motion of the cloud due to drop repulsion, the cloud can be considered initially at rest, and thus $\left.\frac{d\hat{R}}{dt}\right)_{t=t^o} = 0$. Then

$$b = - a \hat{R}^o \tag{20}$$

and

$$a = \omega^o \hat{R}^o \sqrt{\frac{2}{3}} \tag{21}$$

so that Eq. (19) becomes

$$t - t^o = \sqrt{\frac{3}{2}} \frac{1}{\omega^o} \left\{ \sqrt{\frac{\hat{R}}{\hat{R}^o} \left(\frac{\hat{R}}{\hat{R}^o} - 1 \right)} + \frac{1}{2} \ln \frac{\sqrt{1 - \frac{\hat{R}o}{\hat{R}}} + 1}{1 - \sqrt{1 - \frac{\hat{R}^o}{\hat{R}}}} \right\} \tag{22}$$

But from Eq. (7)

$$\omega^o = e\sqrt{\frac{4\pi n^o}{m}} \tag{23}$$

which replaced in Eq. (22), makes it solvable for e:

$$e = \frac{1}{t-t^o}\sqrt{\frac{3m}{8\pi n^o}}\left[\sqrt{\frac{\hat{R}}{\hat{R}^o}\left(\frac{\hat{R}}{\hat{R}^o} - 1\right)} + \frac{1}{2}\ln\frac{\sqrt{1 - \frac{\hat{R}^o}{\hat{R}}} + 1}{1 - \sqrt{1 - \frac{\hat{R}^o}{\hat{R}}}}\right] \tag{24}$$

Using Eq. (9) into (24) one obtains

$$e = \frac{1}{t-t^o}\sqrt{\frac{3m}{8\pi n^o}}\left\{\sqrt{\left(\frac{n^o}{n}\right)^{1/3}\left[\left(\frac{n^o}{n}\right)^{1/3} - 1\right]} + \frac{1}{2}\ln\frac{\sqrt{1-\left(\frac{n}{n^o}\right)^{1/3}} + 1}{1 - \sqrt{1 - \left(\frac{n}{n^o}\right)^{1/3}}}\right\} \tag{25}$$

which gives the individual drop charge as a function of the drop mass, the intial spray density, the ratio of the desired final to the initial cloud density and the time desired to achieve the new spray density.

III. PRACTICAL CONSIDERATIONS

Since an automotive engine must be self-sufficient, the question arises whether or not the Diesel engine can be slightly modified in order to provide the charge needed for a typical droplet cloud that is injected in its cylinders. In order to be able to answer this question, several pertinent quantities must be calculated:

1. The total charge of the cloud. It is easily calculated to be

$$E = e\, n^o\, (4\pi/3)\, \hat{R}^{o\,3} \tag{26}$$

2. The total energy of the cloud. If the cloud were expanding infinitely in time, all its energy would be converted to kinetic energy. Thus

$$E = N \frac{mV_\infty^2}{2} = N \frac{m}{2} \left(\frac{d\hat{R}}{dt}\right)^2_{t\to\infty} \tag{27}$$

From Eq. (12)

$$\left(\frac{d\hat{R}}{dt}\right)^2_{t\to\infty} = \frac{2}{3}\, \omega^{o\,2}\, \hat{R}^{o\,2} \tag{28}$$

whereas by definition

$$N = \frac{4\pi \hat{R}^{o\,3}}{3}\, n^o \tag{29}$$

Using Eqs. (7), (28) and (29) into Eq. (27), one obtains

$$E = \left(n^o e\, \frac{4\pi}{3}\right)^2 \hat{R}^{o\,5} \tag{30}$$

3. The power needed to charge the cloud. Since a charge is needed for each cycle, the power needed to charge the cloud is the ratio of the total

energy by the time of the cycle. But

$$t_c = \frac{120}{rpm} \tag{31}$$

so that using Eqs. (25), (30) and (31) one finds

$$P = \frac{2\pi}{3} \frac{rpm}{120} \frac{mn^o \hat{R}^{o\,5}}{(t^f - t^o)^2} \left\{ \sqrt{\left(\frac{n^o}{n^f}\right)^{1/3} \left[\left(\frac{n^o}{n^f}\right)^{1/3} - 1\right]} + \frac{1}{2} \ln \frac{\sqrt{1 - \left(\frac{n^f}{n^o}\right)^{1/3}} + 1}{1 - \sqrt{1 - \left(\frac{n^f}{n^o}\right)^{1/3}}} \right\}^2 \tag{32}$$

The above expression for the power shows that it is strongly dependent at least upon two parameters: the time desired to achieve the cloud expansion and the initial radius of the cloud. Any simple drop-charging system would presumably be made such that

$$t^f - t^o = t_{comb}\, fr \tag{33}$$

Since the combustion part of the cycle corresponds in average to about 60°CA, Eq. (33) can also be written as

$$t^f - t^o = \frac{t_c}{12}\, fr \tag{34}$$

On the other hand, $\hat{R}^o$ can itself be calculated using basic engine and drop parameters. The total mass injected in the cylinder of the engine at each cycle is

$$m_T = I_r\, I_t\, \rho_d \tag{35}$$

and also

$$m_T = N \rho_d \frac{4\pi R^3}{3} \tag{36}$$

Equating Eqs. (35) and (36) and solving for N yields:

$$N = I_r I_t \frac{3}{4\pi R^3} \tag{37}$$

But from Eq. (29)

$$n^o = N \left(\frac{4\pi \hat{R}^{o^3}}{3} \right)^{-1} \tag{38}$$

so that by eliminating N between Eqs. (37) and (38) and solving for $\hat{R}^o$, one obtains:

$$\hat{R}^o = \left[\frac{1}{R} \left(\frac{3}{4\pi} \right)^2 \frac{I_r I_t}{n^o} \right]^{1/3} \tag{39}$$

It has been proved elsewhere(1) that for a given set of initial drop and drop-surrounding conditions (initial means here at injection)

$$n^o = \frac{A}{R^3} \tag{40}$$

where A is only function of the initial nondimensional inter-drop distance which is constant for given initial conditions. In fact,

$$A = 0.74 \frac{3}{4\pi} \frac{1}{R_2^{o\,3}} \tag{41}$$

where R_2^o is the nondimensional radius of the sphere of influence at injection as defined by Bellan and Cuffel(1). Then

$$\hat{R}^o = \frac{1}{A^{1/3}} \left(\frac{3}{4\pi} \right)^{2/3} (I_r I_t)^{1/3} \tag{42}$$

which proves that $\hat{R}^o$ can also be considered to depend only upon the total volume of injected mass and the nondimensional radius of the sphere of influence of the drop[1].

Additionally,

$$m = \frac{4\pi}{3} R^3 \rho_d \tag{43}$$

so that when Eqs. (33) and (40)-(43) are replaced into Eq. (32), P is expressed only in terms of basic engine parameters, fr, and n^f/n^o for a given set of initial drop and drop-surrounding conditions:

$$P = \frac{1}{2}\left(\frac{3}{4\pi \times 0.74}\right)^{2/3} \frac{R_o^2}{2}\left(\frac{12}{fr}\right)^2\left(\frac{rpm}{120}\right)^3 (I_r\ I_t)^{5/3} \rho_d \times$$

$$\left\{\sqrt{\left(\frac{n^o}{n^f}\right)^{1/3}\left[\left(\frac{n^o}{n^f}\right)^{1/3} - 1\right]} + \frac{1}{2}\ \ln \frac{\sqrt{1-\left(\frac{n^f}{n^o}\right)^{1/3}} + 1}{1 - \sqrt{1 - \left(\frac{n^f}{n^o}\right)^{1/3}}}\right\}^2 \tag{44}$$

The result of Eq. (44) is important because it shows that for a desired drop-temperature and gas-conditions at injection, P can be considered independent of the initial spray density and drop radius; instead, it depends upon the total mass and volume of liquid injected in the cylinder. Other important parameters determining the power needed to charge the cloud are the rpm, the fraction of the combustion part of the cycle in which the expansion of the cloud is achieved, and the desired ratio of initial to final spray density.

Further insight into the problem can be achieved by noticing that $n^f \ll n^o$[1], so that the term in braces in Eq. (44) can be assymptotically expanded in powers of n^f/n^o to yield

$$P \to \frac{1}{2}\left(\frac{3}{4\pi \times 0.74}\right)^{2/3} \frac{R_o^2}{2}\left(\frac{12}{fr}\right)^2\left(\frac{rpm}{120}\right)^3 (I_r\ I_t)^{5/3} \rho_d \left(\frac{n^o}{n^f}\right)^{2/3} \tag{45}$$

as $n^f/n^o \to 0$.

4. The initial cloud voltage. By definition

$$V^o = \frac{E}{\hat{R}^o} \tag{46}$$

and using Eq. (26) into Eq. (46), one finds further

$$V^o = \frac{4\pi}{3} e\, n^o\, \hat{R}^{o^2} \tag{47}$$

Now, by taking into account Eq. (25) and (40)-(43), Eq. (47) becomes:

$$V^o = \frac{1}{2\,(0.74)^{1/3}} R_2^o \frac{12\ \text{rpm}}{\text{fr}\ 120} (I_r\ I_t)^{2/3} \rho_d^{1/2}\ x$$
$$\left\{ \sqrt{\left(\frac{n^o}{n^f}\right)^{1/3}\left[\left(\frac{n^o}{n^f}\right)^{1/3} - 1\right]} + \frac{1}{2} \ln \frac{\sqrt{1 - \left(\frac{n^f}{n^o}\right)^{1/3}} + 1}{1 - \sqrt{1 - \left(\frac{n^f}{n^o}\right)^{1/3}}} \right\} \tag{48}$$

Again, as $n^f/n^o \rightarrow 0$,

$$V^o \rightarrow \frac{1}{2\,(0.74)^{1/3}} \frac{12\ \text{rpm}}{\text{fr}\ 120} R_2^o (I_r\ I_t)^{2/3} \rho_d^{1/2} \left(\frac{n^o}{n^f}\right)^{1/3} \tag{49}$$

5. The average current needed for charging. One of the definitions of $\bar{I}$ is

$$\bar{I} = \frac{P}{V^o} \tag{50}$$

Using Eqs. (44) and (48) into Eq. (50) one obtains

$$\bar{I} = \frac{1}{\sqrt{2}\,(0.74)^{1/3}} \left(\frac{3}{4\pi}\right)^{2/3} R_2^o \frac{12}{\text{fr}} \left(\frac{\text{rpm}}{120}\right)^2 I_r\ I_t\ \rho_d^{1/2}\ x$$
$$\left\{ \sqrt{\left(\frac{n^o}{n^f}\right)^{1/3}\left[\left(\frac{n^o}{n^f}\right)^{1/3} - 1\right]} + \frac{1}{2} \ln \frac{\sqrt{1 - \left(\frac{n^f}{no}\right)^{1/3}} + 1}{1 - \sqrt{1 - \left(\frac{n^f}{no}\right)^{1/3}}} \right\} \tag{51}$$

It is worthwhile noticing that V^o is a weaker function of R_2^o, fr, rpm, I_r I_t, ρ_d and n^o/n^f than P, so that it will be much more difficult to affect the voltage than the power by changing any of the parameters.

IV. RESULTS

Since n-decane is a heavy fuel having properties not unlike Diesel fuels, it is chosen here as a basis for the calculations. Its properties which have been listed by Bellan and Cuffel[1] are used here as well. In the same work, the authors have also calculated R_2^o for an extensive range of equivalence ratios, T_{gs}^o, T_{ga}^o and Y_{Fva}^o; it is reminded again that it was found[1] that R_2^o is constant for a chosen set of above conditions and a fixed value of n^oR^3. (Here the drop radius is constant and the spray density as well as the radius of the sphere of influence increase throughout the cloud expansion in contrast to Ref. 1 where the drop density and the radius of the sphere of influence were constant throughout the evaporation and the drop radius was decreasing with time.) Other quantities needed for the present calculations such as I_r, I_t and R have been measured by Suzuki and Shiozaki[9] and others such as air-fuel mass ratios as a function of the distance from the injector and radially in a cross section of the spray have been measured by Dent et al[10]. The numbers for the air-fuel mass ratio are taken here only as a guideline for the calculations since the values obtained by Dent et al[10] were measured for fuels other than n-decane. In any event, ϕ° will be varied here parametrically, so as to span a range of equivalence ratios typical of Diesel engine sprays.

In order to fully take advantage of the calculations of Bellan and Cuffel[1], R is chosen here to be 2×10^{-3} cm (a typical value measured in Diesel engine sprays[11]), $T_{ga}^o = 550°K$, $T_{gs}^o = 350°K$ and $Y_{Fva}^o = 0$. Table I presents the results obtained by varying ϕ^o and ϕ^f. The list of inputs in Table I shows not only numbers that were used in the calculations, such as R_2^o, I_r I_t, rpm, n^f/n^o and fr, but also values that indicate by how much the mixture ratio and the density of the cloud was affected by expansion, such as n^o, ϕ^o and ϕ^f, as well as numbers that show the improvement achieved on the evaporation time, such as $\mathcal{R}^o$ and $\mathcal{R}^f$. The value of R_2 is taken from Fig. 6 of Bellan and Cuffel(1). Because the curve presented on Fig. 7 of Bellan and Cuffel(1) has such a flat minimum showing that the evaporation time can be optimized over a range of equivalence ratios, for one initial mixture ratio chosen here, calculations have been performed for two final equivalence ratios; the first one corresponds to $\mathcal{R}_{min}$ of Fig. 7 of Bellan and Cuffel(1), and the second one corresponds to a value of ϕ on the rich side of ϕ_{min}, for which the total mixture happens to be stoichiometric, and for which $\mathcal{R}$ is such that $\mathcal{R}/\mathcal{R}_{min} = 1.0002$. Thus, for the second value of ϕ^f, there is no loss in the optimization of the evaporation time, and since the spray is richer than at $\mathcal{R}_{min}$, presumably less energy will be needed to expand the droplet cloud. The results show that an increase in ϕ^o by a factor of 2.6 yields both a negligible variation of the power needed to charge the cloud in order to arrive at the same ϕ^f, and a decrease in the voltage needed for charging of only 19% for ϕ_1^f (corresponding to R_{min}) and 24% for ϕ_2^f. This is because the change in P is approximately due to a factor $R_2^{o^2} (n^o/n^f)^{2/3}$, and similarly the change in V is approximately due to a factor $R_2^o\, n^o/n^f$. When ϕ^o increases and ϕ^f stays constant, R_2^o increases, but n^o/n^f decreases, thereby balancing the effect of R_2^o. According to Eqs. (44) and (48), a much more important role is played by fr, since $P \sim (fr)^{-2}$ and $V^o \sim (fr)^{-1}$; when fr is increased by a factor of 2, P decreases by a factor of four and V^o decreases by a factor of two. The most dramatic change in the value of P is obtained by changing the rpm; since $P \sim (rpm)^3$, a 50% increase in the value of the rpm yields accordingly, a 3.375 increase in the value of P. However, since $V^o \sim$ rpm only, the same change in the value of rpm yields a proportionate increase in the value of V^o. Finally, a 50% increase in $(I_r\ I_t)$ yields an increase in P by almost a factor of two and a corresponding increase in V^o by a factor of 1.3, following Eqs. (44) and (48).

V. DISCUSSION

Incorporation of the fuel-drop charging concept in a self-sufficient Diesel engine very much depends upon the values needed for P, V^o and $\bar{I}$. Table I shows that all values of P and $\bar{I}$ are within ranges that can reasonably be provided by a running Diesel engine. It is, however, desirable from the point of view of the power needed for charging the cloud, that as the rpm increases, the value of fr be increased as well in order to keep P within reasonable limits. The same conclusion should be reached when considering the voltage needed to charge the spray.

Table I shows that V^o is in the range of hundreds of kV. Because of this, there are two questions that arise and must be answered before feasibility of this concept is theoretically established.

1) Is V^o too high, so that a spark will ignite the cloud before ignition by compression has a chance to develop? This situation is undesirable since it would transform the Diesel engine into a spark-ignition engine.

An answer to the above questions can be given by looking at Paschen curves for air(12). Paschen's law was an experimentally discovered fact and states that the sparking potential is a function of the product of pressure and gap length only. If the voltage given by the Paschen's law for a typical Diesel engine pressure at injection, and a typical cloud radius $\hat{R}^o$ as given by Table I, is higher than V^o, then the charged spray will not establish a spark. A typical pressure at injection is 7 atm(9)(10), and a typical value for $\hat{R}^o$ is 2-3 cm which yields a value of 106,400 - 159,600 mm Hg mm for the product of the pressure and gap length as measured for Paschen curves. Extrapolation of the spark - breakdown voltage for plane - parallel plates in air at 293°K(12) for these higher values of this product, shows that the corresponding voltage would be $4 \times 10^5 - 8 \times 10^5$V. When these values of the spark-breakdown voltage are compared to those presented on Table I, one finds that in order to avoid sparking in the charged cloud, the spray should be allowed about 10% of the total combustion time to come to the dilute configuration, even though evaporation and cloud expansion might then overlap more than expected. Since the spark-breakdown voltage increases with the ambient pressure, another way of avoiding sparking in the cloud is to inject the spray at a higher cylinder pressure. Obviously, an optimization process between all the parameters is necessary to maintain the compression - ignition aspect of the engine. However, the numbers presented here show that feasibility of the concept is not in question.

2) Is there a technique for charging the droplet cloud, and then could the drops stand such a charge?

Charged droplets of micron size have already been produced(13)(14), by technology which was developed in the frame of electric propulsion. Both octoil(13) and glycerine(14) droplets were charged by electrically spraying through a metallic capillary maintained at a high positive potential. In order to obtain a thick spray rather than a brush-shaped stream of droplets coming out of one needle(13), a system of such metallic capillaries could replace the single capillary that was used in the above studies. A small extrapolation of the plot of the specific charge in C/kg, versus the radius of the droplet in (μm), presented by Hendericks(13) for octoil, shows that the average specific charge of 2.5×10^{-2} C/kg which would be needed here, certainly falls below Rayleigh's maximum limit(15) which gives the maximum stable specific charge for a given droplet radius. Furthermore, Hendricks and Pfeifer(14) show that for glycerine doped at various degrees with NaCl (in order to vary the electrical conductivity of the liquid), the specific charge varies inversely with the mass flow rate through the needle; this result is obtained for a range of conductivities of the fluid at zero electric field and capillary fields. As the electrical conductivity becomes larger, the specific charge needed for the same mass flow increases as well. Extrapolation of their curve for a capillary field of 4.6×10^7 V/m and a liquid with an electrical conductivity of 0.05×10^{-4} Mhos/m, shows that for the average specific change of 2.5×10^{-2} C/kg needed here, the mass flow rate through the needle would have to be about 10^{-6} kg/sec, which is certainly within the achievable technical range.

The number of needles neded to inject the fuel in the cylinder is:

$$N = m_T \frac{720}{I_t} \frac{rpm}{120} \frac{1}{\dot{m}_N} \tag{52}$$

Taking m_T = 0.054g, I_t = 15° CA, rpm = 1000 and $\dot{m}$ = 10^{-3} g/sec, one obtains $N = 10^4$ needles. Since N is very large, this suggests that instead of needles, one might choose instead a porous system to perform the injection.

VI. CONCLUSIONS

In this paper I have presented a scheme that (1) allows soot control in Diesel engines and (2) optimizes the evaporation time of the injected spray, thereby improving engine characteristics. This scheme consists in diluting the non-dilute spray injected in the cylinder of an engine by electrically charging the fuel droplets with the same charge. The charge per drop was computed as a function of the drop mass, the initial cloud density, the ratio of the desired final to the initial cloud density and the desired time to achieve the expansion. Other quantities related to engine operation, such as the total charge of the cloud, the total energy of the cloud, the power needed to charge the spray, the initial cloud voltage, and the average current have been computed as well. It was shown that the power is proportional to $R_2^{o^2}\,(\mathrm{rpm})^3\,m_T\,(I_r\,I_t)^{2/3}/(fr)^2$ and that the voltage is proportional to $R_2^{o}\,(\mathrm{rpm})\,m_T^{1/2}\,(I_r\,I_t)^{1/6}/fr$. Numerical calculations of all above quantities show that the proposed concept is feasible because (1) the power needed to charge the cloud could be provided by a self-sufficient Diesel engine, (2) both the pressure in the cylinder at injection of the spray and the desired time to achieve expansion of the cloud can be increased, so that the initial voltage of the cloud is below the spark-breakdown voltage (thereby avoiding sparking in the spray before compression-initiated ignition), (3) the technology for charging liquid droplets has already been developed and (4) the results obtained with this technology show both that the needed average specific charge per drop versus the size of the drop is below Rayleigh's stability limit, and that the mass flow rate needed through the metallic capillary that produces the drops to obtain the desired specific charge per drop is well within the technological achievable range.

NOMENCLATURE

A	constant defined by Eq. (41)
a	constant defined by Eq. (15)
b	constant defined by Eq. (16)
$\mathcal{E}$	total electric charge of the cloud, stat C
$\mathcal{E}_C$	$\mathcal{E} \times 3.336 \times 10^{-10}$, total electric charge of the cloud, C
E	total energy of the cloud, ergs
E_J	$E \times 10^{-7}$, total energy of the cloud, J
e	electric charge of a drop, stat C
e_C	$e \times 3.336 \times 10^{-10}$, electric charge of a drop, C
F	force, dyne
fr	fraction of the combustion time during which cloud expansion should be achieved
$\bar{I}$	average current, stat A
$\bar{I}_A$	$\bar{I} \times 3.336 \times 10^{-10}$, average current, A
I_r	injection rate, $cm^3/°CA$
I_t	duration of injection, °CA
M	mass of a droplet cloud of radius $\hat{R} + d\hat{R}$, g
m	droplet mass, g
m_T	total fuel mass injected into the cylinder each cycle, g
$\dot{m}_N$	mass flow rate through a needle, g/sec
N	total number of drops in the cloud
N	number of needles needed to inject m_T into the cylinder
n	spray density, cm^{-3}
P	power needed to charge the drop cloud, erg/sec
P_W	$P \times 10^7$, power needed to charge the drop cloud, W
q	electric charge, stat C
$\hat{R}$	radius of the droplet cloud, cm
R	radius of each drop, cm

R_2	ratio between the half distance between the centers of two adjacent drops and the radius of the drop
R	ratio between the evaporation time of a spray and the evaporation time calculated without accounting for inter-drop effects
$\hat{r}$	radial coordinate, cm
rpm	rotations per minute, 1/min
T	temperature, °K
t	time, sec
V	cloud voltage, stat V
V_V	V x 299.8, cloud voltage, V
Y	mass fraction
y	inverse of the cloud radius, cm^{-1}

Greek Symbols

ρ	density, g/cm^3
ϕ	air-fuel mass ratio of the two-phase mixture
ω	frequency, sec^{-1}

Subscripts

c	cycle
comb	combustion
d	drop
Fva	fuel vapour at the edge of the sphere of influence of nondimensional radius R_2
ga	gas at the edge of the sphere of influence of nondimensional radius R_2
gs	gas at the drop's surface
min	conditions defined for the value of ϕ at which the curve of Fig. 7 of Bellan and Cuffel(1) shows a minimum

Superscripts

o	initial value, namely at injection
f	final value, namely when the drop cloud is fully expanded

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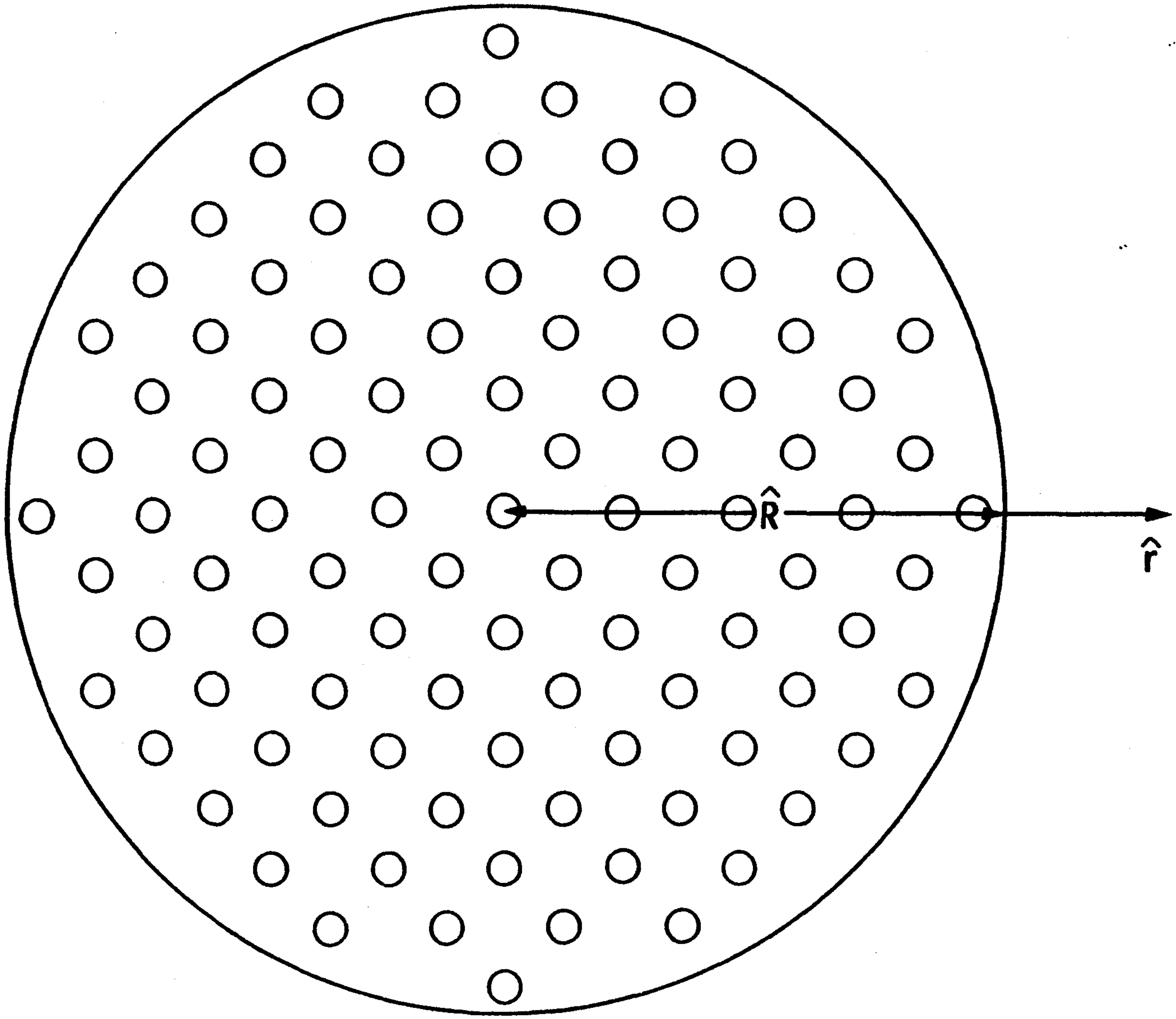

FIG. 1 PHYSICAL PICTURE OF THE SPHERICAL MONODISPERSE, UNIFORM FUEL-SPRAY.

TABLE I

Inputs

ϕ^o	$n^o \times 10^4$ cm^{-3}	R_2^o cm	R^o	$I_r \times I_t$ cm^3	rpm min^{-1}	R^f	ϕ^f	n^f/n^o	fr
1.0	7.144	6.76	*	0.10	1000	0.9761	31.42	0.032	0.05
1.0	7.144	6.76	*	0.10	1000	0.9762	15.71	0.064	0.05
2.6	2.753	9.29	1.165	0.10	1000	0.9762	15.71	0.165	0.05

Outputs

t_c sec	$(t^f-t^o) \times 10^4$ sec	m_T g	$\hat{R}^o$ cm	$e_c \times 10^{13}$ C	$E_c \times 10^3$ C	E_J J	P_W W	V_v^o V	$\bar{I}_A \times 10^5$ A
0.12	5.0	0.054	2.15	4.38	1.30	0.714260	5.95	546,485	1.089
0.12	5.0	0.054	2.15	3.44	1.03	0.440862	3.67	429,341	0.856
0.12	5.0	0.054	2.96	3.80	1.14	0.393018	3.27	345,807	0.947