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APPLICATION OF ALTERNATIVE FUELS FOR INTERNAL COMBUSTION ENGINES

IIP, DEHRA DUN, INDIA

DP/IND/82/001

FINAL REPORT*

Prepared for the Government of India by the
United Nations Industrial Development Organization
Acting as Executing Agency for the United Nations Development Programme

Based on the work of Dr. Gérard De Soete
Expert in Combustion Studies in C.I. engines
Under the post 11-04

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION

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ABSTRACT

Title : Establishment of suitable technologies for the use of
methanol in two stroke S.I. and in C.I. engines.
Project: DP/IND/82/001

Objective:

Object of this six weeks experts activity mainly consisted in

1) provide guidance in the definition and assistance in the realization of fundamental combustion studies aiming at the understanding of the parametric dependency of typical combustion phenomena related to the use of methanol in I.C. engines. More specifically : (a)ignition characteristics of homogeneous methanol/air mixtures by hot gases, this problem being related to the combustion in two stroke engines under part load conditions, (b) spark assisted ignition of methanol droplet spray, this phenomenon being related to C.I. engines using alcohol injection. An experimental rig for these studies has been described and discussed with the research group of IIP's Engine Laboratory in Dehra Dun.Construction of the hardware has been started. Guidance for assembly and operation has been provided. A parametric trials programme has been outlined.
2) Training in fundamental combustion aspects, mostly related to engine combustion. 27 hours has been spent in lecturing to research staff of both the Engines and Industrial Combustion laboratories on theory and experimental diagnostics of combustion kinetics, self ignition, steady state and transient flame propagation regimes, pollutant formation and solid fuel combustion chemistry.

Main conclusions and recommendations:

1) The construction of the experimental rig should be implemented Starting the trials should present no special problems.Other fundamental studies related to methanol combustion may be performed using this rig as a basic equipment.
2) Training in the field of both fundamental and applied combustion problems may usefully be updated at other occasions.
3) Some relatively simple but interesting in situ visualization techniques should be scheduled in the very next future, directly in the engine, using already existing equipment.

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INTRODUCTION

The Indian country intend to develop alternatives to petroleum products. Taking into consideration the possible alternative fuels for each of the major petroleum consuming sectors, the most efficient way to solve the problem seems to be to find replacement fuels in the transport sector. This means finding suitable alternatives for use as partial or total replacement of gasoline in two stroke engines and diesel fuels in compression ignition emgines.

The choice of methanol is very attractive as an alternative fuel if the technological problems of its utilisation are overcome. For the purpose of future application, the Indian Institute of Petroleum (IIP), therefore, proposes to concentrate on using methanol in diesel engines and in two stroke engines.

At IIP work on two stroke engines using methanol-gasoline blends or neat methanol, as well as on the use of methanol in four stroke C.I. engines has been initiated. This work is primarily concerned with engine performance without major modifications of the existing engines.

It is the aim of the project activity to carry out detailed research and development work on automotive and stationary C.I.engines and small two-stroke engines, allowing wider application of alcohol fuels in the country.

Such a study should cover optimization of various engine design parameters, design of new fuels introduction systems, etc. Therefore investigations in the following areas must be undertaken: fuel injection, ignition, engine combustion, engine exhaust emissions, lubrication, wear and engine design, including field studies.

Sub-activity: The optimization of methanol fueled two-stroke spark ignition and four stroke compression ignition engines, and especially the improvement of specific technologies developped for efficient use of methanolneeds the understanding of the parametric dependence of some typical alcohol combustion phenomena such like: spark or glowplug assisted spray ignition, ignition by hot residual gases, mixing patterns of fresh mixture with hot residual gases, aldehydes formation.

To obtain that kind of informations, the use of experimental test rigs, operated outside the engines si very suitable, since the effects of different factors (pressure and temperature history, mixture strenght, droplet size distribution, etc.) may be studied therein in an independent way using single parameter variation, contrarily as in the case of the engine, where it is practically impossible to change only one parameter at once. A further advantage of such experimental test rigs is, that they allow a much better diagnostic of the phenomena, e.g. by optical visualization.

Although indispensable to understand the combustion phenomena related to the use of methanol, the results of these fundamental studies cannot be simply extrapolated to what happens in the engine. Therefore, they should be completed by visualization studies applied directly to the engine to check their appearance under real operation conditions.

Finally, the adequate interpretation of the findings gained in both the fundamental rig studies and direct engine visualization studies, suppose the research crew to be well trained in the fundamental knowledge of the basic combustion aspects

In 1984, the "Institut Français du Pétrole" (at Rueil-Malmaison, near Paris) has been approached by IIP and asked to provide assistance for the realization of this sub-project. It was decided by mutual agreement that Dr.G. de Soete, head of the Department of Fundamental Combustion, would act as a consultant in that matter.

In June 1984 Dr.B.P.Pundir from IIP spent several weeks at the French Petroleum Institute , to take informations concerning the practical modalities and to outline the general form that activity might take. During the discussions between Dr.Pundir and Dr.de Soete the following was decided on :

a) The construction at IIP of a general purpose test rig, suitable to be used for a large number of parametric studies concerning methanol (or methanol-hydrocarbon blends) ignition and combustion, at different pressures and temperatures, having total optical access for shadowgraphy or Schlieren photography.

   Construction of the experimental rig should be started and required optical parts (laser, windows, lenses...) ordered so as to be able to start the first trials at the arrival of

Dr. de Soete in Dehra Dun. Actually, due to different reasons, the research crew of IIP's Engine Laboratory has not been able to start this preparative work before the arrival of the expert.

b) IIP should contact UNIDO in order to obtain the mission of Dr. de Soete to IIP as a consultant for a period of six weeks, at the end of 1986. The consultants task should consist in (1) giving guidance for the projected experimental trials, (2) training of the research people in fundamental aspects of engine related combustion and (3) guidance in selecting appropriate methods for in-situ visualization inside the engine.

As to the attainment of these three original objectives of the expert's activity: (1) he has written a detailed description of the experimental test rig, of the measuring methods and of the research programme to be followed related to two practical problems occuring in the onset of combustion of methanol in the engines, indicating also further use of the rig for the study of other related phenomena; he has discussed the experimental method and the construction of the rig with the research scientists and the heads of the different involved worshops. The manufacturing of the experimental rig has been started and could be operational within some months from now. (2) About 27 hours lectures have been dispensed to train the research crew in fundamental combustion aspects. (3) Discussions with the research scientist have been held on fundamental combustion phenomena as occuring in engines and on practical needs of in situ visualization methods of combustion within engines.

RECOMMENDATIONS

1. For the benefit of optimization of typical technologies related to the use of methanol as an alternative fuel for two-stroke spark ignition and four stroke compression ignition engines, it is recommended to the direction of the Engine Laboratory of IIP to continue its effort for making appropriate fundamental research in the form of parametric studies effectuated in an experimental rig, under conditions approaching as close as possible to the ones prevailing in the engine, but still allowing for single parameter variation, in order to yield good understanding of the dependency of the combustion phenomena with respect to the important factors.

   More particularly, the parametric investigations on (a) conditions of hot gas ignition of homogeneous methanol-air mixtures, and (b) spark assisted methanol spray ignition, as outlined in annexe 3 of this report, should be started and implemented as soon as possible. Construction and equipment of the experimental rig, discussed in detail with the research scientists during the expert's stay, have already been started by now and should normally enable the first series of trials to be started in two months or so from now.

2. The execution of this parametric study as defined higher, does not seem to present difficulties other yhan those which IIP's Engines Laboratory is able to deal with. However, in case of emergent and unforeseen needs, further assistance, e.g. from the French Petroleum Institute, might be recommended.

3. Although the experimental rig described in this report has been planned primarily to carry out the studies mentionned in recommendation 1 , it constitutes a basic equipment which, with only minor transformations, may be utilized later on for other investigations relative to typical methanol combustion problems, e.g. the effects of gasdynamics (turbulent flow, swirl, flow gradients) on the ignition and combustion of methanol-air mixtures and methanol droplet sprays, the

ignition and flame characteristics of methanol-gasoline emulsions, catalytic assisted methanol ignition on catalyst covered hot walls, time/space resolution of mixing pattern between flammable mixture and residual combustion products.

4. The effort of training of the research crews in both IIP's Engine and Industrial Combustion Branches should be continued occasionally, e.g. whenever an updating of fundamental or technological knowledge is required, or if young scientist need to gain specialised knowhow. Many possibilities are open in that respect : lectures on special topics by occasional or invited Indian or foreign specialists, exchanges of research scientists between IIP and other research Institutes, e.g. the French Petroleum Institute, training of graduates at the latter's "Ecole Supérieure du Pétrole et des Moteurs" (E.N.S.P.M.), etc.

5. Direct visualization studies inside the engines should be recommended .
For the immediate future some global and rather simple optical diagnostics inside commercial engines may be already undertoken, for the benefit of the research on engines actually carried out at IIP.
If, for a more remote future, more sophisticated optical diagnostic are envisaged, then already now should care be taken to train research people, specializing them in the appropriate techniques e.g. by means of long term stays in laboratories already specialized in these diagnostic methods.

All recommendations expressedhere,address themselves more directly to the Direction of the Indian Institute of Petroleum, more in particular to the Engines Branch.

I. MAIN DUTIES OF THE JOB DESCRIPTION

The expert has been asked to assist the Indian Institute of Petroleum at Dehra Dun, India, in the following areas:

1. Consultation and advice on the establishment of facilities test rig for basic studies on alcohol combustion.
2. Guidance on research activities related to combustion studies in the engine, including high speed photographie.
3. Training on fundamental combustion, e.g. ignition, turbulent flame propagation, spray combustion, etc., as appied to engine.

The experts activities in these three fields are given in the following chapter.

II. TECHNICAL AND TRAINING ACTIVITIES

As indicated on the travel schedule (see Annexe 1), the expert joined IIP on Saturday 16 November 1985 and left it on Wednesday 8 January 1986. During the period from 28 November through 15 December 1985 he left IIP for a personnal business visit to Japan.

His contacts in IIP were more particularly with the counterpart staff of the Engines Laboratory, the composition of which is given in Annexe 2. The technical part of the activities was made in collaboration with Dr B.P.Pundir and Mr. M.Abraham.

A. Establishment of experimental test rig

As already stated in the introduction, the construction of the experimental test rig had not started upon the experts arrival at IIP.

In an early discussion with Dr.Pundir and Mr.Abraham, the precise purposes of the experimental study were outlined and the expert was asked to prepare a written proposal describing in detail the different parts of the test rig, the diagnostic methods to be used and the study parameters to be varied, in order to enable the rig to be manufactured without further delay in the mechanical workshop of IIP. This proposal, the full text of which is given in Annexe 3, was finalised and handed to Mr Abraham on 26 November.

The central part of the test rig consist of a combustion reactor with total optical access, allowing shadowgraphic or schlieren cinematography of the combustion phenomena or of flow and mixing patterns. If equiped with appropriate facilities it may be used to study a large number of different ignition and combustion phenomena, amongst which the two following have been selected to start the research programme :

a) The ignition of homogeneous methanol-air mixtures by hot gases, related to the phenomenon of ignition by residual combustion products as occuring in two-stroke engines when operated at partial load.

b) The characteristics and optimization parameters of spark assisted methanol droplet spray ignition; together with glowplug assisted ignition or heterogeneous, catalytic methanol decomposition, this is one of the technologies which may be utilized to overcome the handicap of the low cetane number of methanol.

It has been agreed during the discussion to equip the experimental reactor as to meet the requirements of these two phenomena. The equipment, as described in Annexe 3, aims at the obtention of the following informations :

-- The physico-chemical ignition delay as obtained from the pressure/time records, the shadowgraphic pictures and the light emission (accompanying ignition) recorded by a photodiode sensor.

-- The evolution of the volumic combustion rate, obtained (a) in early combustion stages from the shadowgraphic records and (b) in later stages from the pressure/time track.

-- The fraction of fuel burnt, from the time integrated CO_2 and CO concentrations measured by infra red analysis. The determination of burnout is an important information in the case of these non homogeneous methanol/air/residual gas mixtures as well as in the case of droplet combustion, since the phenomenon of gas phase quenching may be severe.

-- The critical conditions of pressure, residual gas temperature, amount and composition of the methanol/air mixtures, with respect to the transition from ignition to non ignition and from total to only partial combustion.

The main parameters to be varied in the planned studies are :

-- The pressure and temperature of the hot residual gas (or air) in which the methanol-air mixtures (repectively the methanol spray) is injected. In order to obtain temperatures high enough to be representative for engine conditions, without needing to heat the reactor walls to unadmissible temperatures, hot residual gases (in the first part of the study) and a "synthetic" air (for the second part of the study) is obtained by previous combustion of appropriate, lean hydrogen/oxygen/nitrogen mixtures, ignited by sparks.

-- For the first part of the programme : equivalence ratio and total volume of the homogeneous methanol-air mixtures injected. Eventually also the speed of injection.

-- For the second part of the programme : the volume of liquid methanol injected; the characteristics of the spray (size and velocity distribution of the droplets); the spark energy; the location of the spark with respect to the injection nozzle; the delay of the spark with respect to the start of the injection.

Although originally the rig has been conceived to be operated under constant volume/stagnant gas conditions, a minor transformation will readily allow it to be used to study the effects of flow characteristics (turbulence, flow gradients) on the phenomena under investigation, if need is felt for.

Construction and equipment

The following actions have been undertoken by the expert in order to speed up the construction of the test rig:

a) Cross-check and detailed discussion of the programme (as given in Annexe 3) with Mr M.Abraham, who is in charge of building the facilitie and performing the trials and with Dr B.P.Pundir, project coordinator of the Engines Laboratory.

b) Previsions of the acquisition of the optical equipment. Whereas most parts of the reactor and its equipment either already exist at IIP or can be manufactured in its workshops, a number of items of the optical equipment of the shadowgraphy bench have to be purchased, eventually from abroad; these are mainly :

-- an Argon/ion laser of about 2 awtts effective power, which for example may be ordered from the firm Spectra-physics (in France or the U.S.A.)
-- Optical quality windows for the reactor
-- an a-phocal lenses system for expansion of the laser into a parallele shadowgraphic beam
-- a total reflection miror

Contacts have been initializes with a dealer in optical equipment in France in order to obtain a cost prevision for lenses, windows and mirror, treated anti-reflexion and with $\lambda/2$ flatness factor.

-- An optical bench and supports for lenses and miror are not directly available at the Engines Laboratory. Although the manufacturing of these items is a precision work usually left to specialized firms, they might be manufactured actually at IIP in a less sophisticated manner, owing to the fact that the precision requirements for theire use in a shadowgraphy method is less severe.
-- A fast framing camera of appropriate quality exists at the Engines Laboratory and may be suitably used.

Any way it is the common feeling of the expert and of the counterpart staff, that the completion of the optical equipment may take a long delay. Therefore, and since a substantial part of the trials may be started without this optical equipment, it has been agreed that the experimental programme would start as soon as the rest of the test rig has been implemented.

c) The heads of the mechanical workshop and of the hyalotechnical workshop of IIP have been contacted (respectively Mr.Singh Nishan and Mr. Stanley Portion) to discuss the details of the construction of the following parts of the test rig:

- -- The reactor itself (dimensions, design, material and characteristics)
- -- The methanol-air injection device (design, dimensions, material, characteristics)
- -- The sonical orifices equiped feedlines
- -- The device for the preparation of the methanol-air mixtures

The manufacturing of these items has started by now.

d) The availibility of the electronic equipment has been checked with Mr.M.Abraham.

- -- The Engines Laboratory disposes of a multichannel variable delayed pulse generator perfectly suitable to meet the requirements of the planned trials (delayed injection, delayed spark firing, camera and oscilloscope triggering)
- -- Less sophisticated but reliable delayed pulse generators can be built and actually have already been built at IIP.
- -- Suitable circuitry for spark ignition can be realized at the Engines Laboratory using the schemas which have been provided.

Calendar

An approximate and tentative calendar has been discussed with the counterpart, yielding the following provisorious execution schedule :

Item :	finalized for :
A) First part of the programme (ignition by hot residual gases):	
1) Manufacturing of hardware parts and ignition circuitry; optical parts to be ordered building of the experimental rig (except optical parts)	30 April 1986

Item	finalized for :
2) Calibration of sonical orifices, of injection duration, of methanol-air feedline (by chromatography), of pressure transducer. Check of the delay circuit. Determination of the pressure/time and temperature/time history for different hydrogen/oxygen/nitrogen mixture compositions	
Preliminary trials to assess the useful range of the variable parameters for the experiences	30 June 1986
3) Running the trial series of that part of the study, as far it is possible without the optical equipment	
Realize the optical bench as soon as optical parts are delivered	
Running the trials series including shadowgraphic records	31 October 1986
B) Second part of the programme (spark assisted ignition of methanol sprays) :	
1) Transformation and adaptation of the rig; adaptation of electronic circuitries	30 November 1986
2) Calibrations and determination of pressure/time and temperature/time histories of the "synthetic" air as a function of the hydrogen-air-nitrogen composition	
Preliminary trials : determination of useful parameter range	31 January 1987
3) Running the trial series of that part of the study	30 June 1987

The execution of the outlined research programme does not seem to present difficulties, others than such which can be mastered by the research crew of the Engines Laboratory. However, if at some critical periods of the programme execution (e.g. between June and October 1986, or between November 1986 and January 1987), the presence of a consultant for a short period (not exceeding two weeks) might be needed, this could be negociated with the French Petroleum Institute.

B. Guidance for research within the engine

Problems concerning the actual research activities directly in the engine, have been discussed with the scientists in charge of them. They mainly belong to the following fields :

Glowplug assisted methanol ignition

Discussion of the practical possibilities of decreasing the electrical power needed fro efficient ignition of alcohol sprays in the compression ignition engine ; reduction of the mass or the surface of the electrically heated part of the plug : improvement of the thermal isolation between glowplug and cylinderwalls; exploiting the heat transfer from the hot combustion products to a "heat storage" plug. Comparison of minimum power needed in the case of a continuously heated glow plug and an intermittent high energy spark.

Optical measurements inside the engines

Generally a lot of interesting informations on ignition and combustion in the engine can be obtained from optical diagnostics applied directly inside the engine.

Roughly speaking these optical methods may be classified into two categories:

1) General visulalization techniques allowing a rather global access to the time dependency of flow and mixing patterns or of ignition and flame development. To this categorie belong : (a) some rather sophisticated techniques such as multimatrix endoscopy laser tomography and holography, many of which require important optical access, not always easy to realize in commercial engines; (b) others, which are more simple and therefore more suitable to be applied directly in commercial two- and four-stroke engines , such like direct flame cinematography and shadowcinematography. Global information on flame speed, including early stages propagation, may

also be obtained by some kind of indirect "visualization", for example using multipoint ionization probes.

2) More specific optical methods for flow characterization (Laser Doppler Velocimetry) or "in situ" chemical analysis (e.g. fast scanning, multipoint Raman spectroscopy, coherent antistokes Raman spectroscopy, laser fluorescence spectroscopy). These are all highly to very highly sophisticated methods, the equipment being very expensive and the proper utilisation of which requiring well trained and highly specialized scientific crews. In many cases their use is restricted to experimental engines, offering special adaptations allowing proper optical access.

The quantitative study of most combustion phenomena inside the engine many times requires the combination of different optical methods belonging to one or to both categories, for example : shadowgraphy coupled with simultaneous laser Doppler anemometry.

In the experts opinion :

a) Informations gained from fundamental studies, although indispensable for an adequate understanding and ulterior optimization of the combustion phenomena occuring in the engine, cannot simply be extrapolated to real, complexe engine conditions where they actually occur. Therefore, confirmation of fundamental results and information on the conditions controlling them, should be gained directly inside the engine by the use of non intrusive optical techniques.

b) Owing to the actual situation at the Engines Laboratory of IIP (more especially with respect to the available equipment and research crew competence) it does not seem to be reasonable planning, for the next future, the application of optical diagnostics using (highly) sophisticated techniques.

The eventual use of such techniques in a more remote future, if decided upon, ought to be carefully prepared (a) by time-taking, adequate specialized training of the research people, for each respective technique, in laboratories already using thoroughly these methods inside the engine; (b) by the construction of appropriate experimental engines , equiped for the use of these methods.

c) For the benefit of the trials being carried out actually, especially in the two-stroke engine, with respect to the understanding of (a) the global mixing patterns of fresh mixture and residual gases and (b) the initial flame propagation and its relation to cyclic dispersion, some global visualization techniques, involving rather simple equipment , may be suitably used already right now :

-- Either the indirect one, using ionization probes fitted to the periphery of the spark plug (such ionization-probe-equiped spark plugs may be obtained eventually from the French Petroleum Institute);

-- or direct flame cinematography, using Sodiumborate seeded intake air to increase the light emission from the burned gases, making thus the flame front position sufficiently contrasted to be viewed by fast framing cameras. Guidance has been given for the construction of a simple , yet very efficient seeding device. The fitting of a simple optical access window of about 20 mm diameter in the head of the two-stroke engine cylinder , should meet no large difficulties.

C. Training on fundamental combustion aspects

Lecture series

During his stay at IIP the expert has provided twenty five hours of lectures on fundamental aspects of combustion, mostly related to engines. The time schedule of this lectures series is given in Annexe 4.

These lectures were attended by research scientists of both the engines Laboratory and the Industrial Combustion Section:

-- from the Engines Laboratory :

MM: M. Abraham, D. Kumar, S. Das and S. Jain

-- from the Industrial Combustion Section :

MM: K.S.Kambo, K.M.Agrawal, H.K. Madan and D. Deepak

The subjects treated in these lectures are summarized in what follows.

1. General combustion kinetics

   Characteristics of chain-radical reactions as occuring during combustion; reaction rates and reaction mechanisms for hydrogen/oxygen and hydrocarbon/oxygen systems.

2. The phenomenon of selfignition.

   Physicochemical mechanisms of selfignition; ignition temperature and ignition delays : their calculation; experimental diagnostic methods for their measurements; effect of pressure, mixture composition and confinement on selfignition temperatures and delays. The role played by selfignition in spark ignition amd compression ignition engines.

3. The phenomenon of deflagration.

   3.1. Steady state flame propagation

   Theory of steady flame propagation. Dependency of flame speed on pressure, temperature mixture composition and turbulence.

   Experimental methods for flame speed measurement.

   3.2. Spark ignition.

   critical ignition energy; optimum spark duration time; effects of electrode walls and turbulent flow characteristics on spark energy and on critical ignition energy.

3.3. Non steady propagation of spark ignited flames in early stages of propagation.

-- effects of spark energy and wall quenching on flame speed
-- Effects of gasdynamic characteristics :
  - turbulent induced statistical dispersion of initial flame speed
  - flame stretch induced by flow gradients, compared to geometrical flame stretch ; effects of flame stretch on flame speed and mass burning rate.
-- Effects of mixture and flow heterogeneities on mass combustion rate in early stages of propagation.
-- Experimental diagnostic methods for the study of early flame stages ; the method of laser tomography and its applications.

3.4. Flame propagation conditions

Intrincic conditions : flammability limits; theoretical and experimental approach

Extrinsic conditions : flame quenching by walls; Quenching theory ; theoretical and experimental values of quenching distances; measuring methods.

4. Emission of pollutants by combustion

4.1. Nitric oxides

-- Gas phase kinetics of NO formation ; "thermal", "fuel-NO" and "prompt-NO" mechanisms.
-- Heterogeneous NO reduction on flame born solid particles
-- Effects of charge staging and turbulent composition and temperature fluctuations on NO emissions.

4.2. Soot and cenospheres

Chemical mechanisms of gas phase soot formation and liquid phase cenospheres formation. Formation of polyaromatic hydrocarbons (PAH). Relationship between cenospheric residus and Conradson Carbon.

Catalytic and non catalytic soot oxydation, application to soot trapping techniques in Diesel combustion.

4.3. Formation of aldehydes and unburnt hydrocarbons in engines. Bulk quenching and wall quenching phenomena.

Colloquium on solid fuel combustion chemistry

On 27 December , from 2.30 to 5.00 p.m., the expert also has given a colloquium on chemical aspects of solid fuel combustion, which was attended by about fourthy research scientists belonging to different divisions of IIP.

The following topics have been treated in this colloquium :

1. Structure and physico-chemical characteristics of solid fuels (soot, coal, petroleum coke, char, wood)
2. Fast pyrolysis reactions. Effects of temperature risetime on nature and amount of pyrolysis products.
3. Kinetics of heterogeneous combustion of the solid matrix
   - -- Chemical mechanism of dissociation chemisorption of oxygen and desorption of CO and CO_2.
   - -- Local reaction rate of combustion , as controlled by either adsorption or desorption. under steady state conditions.
   - -- Time dependency of the activation temperature.
   - -- Effects of pore diffusivity; average reaction rate of combustion in diffusivity controlled regime, kinetics controlled regime and mixed regime.
4. The ignition of solid, pyrolysable fuels.
   - -- Ignition temperature and delays.
   - -- "char" ignition and "whole coal" ignition : two alternative types of ignition resulting from pyrolysis/oxydation competition. Transition from one type to the other as a function of oxygen concentration, temperature and particle size.
   - -- Consequences of "whole coal" ignition : inhibition of initial combustion rate and extinction .
5. Formation and reduction of nitric oxides during solid fuel combustion.

III. CONCLUSIONS

1. In order to acquire good understanding of engine related combustion phenomena, useful for the optimization of specific technologies aiming at improved use of methanol, an experimental programme of parametric studies, bearing a fundamental character has been defined, to be carried out at the Engines Laboratory of the Indian Institute of Petroleum in Dehra.Dun.
   a) A detailed description of the experimental test rig has been elaborated and discussed with the counterpart staff.
   b) Contacts have been established with the research crew and with persons in charge of the workshops to start the constuction of the test rig and to build the appropriate equipment.
   c) A research programme covering an eighteen months period has been outlined, foçussing at the study of two particular problems related to the ignition phenomena of methanol in engines :
      1) the ignition of homogeneous methanol-air mixtures by hot residual gases, related to the ignition phenomena occuring in two-stroke engines operated at part load.
      2) the characteristics of spark assisted methanol droplet sprays ignition, related to the onset of combustion in the compression ignition engine.
   d) The manufactoring of the test rig has been started. The construction may be finished within a few months from now. A tentative time table for the execution of the programme has been established.

2. In order to check in a rational way the advantages of some specific technologies, the application of wicb in the engine are actually studied in the Engine Laboratory, guidance has beun given for the immediate use of simple diagnostics to be carried out directly in the engines.
   The advantages of more elaborated optical diagnostics inside the engine has been discussed and the practical conditions of their proper utilization in a more remote future have been outlined and recommended.

3. Training in basic combustion phenomena, mostly related to engine combustion and industrial combustion, has been provided to the research scientists of the Engines Laboratory and of the Industrial Combustion Section, mainly in the form of a systematic lectures series.

4. Some practical recommendations have been issued to the Direction of the Engines Laboratory of IIP.

ANNEX 1

Traveling Schedule

Departure from Paris on 12 November 1985 at 11.05 a.m.
by flight AF 782

Arrival in Vienna on 12 November 1985 at 0.55 p.m.

Briefing in Vienna on 12 Nov.1985 (afternoon) and on 13 Nov. 1985 (morning)

Departure from Vienna on 13 Nov.1985 at 2.10 p.m.
by flight PA066

Arrival at Delhi on 14 Nov.1985 at 2.50 a.m.

Impossibility to get a seat reservation on the aircraft from Delhi to Dehra Dun, for the next day, imposed a supplementary day of stopover in Delhi.

Departure from Delhi on 16 Nov.1985 at 7.00 a.m.
by Flight PF103

Arrival at Dehra Dun on 16 Nov.1985 at 7.50 a.m.

Interruption of stay in Dehra Dun for personal business :

Departure from Delhi on 29 Nov.1985 at 1.30 a.m.
by Flight TJ 951

Arriving back in Delhi on 15 December 1985 at 2.40 a.m.
by Flight AI 301

Departure from Delhi on 16 Dec. 1985 at 7.00 a.m.
by Flight PF 103

Arriving at Dehra Dun on 16 Dec. 1985 at 7.50 a.m.

Departure from Dehra Dun on 8 January 1986 at 8.10 a.m.
by Flight PF 104

Arriving in Delhi on 8 January 1986 at 9.00 a.m.

Stopover in Delhi on 8 January 1986

Departure from Delhi on 9 January 1986 at 2.55 a.m.
by Flight LH 665

Arriving in Frankfurt on 9 January 1986 at 7.15 a.m.

Departure from Frankfurt on 9 January 1986 at 8.45 a.m.
by Flight OS 408

Arriving in Vienna on 9 January 1986 at 10.05 a.m.

Debriefing in Vienna on 9 January 1986

Departure from Vienna on 10 January 1986 at 1.45 p.m.
by flight AF 781

Arriving in Paris on 10 January 1986 at 3.45 p.m.

ANNEX 2

Senior Counterpart Staff

The Engines Laboratory of IIP , together with the Industrial Combustion Section are branches of the Applications Division, the Director of which is Mr.S.Singhal.
The Engine Laboratory's Project Coordinator is Dr.B.P.Pundir.
This section is composed by three groups :

1) First group : Combustion and Emissions Studies
   Head of group : Dr B.P. Pundir
   Research Engineers : Mr M.Abraham, Mr D. Kumar
   Mr. A.K. Aigal, Mr. S. K. Singhal
   Mr.M.S. Das, Mr S. Maji
   Mr R.K. Sharma
2) Second group : Field and Performance Studies
   Head of group : Mr K.K. Ghandi
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ANNEX 3

Basic Study on ignition behaviour of methanol and methanol/hydrocarbon blends, related to the onset of combustion in two stroke S.I. engines and C.I. engines

The general purpose is the realisation of a reactor equiped with appropriate measuring devices , in order to study parametrically the following two phenomena, respectively related to two stroke S.I. engines and to C.I. engines fuelled partly or totally with methanol:

1. in the two stroke S.I. engine : the ignition of the flammable charge when injected in the hot residual combustion products, as may be observed e.g. at partial load conditions.
2. in the C.I. engine : the characteristics of methanol droplet spray ignition, assisted by (high energy) sparks.

In order to obtain a proper understanding of these complexe phenomena, we believe it to be necessary to perform basic studies in an appropriate laboratory test rig constituted by a constant volume reactor, equiped with visualization and measuring devices to study the ignition and flame propagation behaviour as well as its parametric dependence on temperature, pressure, fuel type and mixture composition, etc.

A. Ignition of homogeneous methanol/hydrocarbon/air mixtures by hot combustion products

Methanol/hydrocarbon/air mixtures will be injected into the hot combustion products resulting from the combustion of hydrogen/oxygen/nitrogen mixtures. The parametric dependence of the temperature and delay of ignition, the combustion rate and the burn-out will be determined.

A.1. Description of the experimental apparatus (see figure 1)

A.1.1. The main reactor

The cylindrical shaped reactor is equiped with two parallele windows (1) of optical quality. The following dimensions might be suggested: inside diameter 80 to 100 mm; length ; 100 to 1500 mm.

The cylindrical walls should be heatable up to 300 degrees centigrade by means of electrical resistors wrapped around them. For most purposes of the study however these heating possibilities are not strictly required. Further characteristics of the main reactor are given in paragraph A.5.

A pair of electrodes (2) is fixed in the reactor walls by isolating gaskets. They are connected with an appropriate ignition circuitry (3). The inlet (4) for the hydrogen/oxygen/nitrogen mixtures is equiped with a two way valve (5) and a one way isolating valve (6). The gas outlet (7) in turn is equipped with a one way isolating valve (8) and a two way valve (9). The two isolating valves 6 and 8, should be able to withstand a pressure equal to the maximum value reached during the trials.

Linked with the main reactor over a solenoide one way valve (10) is the injection device for the methanol/air or methanol/hydrocarbon/air mixtures.

A.1.2. Methanol/air injection device

It is composed by a cylinder (11) in wich a piston (12) can freely be moved. Tightening of that piston against the cylinder walls may be obtained by a pair of o-rings, providing at the same time guidance of the piston movements. Piston (12) is moved upward, and kept in the upside position by a small vacuum pump(13), isolated from cylinder (110 by a one way valve (14). To bring the piston (12)down, air from a high pressure bottle (15) is used; it enters cylinder (110 from the top , through a solenoide one way valve (16). The pressure used to bring piston (12) down can be preset by a pressure reducing valve (17). It is important that valve (16) be able to withstand that preset pressure without leakage.

In the cylinder (11) the experimental methanol/air mixtu[illegible] is introduced over a one way valve (18), while the piston (12) is kept in the upside position. This gas mixture is prepared by a special feedkine (see paragraphe A.4) . The lower cylinder part is rinsed by the methanol/air mixture using the one way outlet valve (19). If possible, it is better to replace the two one way valves (18) and (19) by two two-way valves , the second outlet of each being interconnected in a way to provide a bypass of the cylinder (11) (this bypass not being indicated on figure 1). This improvement allows a much more stable composition to be maintained for the methanol/air mixture, since the pressure drop is then not alterated when isolating the cylinder(11)

Both cylinder (11) and main reactor should be rinsed after each trial by their respective mixtures during a time (t_c, respectively t_r0 sufficiently large to ensure the complete evacuation of the combustion products of the previous trial. This time may be evaluated on the assumption that rinsing with about twenty times the respective volumes of cylinder (11), v_c, and of the main reactor, v_r, will be sufficient to reach that goal. If D_c and D_r are the respective flow rates through cylinder (11) and main reactor, then the respective minimum rinsing times are given by :

$$t_c = 20\ v_c/D_c$$

$$t_r = 20\ v_r/D_r$$

In order to change the volume v_c of the cylinder (11), cylindrical shaped inserts (20) of variable height may be located in the upper part of the injection system.

A.1.3. Feedline for main reactor

The hydrogen/oxygen/nitrogen mixtures are obtained from separate bottles of compressed nitrogen (a), oxygen (b) and hydrogen (c). Each of these three feedlines possesses its own pressure reducing valves: a coarse reduction valve (d1) 9down to about 10 bars) and a fine reduction valve (d2) (e.g. between 0 and 10 bars). The flow rate of each component is metered separately by means of a sonical orifice (e), equiped with a high precision manometer (f). Fulfilment of the sonical regime condition may be checked by a further manometer (g) located downstream. Sonical regime is achieved for :

$$(P_f)_{abs} \geqslant 2\ (P_g)_{abs}$$

$(P_f)_{abs}$ and $(P_g)_{abs}$ being the absolute pressures as obtained from manometer (f), respectively (g). Under these conditions the mass flow rate through the orifice is given by the relationship :

$$dM/dt = K\ (P_f)_{abs}\ S\ /\ T^{0.5}$$

where K is a coefficient proper to the gas, S the hydraulic section area of the sonical nozzle and T the absolute temperature upstream of the nozzle. If ambient temperature is not changing too much, T may be considered as a constant and has not to be measured . If sonical orifices of not appropriate aerodynamical shape are utilized, then it is required to calibrate the mass flow rate as a function of absolute pressure, by means of a gas counter or, for very small flow rates, a soap bubble tube.

A.1.4. Feedline for the methanol/air mixtures

In what follows a typical feedline for methanol/air mixtures is described; its adaptation to fuel mixtures (e.g. methanol+ hydrocarbon) is readily extrapolated.

The methanol+air mixture might be prepared by a conventional carburetting method. However, for continuous flow operation, it may be done more properly by the vapor pressure method shown also on figure 1. Air from a cylinder (15) is expanded by two successive, coarse (21) and fine (22) pressure reducing valves, prior to being metered by a sonical nozzle (h). Part of the air flow is bypassed through a double scrubber system, containg the liquid fuel (i). The latter is kept at a constant temperature , T_j, by means of a stirring/thermostating system (j).

The total flow rate of air from nozzle (h), $\dot{v}_{air}$, is divided over the two parallele channels I and II by means of two needle valves (l_1) and (l_2). The air flow rate through channel II ,$(\dot{v}_{air})_{II}$, is metered by a rotameter (m). The pressure in the scrubbers , P_t, is indicated by U-tube manometer (k), using preferentially butyl-diphtalate as a manometer liquid, for precision reasons. Be P_v the vapour pressure of the fuel at temperature T_j. We then have the following expression of the volumic flow rate of the fuel :

$$\dot{v}_{fuel} = \left[\dot{v}_{air} - (\dot{v}_{air})_{II}\right] P_v / (P_t - P_v)$$

The air flow through the scrubbers should not be too large, in order to avoid aerosol entrainment of the fuel. The second scrubber acts as a regulating device, adding fuel vapor in cases where the air leaving the first scrubber should not be saturated, condensing excess fuel vapor in cases of over-saturation.

If fuel mixtures are used instead of neat methanol, the respective volumic fuel rates , $(\dot{v}_{fuel})_i$, of each co;ponent i , may be obtained from the Raoult law.

A.2. General scenario of a trial

A.2.1. Valve (16) being closed, valve (14) is opened and piston (12) is rised to its upper position by means of the vacuum pump.

A.2.2 Adjustment of mixture composition and flow rates both through feedlines of the hydrogen/oxygen/nitrogen mixture and of the methanol/air mixture.

A.2.3. Rinsing of the main reactor during a period of at least the value t_r, and of the injection cylinder (11) during a period of at least the value t_c. During that operation, valve (10) remains closed.

A.2.4. Valves (6), (8), (18) and (19) are closed. The eventual existence of a line bypassing valves (18) and (19) has already been suggested as a useful improvement. In an analogous way, a bypass between valves (6) and (8) would be equally useful.

A.2.5. The air pressure on valve (16) is adjusted by pressure reducing valve (17).

A.2.6. The spark is fired between the electrodes (2,2). The spark circuitry (3) triggers a signal delaying circuitry or delayed pulse generator unit (23), which in turn, after an adjustable delay θ, commands the simultaneous opening of the two solenoide valves (16) and (10). Consequently, piston (12) is driven downward and the methanol/air mixture is forced into the main reactor. There it mixes with the combustion products of the hydrogen/oxygen/nitrogen mixture and, for appropriate conditions, is ignited by the latter.

A.3. Measurements effectuated during and after the combustion of the methanol/air mixture

A.3.1. Pressure evolution

A pressure transducer (24) (e.g. AVL piezoelectric transducer) equiped with a charge amplifier (25) and duly calibrated allows the pressure/time history to be recorded on an oscillographe (26). From this record the following informations may be obtained :

--- the existing pressure at the moment of injection of the methanol/air mixture,

--- the pressure evolution during the combustion of that mixture and especially the maximum pressure variation $(dP/dt)_{max}$, which is a measure of the maximum combustion rate.

--- the total combustion time (τ) of the charge, indicated by the maximu of the pressure/time curve.

The typical pressure/time records obtained with methanol/air mixture inje tion should usefully be compared with "blanc" records in which pure air is injected instead of a methanol/air mixture.

A.3.2.Ignition delay

The ignition delay (δ) may be defined here as the time elapsed between the opening of valve (10) and the first appearance of combustion of the methanol/air mixture.

For the detection of that ignition instant :

-- the recorded pressure/time curve is not very suitable;

-- the fast framing cinematography (see paragraphe A.3.3) is better but may be not sufficiently precise if the framing speed is to low.

-- the best method is to use a sensitive photomultiplier or photodiode looking into the reactor (this photosensor is not represented on figure 1). The output of this photomultiplier may be displayed on oscillographe (26) together with the pressure/time curve.

Actually in the present case, we have to deal with a complexe, physico-chemical ignition delay , accounting for both the time needed to achieve a sufficient degree of mixing between the methanol/air mixture and the hot combustion products , and the chemical induction time or self-ignition delay "sensu stricto".

A.3.3.Volumic combustion rate

Once ignited, the combustion rate of the methanol/air mixture as a function of time may be estimated by monitoring the volume/time history of the burnt gases. For later stages of propagation this may principly be done by using the pressure/time records. For early propagation stages however, the best precision is obtained from fast framing cinematography, using either Schlieren- or shadowgraphic technics. The latter is shown on figure 1, using a laser beam as a light source (27) and a fast framing camera (28). The laser beam is expanded into a parallele beam, covering the windows (1) , by means of an a-phocal lenses system (29,30). The shadow image, formed on a depolished glass screen (31), is photographed by the camera, the latter being triggered e.g. by the spark .

A.3.4.The fraction of fuel burnt

When studying the ignition of flammable mixtures by hot gases one should be aware that, upon mixing, the flammable mixture undergoes simultaneously a progressive heating and a progressive dilution . The latter of the two effects may cause severe bulk quenching (= gas phase quenching) resulting in incomplete combustion of the injected charge.

Therefore the fraction of methanol burnt should be checked for each set of experimental conditions. A priori this may be done in two ways :

A.3.4.1. By measuring the amount of methanol left after combustion.
This may be done e.g. using gaschromatography.
The method seems to present two practical disadvantages :

a- Gaschromatography being a discontinuous analysis method, the samples used should be representative and therefor should be taken after the combustion products have been thoroughly homogenized. Owing to the geometrical shape of the main reactor 9and especially the presence of the windows), this homogenizing operation would require a fan situated within the reactor.

b- The original fuel may be partly pyrolysed or only partially burnt during bulk quenching A chromatographe equiped with a flame ionization detector may miss these intermediate products.

A.3.4.2. By measuring the amount of CO_2 and CO formed
This can be done by on-line CO_2 and CO analysis, e.g. non dispersive infra red analysers (32). This continuous analysis method allows integration as a function of time to yield the total amount of CO_2 and CO formed , avoiding the disadvantages mentioned earlier.

The combustion being finished and valve (10) being closed again, a known constant flow rate of nitrogen, $\dot{v}_{N2}$, is sent through the main reactor, entering by valve (5) and leaving by valve (8) and (9), prior to be sent to the analysers; the latter are equiped with a trace recorder (33), allowing digital or manual integration of the CO(t) and $CO_2(t)$ curves. The fraction of carbon burnt is given by the following expression:

$$F_b = \frac{\dot{v}_{N2} \quad {}^{t}(X_{CO2} + X_{CO})\,dt}{v_c \cdot X_{CH3OH} \cdot n_C}$$

which applies for methanol/air mixtures. In this expression:

v_c = volume (at normal pressure and temperature) of methanol/air mixture injected into the reactor.

X_{CO2}, X_{CO} = molefraction of species CO_2 and CO given by analysis at time t

X_{CH3OH} = mole fraction of methanol in the injected mixture

n_C = number of carbon atoms per molecule of fuel (= 1 for methanol0.

A.3.5.Critical conditions

From the above mentioned measurements, the critical parameter values for ignition and for total combustion may be determined. For this to be done, the parameter considered will be varied over a range which is large enough to obtaim the transition from ignition to non ignition, respectively the transition from partial combustion to total combustion.

Remark : Due to eventual wall quenching effects, the value of F_b may as well remain lower than unity for all trials. Therefore, for the sake of comparison , it might be useful to determine F_b values with homogeneous methanol/air mixtures, introduced directly into the main reactor and ignited there by a spark.

A.4. Parameters to be varied during the trials

A.4.1.Composition of the hydrogen/oxygen/nitrogen mixtures

The choice of hydrogen as a fuel to produce the hot gases is based on the need of avoiding CO_2 and CO formation, which would interfere with the measurement of F_b. Although it would be still possible to determine the methanol fraction burnt even if CO and CO_2 pre-exist in the hot gases, the precision of the obtained value would be much smaller.

For security reasons one should avoid the creation of detonation and the therewith associated high dynamic pressure waves, which are very likely in hydrogen/oxygen mixtures. Therefore only lean and highly diluted hydrogen/oxygen/nitrogen mixtures should be used, i.e. lean mixtures situated between the flammability limits and the detonation limits. On figure 2 these mixtures are situated in the area limited by curves a and b and by the stoichiometric line.

The characteristics of these hydrogen/oxygen/nitrogen mixtures, together with the initial temperature (T_{r_1}) and pressure (P_{r_1}) in the reactor, as well as the injection delay time θ all contribute to define the characteristics of the hot combustion gases (composition, temperature, pressure) into which the methanol/air mixture is injected. These characteristics may be varied as parameters. The choice of delay time θ is of particular importance, since the hot gases progressively loose energy to the reactor walls. The mean temperature of the hot gases at the injection time ($T_{r\theta}$) may be estimated from the pressure recorded at that time ($P_{r\theta}$). Provided $T_{r\theta}$ is high enough to avoid water vapor condensation, one has from the generalized gas law :

$$T_r = T_{r_1} \frac{P_{r\theta}}{P_{r_1}} \frac{N_r}{N_p}$$

where N_r/N_p is the ratio of mole numbers respectively in the reactants and in the combustion products. For lean hydrogen/oxygen/nitrogen mixtures, this ratio is given as :

$$N_p/N_r = 1 - X_{H_2}/2$$

X_{H_2} being the molefraction of hydrogen in the reactants.

It may be recommended to dispose also of an experimental means to measure the value of the temperature, e.g. by a thermoelement (platinum/platinum+rhodium) located inside the main reactor to monitor the temperature as a function of time. The output of that thermocouple may be displayed on the oscillographe (26) together with the pressure track.

For reasons which may be readuly understood, it would be suitable to choose the experimental values of $P_{r\theta}$ and $T_{r\theta}$ in such a way as to be representative of the values prevailing in a two stroke engine, e.g. ;

$$0.7 \leqslant P_{r\theta} \leqslant 1 \text{ MPa}$$

$$700 \leqslant T_{r\theta} \leqslant 900\ ^{o}C$$

The maximum value of the temperature reached in the main reactor depends on the adiabatic flame temperature (T_f) of the hydrogen/oxygen/nitrogen mixture as well as on the heat losses to the reactor walls. That maximum value may be adjusted mainly by adjusting the nitrogen content of the mixture.

A.4.2.The methanol/air mixture

The effect of the following parameters may be usefully studied:

a.Composition of the fuel

Either neat methanol or methanol/hydrocarbon blends. As to the hydrocarbons, the use of pure products (hexane, heptane, etc.) or known mixtures of pure hydrocarbons is by far to be preferred over commercial gasolines, for the sake of proper determination of the burnt fraction F_b.

As already stated in paragraphe A.1.4., in the case of hydrocarbon/methanol blends, the vapor pressures P_{vi} of each of the fuel components i should be calculated by the multicomponent rule of Raoult, stating that the molefraction X_{iv} of component i in the vapor phase is equal to its molefraction in the liquid phase (X_{il}) multiplied by its vapor pressure P_{vi}. Accordingly the gas phase molefractions X_{iv} will vary with time during rinsing of the cylinder (11).

b. Equivalence ratio of the mixture

c.The volume (v_c) of the methanol/air mixture injected into the main reactor.

A.4.3. Other parameters

Other parameters which may affect ignition characteristics and burnout of the methanol/air mixtures are :

a.Speed of injection of the mixture, which can be changed by varying the pressure applied to piston (12), or by changing the inside diameter of injection tube exit.

b.Shape of the methanol/air injected jet: deep penetrating jets a priori are expected to behave differently from broad angle jets. Special geometrical shape of the injection tube exit may be used.

4.5. Approximate estimation of reactor characteristics

A first order estimation of the reactor characteristics, from a security point of view, may be made as a guidance for construction.

The assumptions used are as follows:

a. Shape of reactor : as shown schematically on figure 1; cylindrical walls without longitudinal welding; flat flanges welded to the cylindrical part on both sides.

b. Windows in tempered pyrex or borosilicate crownglass of optical quality (flatness : /4 sufficient for shadowgraphy). Flexion resistivity assumed to be 50 MPa = 50 Newtons/mm^2 (= n_f).

c. Window sealings:

-- for reactor operated at almost ambient temperature, O-ring sealings are recommended. There also exist O-rings able to support higher temperatures. Each window should be supported by two O-rings, one on each face. Windows should not be in direct touch with the metalic flanges.

-- If suitable O-rings are not available or if wall temperatures are too high, use flat gaskets of "cligerite" (graphite loaded asbestos).

d. In what follows, wall temperature not exceeding 300 °C will be admitted.

e. All except windows in austenitic stainless steel. As a guideline, the pressure rupture limit (by traction) (R_t) is assumed to be equal to 290 Newtons/mm^2 (= 290 MPa) at a temperature of 300°C.

Calculation formulae used

a. Wall thickness of the cylindrical part (e_c)

$$e_c = r\left[\sqrt{\frac{\frac{R_t}{s} + P_m}{\frac{R_t}{s} - P_m}} - 1\right]$$

s = security coefficient set equal to 3.5

b. Thickness of the windows (e_w)

$$e_w = r \, 2 \, B \sqrt{\frac{P_m}{n_f / H}}$$

B = coefficient equal to 0.555 for tempered pyrex

H = security coefficient set equal to 7

r = radius of reactor (same units as e_c and e_w)

P_m = maximum admissible pressure (same units as n_f and R_t)

Examples of results for different values of r and P_m

P_m (MPa)		r (mm)				
		20	30	40	50	60
2	e_c(mm):	0.49	0.73	0.98	1.22	1.47
	e_w(mm):	11.7	17.6	23.5	29.4	35.2
3	e_c:	0.73	1.11	1.48	1.34	2.21
	e_w:	14.4	21.6	28.8	36.0	43.2
4	e_c:	0.99	1.49	1.98	2.48	2.97
	e_w:	16.6	24.9	33.2	41.5	49.8
5	e_c:	1.25	1.36	2.49	3.11	3.73
	e_w:	18.6	27.9	37.1	46.4	55.7
6	e_c:	1.50	2.26	3.01	3.76	4.51
	e_w:	20.3	30.5	40.7	50.9	61.0
7	e_c:	1.77	2.65	3.54	4.42	5.30
	e_w:	22.0	33.0	44.0	54.9	65.9

B. Spark assisted methanol droplet spray ignition

The use of sparks to assist the onset of combustion of neat methanol in a compression ignition engine in order to overcome the disadvantage of insufficient cetane level, offers interesting possibilities. Reliable spark ignition of homogeneous methanol/air mixtures generally is limited to near-stoichiometric composition and therefore looses one of the interesting features of diesel operation, viz. the possibility of operation at very low overall equivalence ratio values.

Heterogeneous mixtures of low equivalence ratio, obtained by liquid methanol spray injection may be ignited either by glow plugs or by (high energy) sparks. The advantage of the latter over the former technique consists in the possibility to release the external energy at the exact time where it is needed and only at that time, resulting principly in a saving of energy.

Methanol spray ignition by sparks depends à priori on

- -- the characteristics of the spray (droplet size and velocity distribution, vaporization rate and thence gas temperature)
- -- position of the droplet spray with respect to the spark
- -- the spark characteristica : total energy, duration , single spark or spark train.
- -- the aerodynamic flow conditions of the gas (air) into which the spray is injected.

The parametric study of these effects on ignition delay and burnout is rather difficult to realize in a systematic manner directly in the engine; it constitutes a typical case where systematic information may be obtained from an experimental laboratory study.

B.1. Experimental apparatus

For the study of all but the last parameter (aerodynamic flow conditions) mentioned higher, basically the same experimental rig as described in section A, may be used, except for the following differences:

a. The main reactor is filled either with pure air or with an air equivalent mixture.

b. The homogeneous methanol/air mixture injection system is replaced by a conventional diesel injection pump, able to be actuated in single stroke, for the injection of liquid methanol.

c. The ignition circuitry is able to deliver variable spark energies up to one joule (effective).

Radial and axial distance of the injector nose with respect to the spark can be varied. e.g. upon mounting the injector on a plate allowing it to slide along a slit of the reactor sidewall, as shown schematically on figure 3.

B.1.1. Injection system

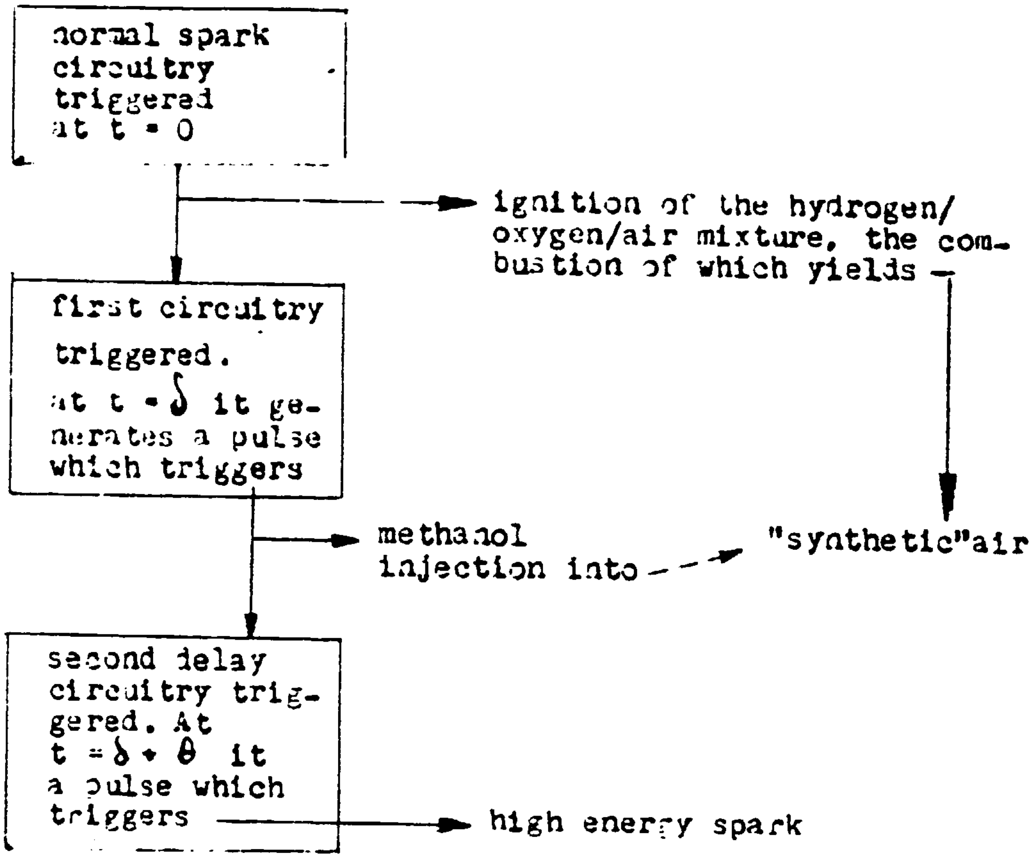
Consists in a diesel injector equiped with a conventional injection pump, connected to a methanol feedline. The injection pump is activated by a discontinuous triggering device, for example a pneumatic or magnetic plunger.

B.1.2. Ignition circuitry

A typical high energy spark circuitry is shown on figure 4. A capacitor (1) of about 2 microfarad is charged to a variable tension (its maximum value being for example 1500 volts) by means of a feedline comprising an autotransformer (2) (0 to 220 volts), a high voltage transformer (3) (transformation ratio 1/15), a diode or diode combination (4), a charging resistor (5) of about 1 Megohm (all values given are approximate). Variation of the autotransformer (2) allows the capacitor (1) to produce sparks of variable energy up to about 1.5 Joules.

The high energy spark is triggered by a low energy, high voltage spark obtained from a capacitance/inductance circuitry composed by an isolation transformer (6), a diode operated AC/DC transformer (7), a capacitor (8) of about 0.5 microfarad (charged at 300 volts) and a high performance induction coil (9) delivering about 40 kVolts.

The plunger of the injection pump (10) starts the injection and triggers a delayed pulse generator circuitry (11); the latter activates thyristor (12) (triggering the spark) after a variable delay time ϑ. A spark circuitry of the type described priate temperature, a delay circuitry is required, the delayed signal of which is actionning the injection pump at time δ after the first spark. Thus the sequence is as follows :



Since this procedure requires a more important equipment, in a first period of the trials one may simplify by using "real" air instead of"synthetic" air, loosing however the advantage of high temperature gases.

If the initial pressure (P_{ri}) is of the order of 3 MPa, the ignition of the methanol spray may result in a final pressure of 7 to 14 MPa, depending on the quantity injected.

B.2. Measurements effectuated during and after ignition

They are substantially the same as in part A of the study (see section A.3.)

B.3. Parameters to be varied

a. Volume of methanol injected (i.e. overall equivalence ratio)

b. Location of spark with respect to injection nozzle, i.e. its axial distance (X) and its radial distance (R) as indicated on figure 3.

c. The spark energy

d. The timing of the spark after the start of the injection (- delay τ).

e. Eventually : initial pressure and temperature of the "synthetic" air at the instant of injection.

f. The characteristics of the spray : it might be recommended to charaterise the droplet size and velocity distribution of the utilized injectors by the Malvern technique.

Other parameters may be checked in further work, e.g. spark duration, spark train systems and aerodynamical flow conditions , the latter however requiring a transformation of the reactor, allowing for example the establishment of a continuous turbulent air flow normal to the reactor axis.

Figure 1

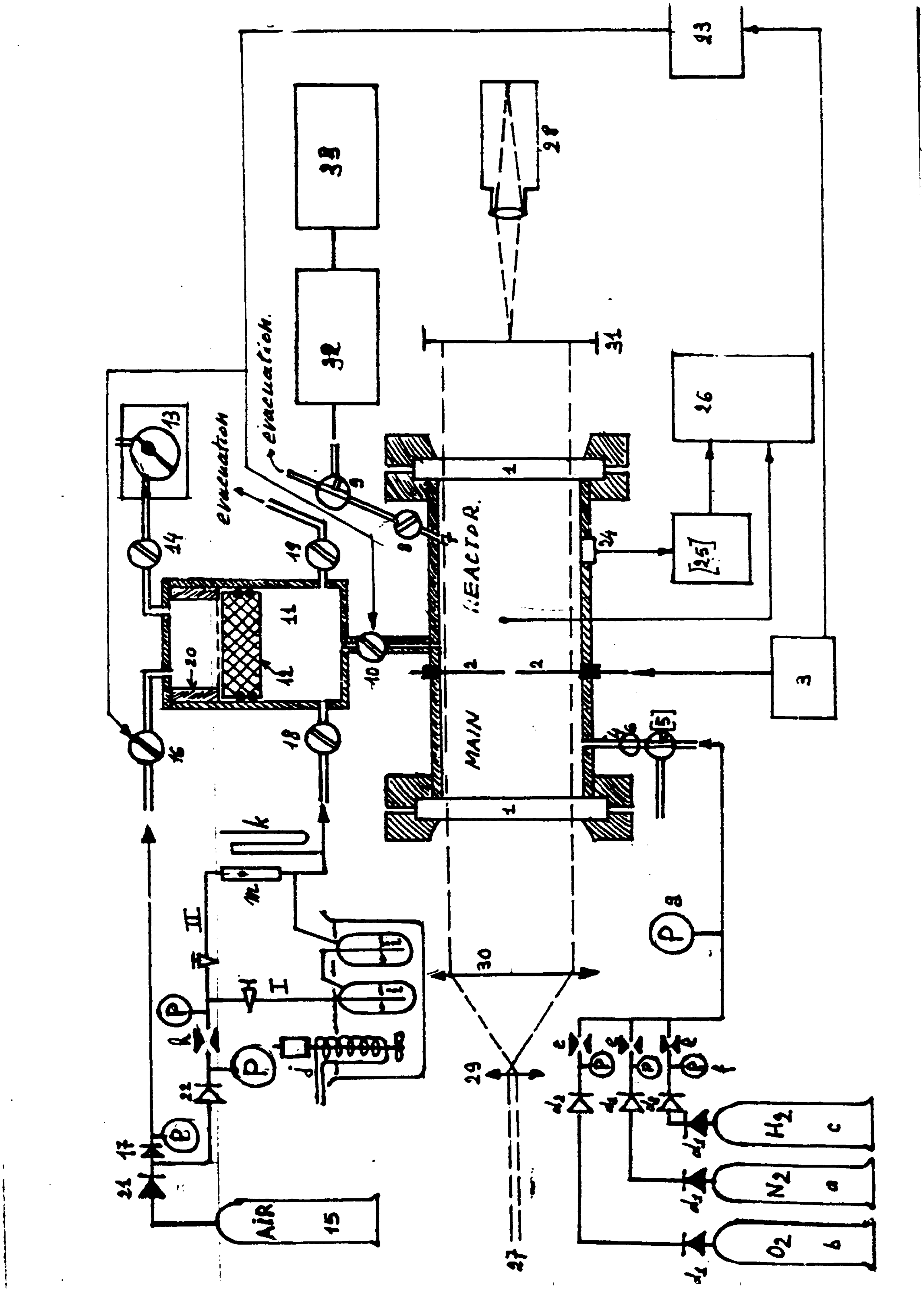
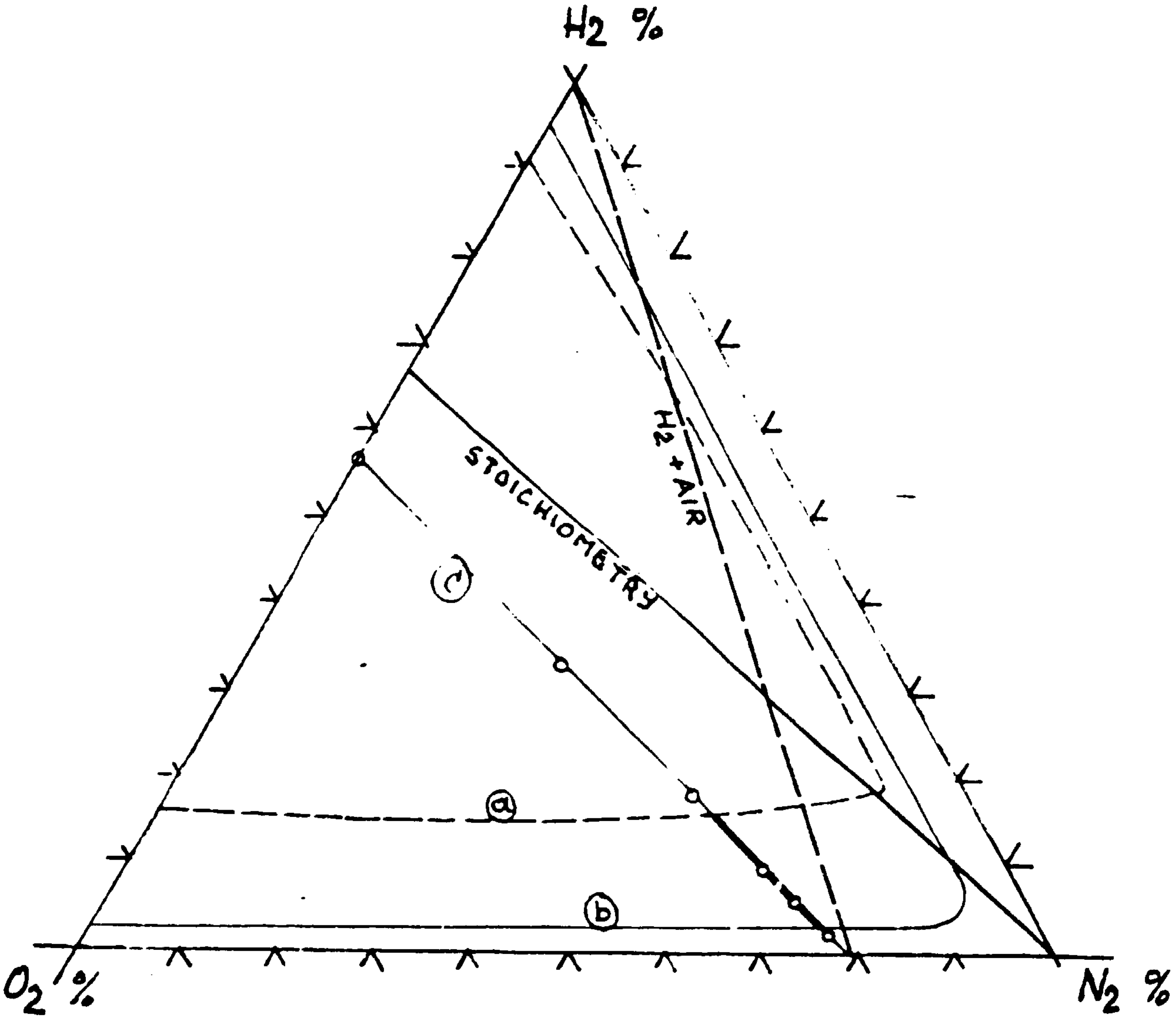

MAIN REACTOR
AIR
15
21
17
22
I
II
k
m
16
18
19
14
13
20
12
11
10
evacuation
evacuation.
9
8
32
33
28
31
1
2
3
24
25
26
27
29
30
O2
N2
H2
a
b
c
d1
e
f
g
5
6

Figure 2

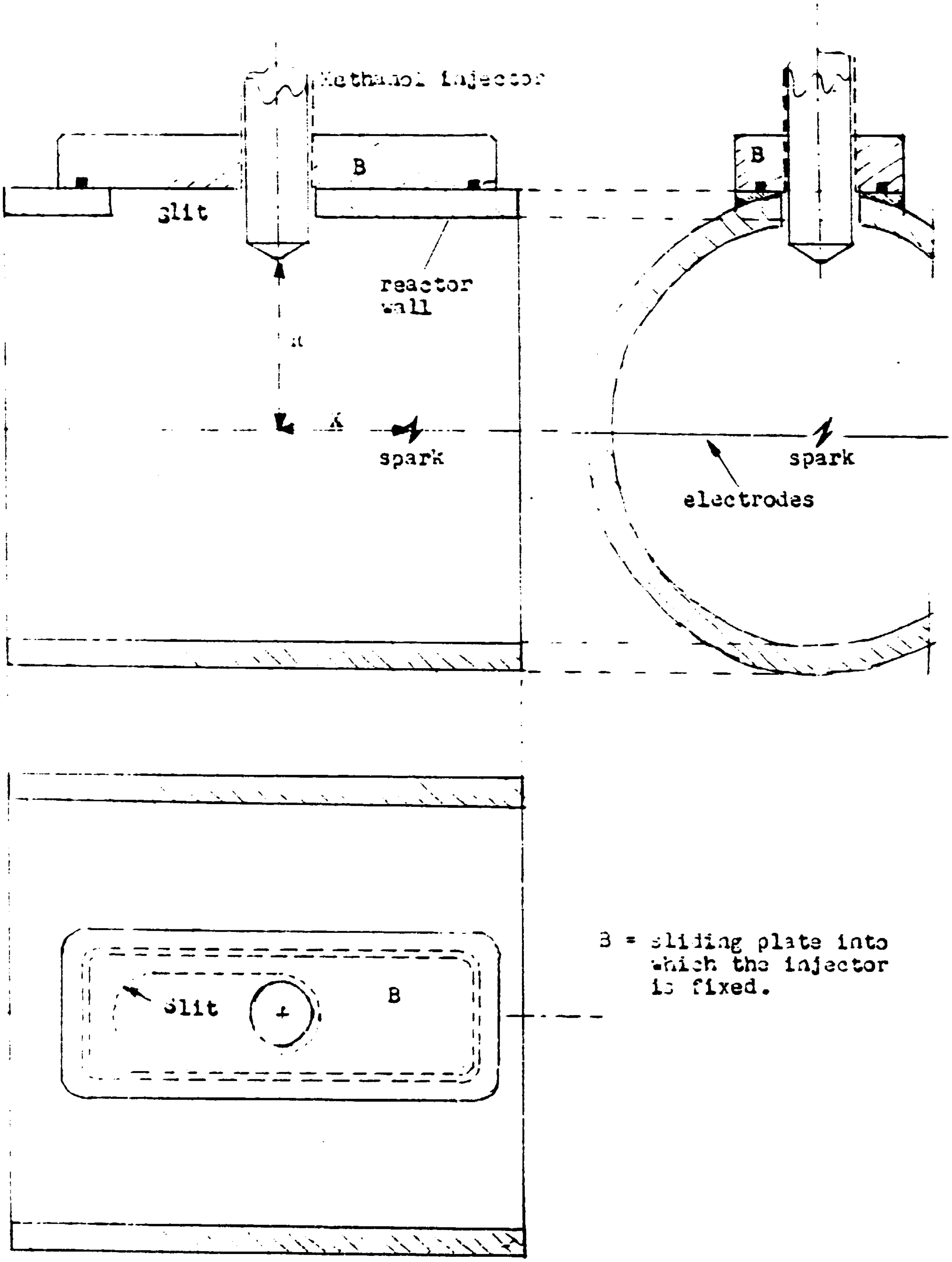


LIMITS (a) OF DETONABILITY ------

(b) AND FLAMMABILITY ———

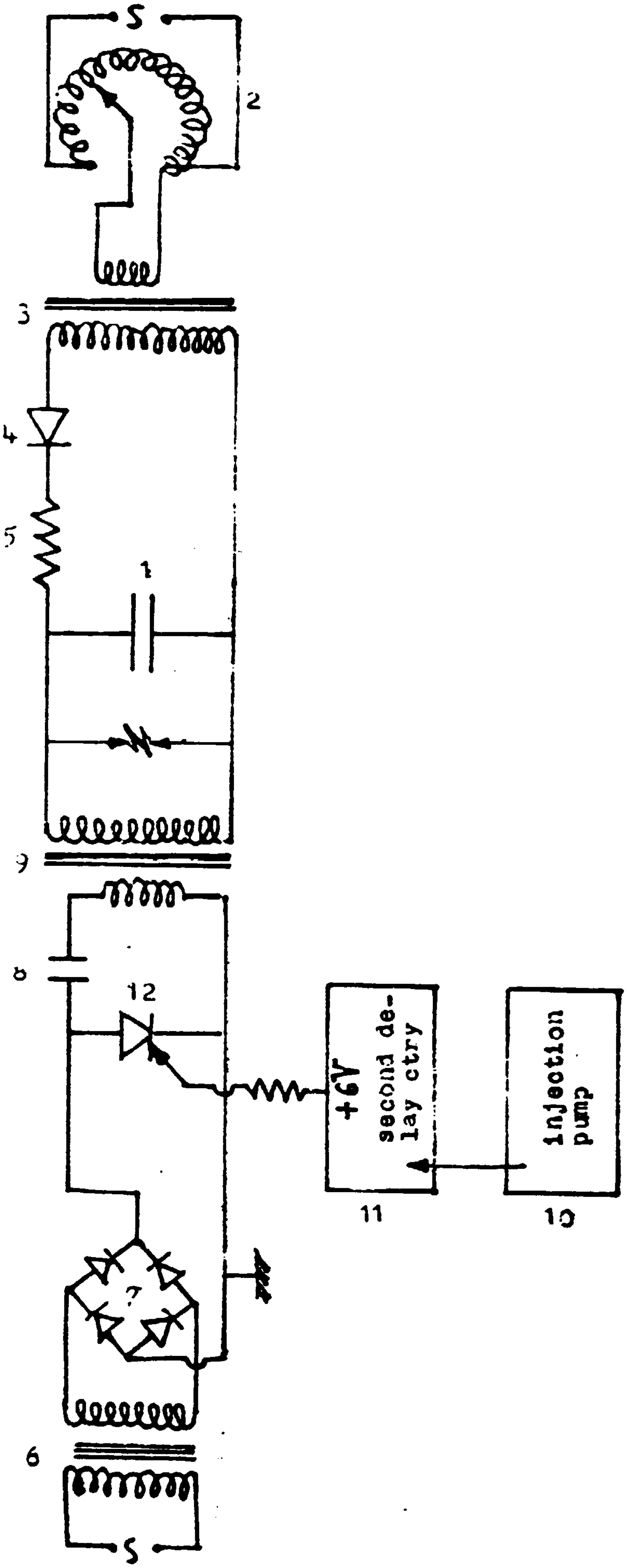
AT NORMAL PRESSURE
AND TEMPERATURE

Figure 3



B = sliding plate into which the injector is fixed.

Figure 4



ANNEX 4

Schedule of lectures on fundamental combustion phenomena related to engines

25 Nov. 1985 (3.30 to 5.00 p.m.)
Kinetics of combustion chemistry

26 Nov. 1985 (11.00 a.m. to 0.30 p.m.)
Kinetics of combustion (continued)

16 Dec. 1985 (11.00 a.m. to 1.00 p.m.)
Kinetics of combustion (continued)

17 Dec. 1985 (10.00 to 12.00 a.m.)
Selfignition : calculation of ignition temperature and ignition delays.

19 Dec. 1985 (3.00 p.m. to 4.30 p.m.)
Self-ignition (continued) : experimental determination of ignition temperatures and delays. Effects of pressure mixture composition and walls on ignition temperatures and delays.

20 Dec. 1985 (11.00 a.m. to 0.30 p.m.)
Self-ignition (continued) : role of self-ignition in the phenomenon of engine knock: relation between ignition delay and octane number.

23 Dec. 1985 3.00 p.m. to 4.30 p.m.)
Deflagration : steady state flame propagation ; definition, calculation and experimental measurement of flame speed.

24 Dec. 1985 (11.00 a.m. to 0.30 p.m.)
Deflagration (continued) : diagnostics by laser tomography method. Effects of composition, temperature and pressure on flame speed. Flammability limits; theire dependence on dilution and pressure and temperature.

26 Dec. 1985 (3.00 p.m. to 4.30 p.m.)
Confinements effects on flame propagation in the steady state : flame quenching, theoretical and experimental approach. Spark ignition.

27 Dec. 1985 (11.00 a.m. to 0.30 p.m.)

Spark ignition (continued): minimum ignition energy; effects of gasdynamics and confinement on spark energy and on critical ignition energy. Flame propagation in early stages (non steady state conditions) : effects of spark energy on flame speed.

30 Dec. 1985 (3.00 p.m. to 4.30 p.m.)

Flame propagation in early stages (continued): turbulence induced statistical dispersion of flame speed.

31 Dec. 1985 (11.00 a.m. to 0.30 p.m.)

Flame propagation in early stages (continued) : effects of flow gradients on early flames ; effects of geometrical and gasdynamical stretch on mass burning rate under either adiabatic or non adiabatic conditions.

1 Jan. 1986 (3.00 p.m. to 4.30 p.m.)

Flame propagation in early stages (continued) :
Effects of gasdynamical stretch, coupled with non adiabatic wall effects, in early stages.
Effects of local flow and composition heterogeneities on mass burning rates in early stages.

2 Jan. 1986 (3.00 p.m. to 5.00 p.m.)

Pollution due to combustion :
Soot formation and poly-aromatic hydrocarbons formation in the gas phase. Formation of carbonaceous residus (cenospheres) during combustion of heavy residual fuels.

3 Jan. 1986 (3.00 p.m. to 4.30 p.m.)

Pollution due to combustion (continued) : Formation of Nitric oxides; gas phase mechanisms of NO formation : thermal NO mechanism; fuel-NO mechanism; "prompt" -NO mechanism; relative importance of temperature and oxygen concentration.

6 Jan. 1986 (3.00 p.m. to 4.30 p.m.)

Formation of nitric oxides (continued) : Heterogeneous nitric oxide reduction mechanisms on flame born solid particles (soot, char, ashes, coal) ; Effects of natural and artificial charge stratification on nitric oxide formation in the cases of free expanding flames (engines), stabilized flames and diffusion flames; effects of turbulence induced temperature and composition fluctuations on nitric formation rates.

7 Jan. 1986 (3.00 to 4.30 p.m.)

Formation of nitric oxides (continued) : Nitric oxide diagnostic methods.

Emissions of aldehydes and partial burnt hydrocarbons from internal combustion engines.