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6 November 1987
ENGLISH

APPLICATION OF ALTERNATIVE FUELS FOR INTERNAL COMBUSTION ENGINES, IIP, DEHRA DUN

DP/IND/82/001/11-04

INDIA

Technical report: Basic study on ignition behaviour of methanol, related to the onset of combustion in methanol fueled two-stroke S.I. engines and C.I. engines*

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. Gerard de Soete, expert in combustion studies in C.I. engines

Backstopping officer: H. Seidel, Engineering Industries Branch

United Nations Industrial Development Organization

Vienna

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V.87 91523

EXPLANATORY NOTES

* Value of local currency during the period of the mission:
  1 U.S. Dollar = 12.90 Rupees

* Unusual technical abbreviations and acronyms :
  I.I.P. = Indian Petroleum Institute (Dehra Dun, India)
  C.I. = compression ignition
  D.P.G. = delayed pulse generator
  H.E. = high energy
  L.E. = low energy
  P.M. = photo multiplier
  S.I. = spark ignition

ABSTRACT

Title :Basic study on ignition behaviour of methanol, related to the onset of combustion in methanol fueled two stroke S.I. engines and C.I. engines.

The activities during that three-week return mission have been :

1. The first part of the study, related to the ignition of methanol vapor/air mixtures by hot combustion products, being in progress, the hitherto obtained results have been discussed. Proper interpretation of these results needs (1) some complementary experimental checks, which have been effectuated during the mission, and (2) urgent installation and finalisation of the optical visualisation equipment (Shadow-cinematography and photomultiplier measurements) which until now are not operational.
   That part of the study, already well advanced, is to be continued.
2. As to the second part of the study, related to spark assisted ignition of liquid methanol sprays, a detailed research programme has been outlined and discussed with the counterpart staff. The hardware parts, required for the adaptation of the rig to that second phase, should be prepared or ordered as soon as possible.

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INTRODUCTION

As outlined in the previous reports (references 1 and 2), the GENERAL PROJECT ACTIVITY is to carry out research and development work on automotive C.I. engines, stationary C.I. engines and small two stroke S.I. engines, allowing application of alcohols as replacement fuels. In support to the applied part of the project activity, it has been agreed to start a fundamental sub-activity, aiming at the understanding of some typical methanol combustion phenomena playing a role in the engine, at the Engines Laboratory of the I.I.P. in Dehra Dun.

During the expert's first mission in November 85/January 86 (see reference 1), one of the tasks precisely consisted in preparing the concept, construction and equipment of an experimental rig for the investigation of the following basic phenomena :

1. Auto-ignition of premixed alcohol vapor/air mixtures by hot gases, simulating the hot residual gases of the two stroke S.I. engine.
2. Ignition of liquid methanol sprays by H.E. sparks, as related to the phenomenon of spark (or glow plug) assisted ignition in the four stroke C.I. engine.

At the end of that first mission, a detailed construction and equipment outline was handed to the counterpart staff (see reference 1, appendix 3) and a tentative calendar of finalisations was established in common agreement with the counterpart staff.

Substantial retard having been accumulated in 1986 in the manufacturing of the rig, the expert's second mission in November/December 86 (see reference 2) mainly consisted in the following tasks :

* Assist the counterpart staff in order to implement the assembly of the experimental rig and its equipment
* Define a detailed outline of the trials constituting the research programme for the first part of the study (ignition of methanol/air mixtures by hot gases)

* Make instrument calibrations and start the preliminary trials.

At the time of the expert's <u>third mission</u> (i.e. the actual one) the research work relative to the first part of the study (ignition of methanol vapor/air mixtures by hot gas) had already acceptably well progressed, with only a small retard with respect to the calendar fixed in reference 2. During the present mission, the expert's activities mainly consisted in

* Discussion with the counterpart staff of the hitherto obtained results.
* Performance of some experimental checks needed for proper interpretation of the results
* Giving guidance for the set up of the optical bench for laser-shadowgraphic visualization of the combustion phenomena
* Redaction of a tentative research programme for the execution of the second part of the experimental study relative to spark assisted ignition of liquid methanol sprays.

As far as the first part of the study (which is now in progress) is concerned, the trials suffer from the fact that an important part of the measuring equipment is still not available (especially : the absence of a high voltage power supply for the use of a P.M., as well as a suitable camera for shadowgraphy recording - the existing one being shipped abroad for repair).

RECOMMENDATIONS

1. Recommendation adressed to the Direction of the Indian Institute of Petroleum.

Notwithstanding the fact that the financial support granted by Project DP/IND/82/001 has come to an end, the execution of the already well started and reasonably progressing basic research programme related to the use of methanol in engines should be supported and continued. Main motivation is the necessity to acquire good understanding of engine related methanol combustion phenomena as a condition for the optimisation of specific technologies aiming at increased use of methanol as an alternative fuel. In this phase of basic, parametric "upstream" research, the Engines Laboratory of I.I.P. can play a leading role.

2. Recommendations addressed to the Project Coordinator and to the research staff of I.I.P.'s Engines Laboratory.

2.1. To grant the quality of the research and to improve the interpretation of the findings, as well as to avoid unnecessary waistes of time, an effort should be made to implement as soon as possible the optical equipment, especially with respect to the use of a photomultiplier and a fast framing camera.

2.2. To ensure a start without delay of the second part of the study, related to spark assisted liquid methanol spray ignition, a suitable high energy spark circuitry should be ordered or constructed as soon as possible.

2.3. The adaptation of the experimental rig for the execution of that second part of the study cannot be finalised before the end of the trials of the first part. However substantial gain in time can be made upon preparing in advance the hardware parts required for that transformation.

2.4. As a general rule, whenever parts of equipment have to be ordered in foreign countries, and especially when ordered in the consultant's country, it is recommendable to send copies of the orders to the consultant's office. This will enable him to prompt the execution of these orders according to the calendar given by the manufacturer, which may result in avoiding unacceptable long delays of delivery.

I. MAIN DUTIES OF THE JOB

A. General Job description

In 1985 the expert had been asked to assist the research team of the Engines Laboratory of I.I.P. in the following :

1. Consultation and advice on the establishment of an experimental testrig for basic studies on alcohol combustion related to two stroke S.I.engines and four stroke C.I. engines.
2. Guidance on research activities related to combustion studies in the engine, including high speed photography.
3. Training on fundamental combustion as applied to engines.

Whereas tasks 2 and 3 mainly have been executed during the expert's first mission in November 1985/January 1986 (see reference 1) task number one., by far the most extensive, has constituted the partial objective of the first mission and the exclusive objective of two further missions : one in November/December 1986 and the present one in October 1987. For more clarity, we provide in what follows a short overview of the evolution of the subject of task one :

a) <u>During the first mission</u> :

** the expert defined , in agreement with the counterpart staff, the objectives of basic study, comprising two parts :

- PART I : Investigate the ignition behaviour of premixed methanol vapor/air mixtures by hot gases. Determine the limiting temperature and pressure conditions of selfignition, the selfignition delays as well as the relative burnout of the fuel. This first part of the study may throw some light on abnormal combustion modes of methanol appearing in two stroke S.I. engines.
- PART II : Investigation of the characteristics and optimization of spark assisted liquid methanol spray ignition, related to the onset of combustion in the C.I. engine.

** Detailed description was provided by the expert of the experimental rig to be constructed and the measuring techniques to be used (see reference 1, annex 3), in order to meet the two objectives of the study.

b)At the periode of the <u>second mission</u>

Substantial retard had been accumulated in the construction and outfitting of the rig and its preparation for the execution of the first part of the study.Therefore, the expert's activities were :

** Assistance to the counterpart staff in order to implement the assembly and the equipment of the experimental facility.It should be mentionned that, although at the end of that mission, the rig was functionnal and the trials could be started, its optical part of measuring equipment was still incomplete in that (a) the cinematographic high speed camera was out of order, (b) no laser had as far been ordered and (c) no high voltage Direct Current power supply was available for the P.M. Any way the trials of the first part of the study could at least be started.

** Redaction of a detailed research programme , describing the successive trial series to be run for the execution of <u>Part I</u> of the study(see ref.2, annex 3).

** Description of, and assistance for (a) calibration of the apparatus and the diagnostic techniques and (b) the preliminary trials of Part I of the experimental study.

At the end of that second mission, and apart from the optical complement of the trials, the first part of the study, relative to the hot gas ignition of methanol vapor/air mixtures, was ready to be run.

B. Status of the project at the beginning of the present mission

Although started with some retard with respect to the calendar established during the second mission, a fairly amount of work had already been done ; some hundred fifty individual trials had been effectuated, covering partly the work related to series A.1 and A.2 of the research programme (described in reference 2, annex 3). However some difficulties appeared to exist in the interpretation of the results, mainly related to (a) the relative imprecision of the ignition criterium (due to incomplete equipment) and (b) the fact that neither mass of methanol injected nor injection rates and durations had been determined.

As far as the optical equipment was concerned :
The fast framing camera was stillunder repair in the U.S.;
The D.C.power supply for the photomultiplier is still not available;
The laser (4 watt tunable argon ion laser, Spectra Physics) had arrived

C. Objectives of the activity being reported on

The objectives of the activity during the present mission appear as the logical consequence of the foregoing situation. They mainly consist in the following points :

a - Enable the research team to finalise the remaining trials making part of the first objective of the study (homogeneous methanol/air mixtures ignition) by :
  * discussion of the findings obtained until now
  * making some supplementary experimental checks to help the interpretation of the results
  * indicating improvements in the treatment of the results
  * Define the trial series still to be made for the implementation of part I of the study
  * Giving guidance for the realization of the optical bench for laser-shadowgraphic visualization of the ignition phenomena.

b - Prepare the start of part II of the study, related to liquid methanol spray ignition , upon giving detailed outlines of the research programme relative to it.

II. TECHNICAL ACTIVITY

The expert joined I.I.P. on Friday 2nd October and left it on Tuesday 20th October 1987 (see Traveling Schedule in Annex 1)
His contacts at I.I.P. were mainly with the UNDP Project coordinator and with the research team of the Engine Laboratory , especially with Mr M.Abraham (see Annex 2 : Senior Counterpart staff).

A.Discussion of the hitherto obtained results

The trials effectuated hitherto suffer from the incompleteness of the measuring equipment, this situation making their proper interpretation difficult if not impossible. Indeed, since neither shadowgraphic visualization nor Photomultiplier output is available until now, the only possibilities to track selfignition of the methanol/air mixture is (1) the pressure/time evolution and (2) the variation of the burnt fraction F_b as a function of temperature and pressure. Actually a light emission time track, although available from a photoresistor does not reveal the slightest signal ; this does not prove the non existence of light emission (linked to ignition) but occasionally only shows the sensitivity of a low voltage phototransistor not to be sufficient to detect the light emission (already relatively weak in the case of alcohols) accompanying ignition of the mixture.

1- The observed pressure/time track

Even when injection is effectuated into a relatively hot gas (1000 to 1300 K), the oxidation of the methanol/air mixture does not cause a sharp contrated pressure rise which could be used as the indication of selfignition and from which an ignition delay δ could be determined (see reference 2, figure 9).

Figure 1 shows a typical example of the measured pressure/time evolution with and without injection. 's injection starts,one observes an increase of the pressure (compared to the one that is measured without injection) due to one or both of the following factors:

* the progressive increase of mass in the reactor (that partial pressure however is partly compensated by the cooling effect of the injected mixture, see Annex 3, equation 3.3);
* the heat release and subsequent temperature increase due to oxidation of the methanol.

To some extent at least, there always occurs some oxidation, as shown by the measured values of F_b (see next point). The absence however of a less or more sharp pressure rise (like it is usually observed for selfignition of homogeneous hydrocarbon/air mixtures) tends to indicate that we are not dealing here with a clearly defined, sudden combustion affecting the whole methanol/air mixture at the same time. One should remind, that ignition does not consist in a transition from "no reaction", but in the transition from slow oxidation to fast oxidation (or combustion).

2- The variation of F_b with temperature

The same lack of clear-cut transition between slow and fast oxidation of the methanol/air mixture is shown by the variation of the fraction burnt (F_b) as a function of the temperature and pressure of the hydrogen combustion products. We like to remind, that the hot gases into which the methanol/air mixture is injected, are obtained by the combustion of hydrogen/oxygen/nitrogen mixtures and that therefore the pressure (P_v) at the start of ignition and the temperature (T_v) are linked to each other as well as to the adiabatic combustion temperature of the hydrogen mixture (T_{ad})(see reference 1, Annex 3).

The adiabatic combustion temperature T_{ad} is supposed (as usually done) to affect homogeneously the combustion products at the end of combustion , i.e. at the moment the pressure reaches its maximum value (P_{max}) ; its value is used to estimate the subsequent temperature values by a first approximation relationship :

$$T = P.T_{ad}/P_{max} \quad (1)$$

as has been discussed in reference 2. The value of T_{ad} should be determined with some precision, e.g. by calculation using an appropriate computer programm taking into account that pressure is varying during combustion. Although such a computer programme is available at I.I.P., no values of T_{ad} have been computed in that way until now. Therefore, in what follows we shall use approximate values of T_{ad} , computed for constant pressure combustion, the reactants being at standard pressure and temperature. The thus calculated values are somewhat too low, and should be corrected in the future by the mo appropriate computation. For the hydrogen/oxygen/nitrogen mixtures utilised in part I of the study, these approximate values are given on figure 2.

The fraction burnt is calculated from the CO and CO2 formed, according to equation (@.13) of Annex 4. Typical examples of F_b/temperature curves are provided on figures 3 and 4.

* Figure 3 relates to the case where total injection of the methanol/air mixture has been used. By "total" injection one should understand here, that the injection valve has been closed after egality of the pressure in the reactor and in the injection cylinder has been obtained . In that case a maximum fraction of the initial amount of methanol/ air mixture (α) has been injected. For the determination of α see Annex 3. Under these conditions, the injection duration is normally quite long, which bears as consequence
  a) that the oxidation of the methanol/air mixture is "distributed" over a relatively long time, since it is

controlled by the injection rate and duration. The injection rate (D_i) strongly decreases with time (see figure 3.5 of Annex 3).

b) the temperature in the reactor varies substantially between the start and the end of the injection ; therefore it is difficult to define a meaningful value of a "mean" temperature $\overline{T}$ between start and end of the injection.(For that reason, the temperature at the start of injection, T_v, has been plotted on the abscissa of figure 3)

* Figure 4 relates to the case of constant duration injection, the injection valve being closed after a preset injection duration t*. Apparently the advantage here is the possibility to select short injection durations, avoiding thus occasionally the methanol oxidation to be controlled by the injection rate and duration. Trials of that type had not been madebefore but only during the mission.

Whether the methanol/air mixtures oxidation is controlled by the injection rate or not , it any way is at least partly controlled by its mixing with the hot gases , which (1) controlls the heating up of the methanol/air mixture but (2) at the same time imposes a severe dilution on the latter.

From figures 3 and 4 one deduces the following features of the methanol oxidation :

a) The fraction of methanol burnt (F_b) increases with temperature of the hot gases. Figure 4 shows a continuous increase, whereas figure 3 shows a sudden and important change in the slope $d(F_b)/dT$, which might be related to a transition from slow oxidation to combustion, i.e. ignition.

b) The ratio CO/CO_2 in the methanol combustion products passes by a maximum : increasing first with increasing combustion efficiency, it drops rapidly to small values when F_b approaches unity.

B. Improvements and complementary checks

From the discussion of the already performed trials and the experimental scenario used, it became clear that there was a need for (1) some complementary experimental checks and calculations and (2) some important improvements and implementations of the experimental rig.

1- Experimental checks and calculations

a) Looking for the possibility of detecting sharp cut ignitions, it was decided to utilise less diluted hydrogen/oxygen/nitrogen mixtures (compared to the ones that have been proposed on table 2, annex 3 of reference 1) in order to reach higher temperatures and pressures in the combustion products.

b) It was also decided to use preferentially constant duration injection, for reasons explained in Section A.

c) A theoretical and experimental investigation has been carried out to get information on the injection duration as a function of reactor pressure and temperature, the injection rate as a function of time, and the fraction of methanol/air mixtures injected as a function of injection duration.
The details of the procedure and the results of that investigation are given in Annex 3.

d) Calculation of more precise values of combustion temperatures of the utilised hydrogen/oxygen/nitrogen mixtures will be made by the counterpart staff, using an appropriate computer programme accounting for pressure variations.

2- Improvements and implementations

a) The general scenario followed in all trials implying the previous compression of the methanol/air mixture in the cylinder prior to the opening of the solenoid injection valve, a preheating of the cylinder up to about 70°C has been installed to prevent any condensation of the methanol vapour during compression.

b) A very necessary implementation will be the acquisition of a suitable high voltage direct current power supply, suitable for the utilisation of the photomultiplier. A sensitive emission pick-up probe seems indeed to be indispensable to judge about the nature of ignition. Inquiries as to the availibility of this kind of power supply have already been made.

c) During the present mission, the optical bench for shadowgraphic visualization, comprising a 4 watt tunable argon-ion laser and an a-focal lenses system has been set up. Advice for installation and use has been given.

However, the visualization still requires the return of the fast framing movie camera, which has been sent abroad for repair.

d) The infra red analysers of CO and CO_2, actually used, present a rather coarse sensitivity, too coarse indeed to ensure sufficient precision in the determination of the burnt methanol fraction. It appears that, at least in a next future, no substantial improvement can be expected in that matter.

C. Future trials previsions (of part I)

Taking into account the research programme outlined earlier (see reference 2, annex 3), the experimental results obtained hitherto, as well as the slight retard in the execution of part I of the study, previsions have been discussed with the counterpart staff. Apart from the continuation of the actually ongoing trials aiming at the effects of temperature, equivalence ratio of the methanol/air mixtures and the quantities of them injected, the effects of the following parameters should be preferentially looked at :

* The compression ratio in the injection cylinder. Increasing the end pressure ($P_{i,e}$) results in faster injection rates and faster turbulent mixing with the hot gases. The endpressure $P_{i,o}$ may be increased by increasing the total volume of the injection cylinder or by decreasing the endvolume after compression.
* The comparison with hydrocarbon ignition.
  Trials having shown relevant effects of one or more of the variable parameters during methanol/air injection, should be duplicated with hydrocarbon/air injection for the sake of comparison.
  In order to simplify the calibration procedure of the injected mixtures, a gaseous hydrocarbon (butane, propane) could be utilised.

In principle these trials may be executed before the rig has been completed for P.M. measurements and shadowgraphic visualization. However, as soon as these complementary equipments are operational, they should be utilised. Moreover, relevant trial series effectuated earlier without these equipments, should be duplicated with them, to gain better understanding of those earlier results.

D. Tentative research programme for part II of the study

The preparation of part II of the basic study, related to spark assisted liquid methanol spray ignition, has been pursued on two levels during this mission.

1. Adaptation of the experimental rig

As explained in reference 1, annex 3, the same basic equipment and rig, already in use for part I of the study, will be utilised for part II. Notwithstanding that, some important adaptations have to be made ; they have been discussed from a practical point of view with Mr Mathew Abraham. Mainly these modifications relate to the following items :

a) The liquid methanol injection device

It comprises a conventional high pressure injector completed with an injection pump and liquid methanol feed-line. Since single stroke injection is required, the injection pump should preferentially be actuated by an electromagnetic plunger. The pump should be chosen in such a way as to ensure the injection of variable quantities of methanol, resulting in overall equivalence ratios comprised between about 0.25 and 1.

b) The high energy spark circuit

The circuit required to feed the high energy spark of at least one joule effectively, should allow for continuous or discontinuous variation of the spark energy (E_s) , for example upon changing the capacity. It may be either constructed at I.I.P. according to the general schema provided on figure 4 of reference 1, or ordered from one of the two following addresses :

1) Electronic Hard Logiciel
30, rue Gounod
93290 Tremblay-les-Gonesses, France

2) EYQUEM
1, rue Lavoisier
92009, Nanterre, France (telex : 612622 F)

In the latter case, and since we have to deal with non current commercialized equipment, the Counterpart staff may usefully pass its order through the intermediate of the expert, who shall then be able to indicate the specifications to the constructor and follow up the order.

c) Spark location with respect to injector.

Unlike indicated in figure 3 of reference 1 and more conveniently with respect to the possibility of visualization of the ignition phenomena, sparkplug and symetry axis of the injector should be located in the same transversal section of the main reactor , preferentially in the middle section (there where the gas injection nozzle is actually located).The radial position of the spark gap, with respect to the symetry axis of the injector, should be variable between zero and the radius of the main reactor.

d) A schematic representation of the general scenario of a typical trial, together with indications of the different time lags, is given on figure 4.1 of Annex 4.

2. Outline of the research programme for part II

A tentative research programme for the execution of part II of the study has been elaborated, the details of which may be found in Annex 4. It provides informations on calibrations to be made, calculation of the composition of the hydrogen/oxygen/nitrogen mixtures to be used in order to create the "synthetic" air, the measurements to be made, the parameters to be varied, and outlines to some extend the different series of trials to be performed.

III.CALENDAR

Actually like things are for the moment, it is not easy to foresee deadlines for the execution of the different parts of the work to be done in the forthcoming months.

The time needed for the execution of each of these parts may be roughly estimated as :

1) implementation of the trials constituting the continuation of part I of the study : approx. 3 months
2) adaptation of the rig for the second part of the study, including calibrations and preliminary trials : approx. 2 months
3) Run the trial series of part II of the study : approximately 5 months.

However, at least two of these three tasks cannot be executed in a continuous way :

* Implementation of the remaining trials of part I depend strongly on the delays of getting the camera and the P.M.power supply ready.
* The adaptation of the experimental rig will have to

"wait" on the ordering and the delivery of the H.E. spark circuit.

It is to say that a compromise should be found between what "is" to be done and what "can already" be done... For example : although the rig cannot be transformed before the end of the trials of part I (including the duplicated trials with visualization), it is clear that hardware parts required for that transformation already can be ordered or constructed.

IV. CONCLUSIONS

1. After a rather long retard accumulated in the construction of the experimental rig, the research work relative to part I of the study (ignition of methanol/air mixtures by hot gases) has started and is already reasonably well advanced.
2. Unfortunately, the optical measuring equipment being still incomplet (fast framing camera being under repair abroad), many of the trials effectuated hitherto still bear a provisorious character , thence are difficult to interprete and need to be duplicated upon the arrival of the optical items.
3. Some improvementsof the experimental method have shown to be needed and most of them have already been effectuated during this mission.
4. Preparation of part II of the study, related to spark assisted liquid methanol spray ignition has been updated. The research programme relative to this second part has been outlined in detail.
5. As far as the next future is concerned : the continuation of the trials of part I, the adaptation of the rig for the second part of the study and the execution of the trials of that second part, will require a compromise between successive and simultaneous actions . In that respect the expert would like to insist on the necessity

to start without delay the construction or ordering of a suitable H.E. spark circuitry and to obtain a power supply for the Photomultiplier.

6. Last but not least at all, a very important remark. The execution of the basic research programme related to the use of methanol in engines is well on its rails. At the same time , the financial support granted by Project DP/82/001 has stopped. It is not of the experts competence to find or to indicate new ressources for the continuation and implementation of this research programme. But it is part of the experts duties to throw the attention of the Direction of I.I.P.,once more, on the importance to continue that type of basic investigation in order to acquire good understanding of engine related methanol combustion phenomena as a condition for the optimization of specific technologies aiming at increasing use of methanol as an alternative fuel.

V. REFERENCES

1. G.G.de Soete,"Establishment of suitable technologies for the use of methanol in two stroke S.I. engines and in C.I.engines", Report of first mission of the expert (in November 1985/January 1986). Project DP/IND/82/001.
2. G.G.de Soete,"Applications of alternative fuels for internal combustion engines", Technical report of the second mission (November/December 1986),Project DP/IND/82/001.
3. Van Tiggelen, A. and Coworkers, "Oxydations et Combustions", Editions Technip, Paris, 1968, Vol.I, Chapt.1., fig.8.

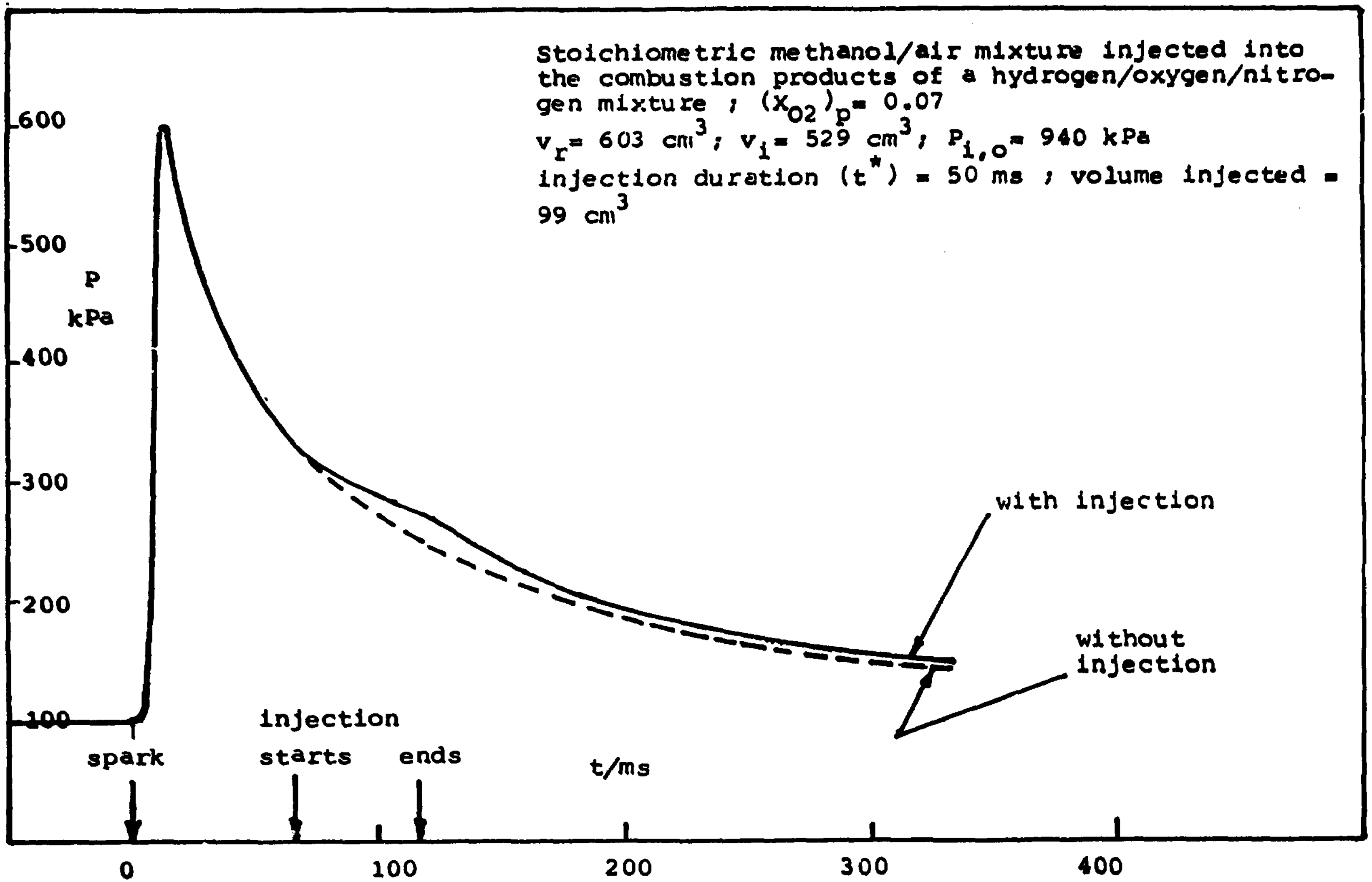

Stoichiometric methanol/air mixture injected into the combustion products of a hydrogen/oxygen/nitrogen mixture ; $(X_{O2})_p$ = 0.07
v_r = 603 cm^3 ; v_i = 529 cm^3 ; $P_{i,o}$ = 940 kPa
injection duration (t^*) = 50 ms ; volume injected = 99 cm^3
P
kPa
600
500
400
300
200
100
with injection
without injection
injection
spark
starts
ends
t/ms
0
100
200
300
400

Figure 1

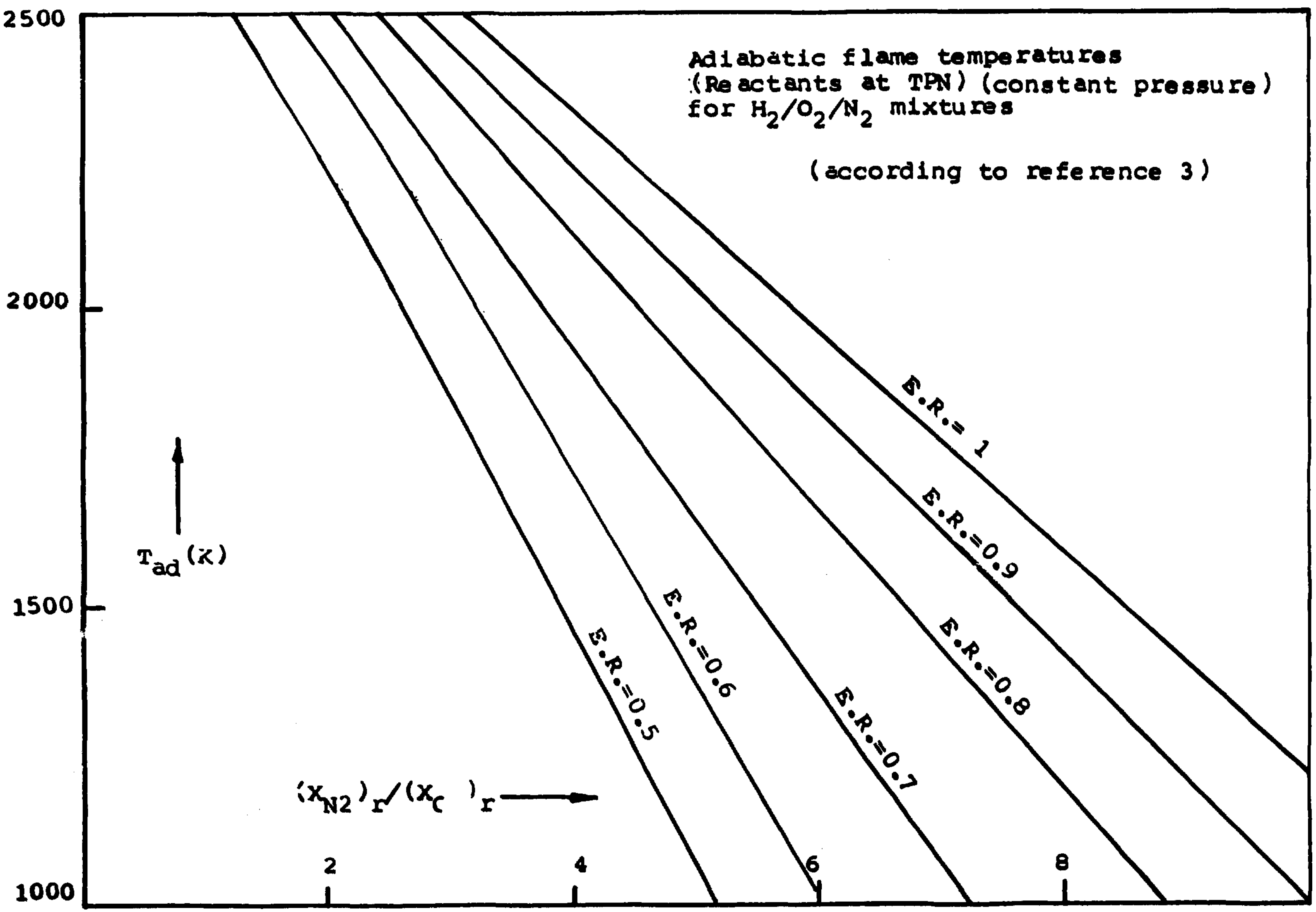
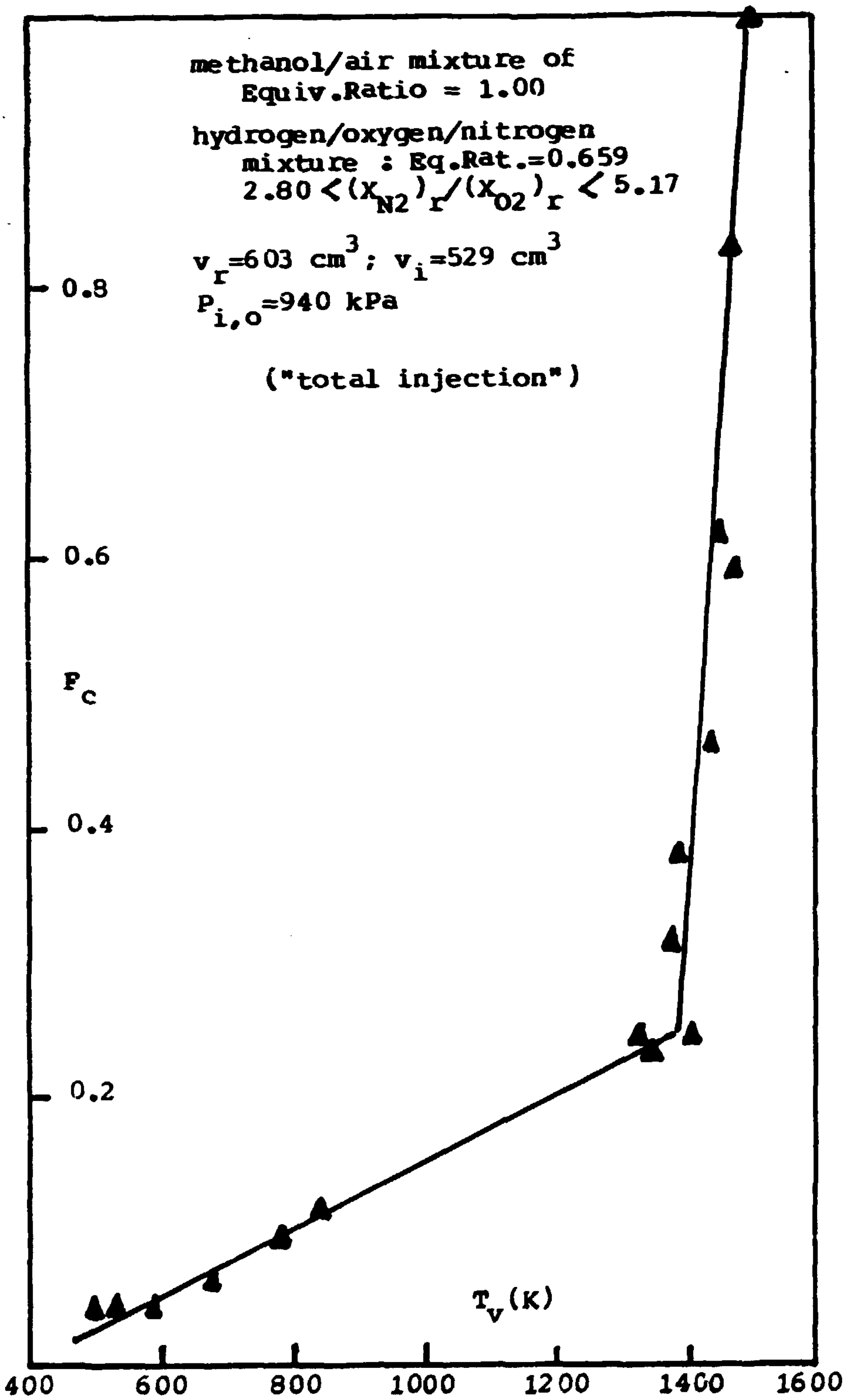
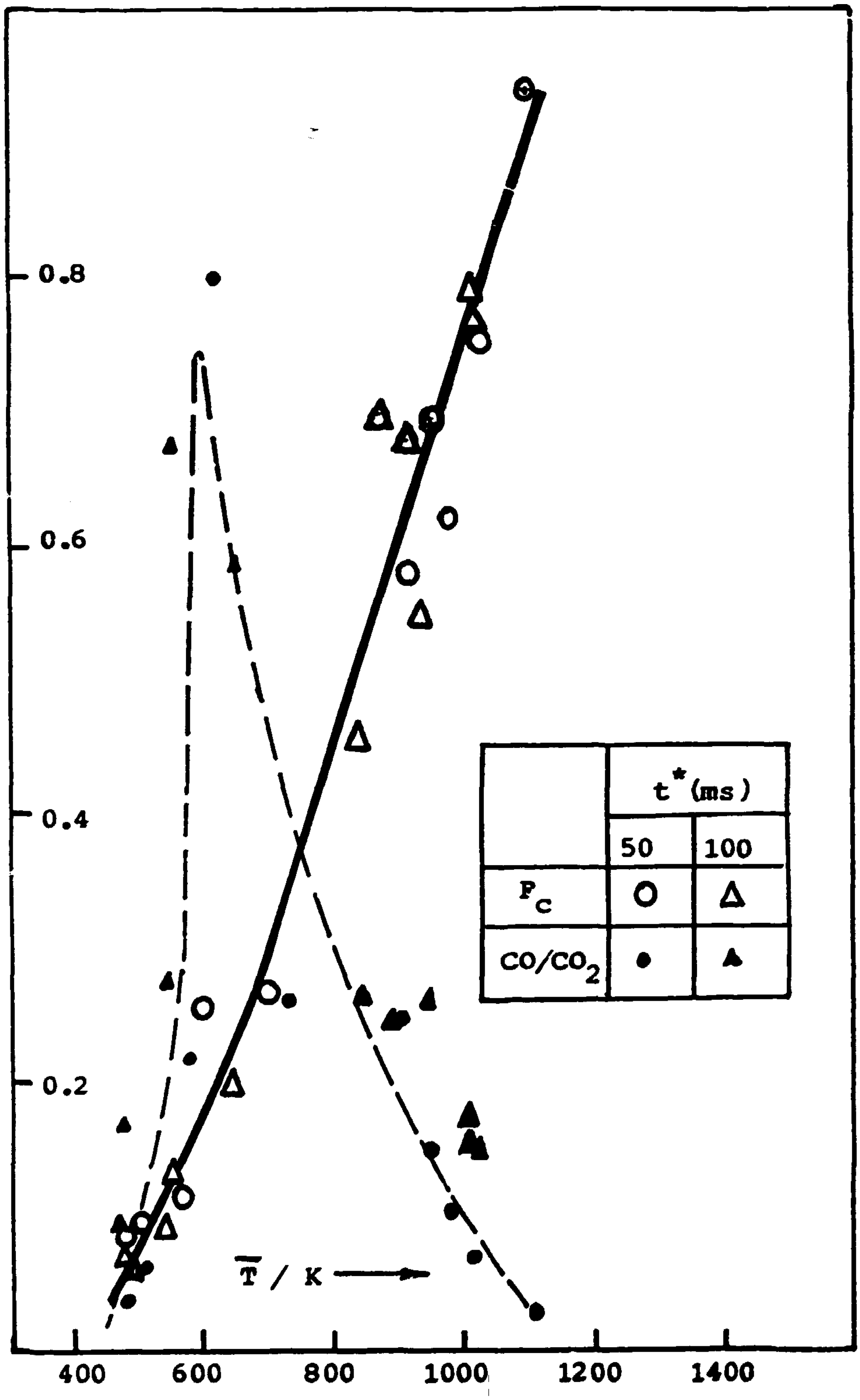

Adiabatic flame temperatures
(Reactants at TPN) (constant pressure)
for $H_2/O_2/N_2$ mixtures
(according to reference 3)
2500
2000
1500
1000
T_{ad}(K)
E.R.= 1
E.R.=0.9
E.R.=0.8
E.R.=0.7
E.R.=0.6
E.R.=0.5
$(X_{N2})_r/(X_C)_r$
2
4
6
8

Figure 2

Figure 3


methanol/air mixture of
Equiv.Ratio = 1.00
hydrogen/oxygen/nitrogen
mixture : Eq.Rat.=0.659
2.80 < $(X_{N2})_r/(X_{O2})_r$ < 5.17
v_r=603 cm^3; v_i=529 cm^3
$P_{i,o}$=940 kPa
("total injection")
F_c
0.2
0.4
0.6
0.8
T_v(K)
400
600
800
1000
1200
1400
1600



(constant duration injection; mixture compositions as in figure 3)

ANNEX 1

Traveling Schedule

Departure from Paris on 30 September 1987 at 0.15 p.m. by flight AF 174 to Delhi.

Arrival in Delhi on 1 October 1987 at 3.35 a.m.

Briefing in Delhi at U.N.D.P. on 1 October 1987.

Departure from Delhi on 2 October 1987 at 7.10 a.m. by flight PF 103 to Dehra Dun.

Arrival in Dehra Dun on 2 October 1987 at 8.00 a.m.

Departure from Dehra Dun on 20 October 1987 at 8.10 a.m. by flight PF 104.

Arrival in Delhi on 20 October 1987 at 9.00 a.m. Debriefing.

Departure from Delhi on 21 October 1987 at 1.00 a.m. by flight AF 181 to Paris.

Arrival in Paris on 21 October 1987 at 8.30 a.m.

ANNEX 2

Senior Counterpart Staff

Except for Mr C. Ramachandran, who has retired since last year, no changes have occured in the Senior Counterpart Staff of the Engines Laboratory of I.I.P., the Head of which is Mr Sudhir Singhal.

An organisatory change occured in 1987 concerning the attribution of particular responsibilities : the three permanent Groups (Combustion and Emissions / Field and Performance studies / Lubrication and Tribology) have been replaced by "floating" groups constituted according to the research needs and comprising the competent people for the execution of a given task.

The Senior Counterpart Staff is actually constituted as follows :

Mr Sudhir Singhal (Head of the Laboratory)
Dr B.P.Pundir (Project Coordinator)
Mr M. Abraham
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ANNEX 3.

Characterisctics of the methanol/air mixture injection

Proper interpretation of the combustion behaviour of the methanol/air mixtures, supposes the injection characteristics (fraction injected, injection velocity, duration, etc) to be known, at least in a qualitative manner. In the case of the present experimental trials, a precise a-priori calculation of these characteristics is not possible, mainly because the pressure and temperature evolution in the reactor strongly depend on (1) heat losses to the walls and (2) heat released by the exothermic combustion during the injection itself. First approximation values of the injection characteristics may however been estimated upon neglecting the two latter phenomena, i.e., neglecting the heat losses during injection, and assuming the combustion not to start before the end of the injection.

Assuming the dissociation of the water vapour,obtained from the hydrogen combustion, to be negligibly small (which seems to be a reasonable assumption, owing to the relatively low combustion temperatures one is dealing with in the present trials), the temperature (T_v) at the moment (t_v) the injection starts may be calculated from the maximum pressure (P_{max}) achieved at the end of the hydrogen combustion, the adiabatic combustion temperature (T_{ad}) of the hydrogen mixture and the pressure (P_v) measured at t_v :

$$T_v = T_{ad} . P_v / P_{max} \qquad (3.1)$$

Before opening the injection valve, the pressure in the injection cylinder is $P_{i,o}$ and the temperature ambient (T_o). Assuming isothermal expansion of the injected gases and almost instantaneous mixing of these gases with the hot combustion products of hydrogen, one may estimate the temperature (T_r) and pressure (P_r) in the reactor, corresponding to a given fraction α_t injected at a time t after t_v.

Designating by:

v_r the volume of the main reactor

v_i the volume of the injection cylinder before compression , i.e. the volume of the methanol/air mixture at TPN.

d_r volumic mass of the hydrogen combustion products at T_v and P_v

d_{ro} (the same at TPN), thus $d_r = d_{ro}\ T_o\ P_v/T_v\ P_o$, the subscript "o" indicating standard conditions

d_{io} volumic mass of the methanol/air mixture at T_o and P_o

c_r and c_i : heat capacity of the hydrogen combustion products, respectively the methanol/air mixture considere as constant and identical

the temperature T_r may be written as :

$$T_r = \frac{v_r\ d_r\ c_r\ T_v + \alpha_t\ v_i\ d_{io}\ c_i\ T_o}{v_r\ d_r\ c_r + \alpha_t\ v_i\ d_{io}\ c_i} \qquad (3.2)$$

Since both mixtures are highly diluted by nitrogen , one may further assume that $d_{ro} = d_{io}$, thus :

$$T_r = \frac{(v_r\ P_v/P_o) + \alpha_t\ v_i}{(v_r P_v/P_o T_v) + (\alpha_t v_i/T_o)} \qquad (3.3)$$

Neither heat losses nor heat release being assumed to take place after injection starts, the ratio P_r/P_v is given by the following expression :

$$P_r/P_v = T_r\ n_r/n_v\ T_v \qquad (3.4)$$

where n_v and n_r are the numbers of molegrammes in the reactor, respectively at t_v (corresponding at P_v and T_v) and at t (corresponding at P_r and T_r):

$$P_r/P_v = \frac{(v_r P_v T_o/P_o T_v) + \alpha_t\ v_i}{v_r P_v\ T_o\ /\ P_o T_v} \times \frac{T_r}{T_v} \qquad (3.5)$$

Substitution of eq.(3.3) into eq.(3.5) yields :

$$P_r = \frac{\left[(v_r P_v T_o/P_o T_v) + \alpha_t v_i\right]\left[(v_r P_v/P_o) + \alpha_t v_i\right]}{(v_r T_o/P_o)\left[(v_r P_v/P_o T_v) + (\alpha_t v_i/T_o)\right]} \qquad (3.6)$$

which, upon substitution of eq.(3.1), may be resolved to yield the injected fraction α_t as a function of P_v, P_{max} and P_r :

$$\alpha_t = \left[B + (B^2 - 4AC)^{1/2}\right] / 2A \qquad (3.7)$$

with : $A = -v_i^{\,2}$

$$B = v_f v_i \left[(P_{max} T_o/P_o T_{ad}) + (P_v/P_o) - (P_r/P_o)\right]$$

$$C = (v_r^{\,2}\; P_{max} T_o/P_o^{\,2}\; T_{ad})(P_r - P_v)$$

When the pressure in the injection cylinder becomes equal to the pressure P_r in the reactor, the injection stops. The total fraction injected at that time will be designated by α. At that moment (t_e) the injection stops, the pressure in the injection cylinder is given by :

$$P_{i,e} = P_{i,o}(1 - \alpha) = P_{r,e} \qquad (3.8)$$

$P_{r,e}$ being calculated by eq.(3.6) upon substituting α_t by α .

From the identity of eqs (3.6) and (3.8), the total fraction injected (α) may be calculated as

$$\alpha = \left[-b + (b^2 - 4ac)^{1/2}\right] / 2a \qquad (3.9)$$

with : $a = v_i^{\,2} + (v_i v_r P_{i,o}/P_o)$ (3.10)

$$b = v_i v_r \left\{\left[(P_{i,o} + P_o) P_{max} T_o/P_o^2\; T_{ad}\right] - \left[(P_{i,o} - P_v)/P_o\right]\right\} \qquad (3.11)$$

$$c = -\, v_r^{\,2}\; P_{max}(P_{i,o} - P_v) T_o/T_{ad}\; P_o^{\,2} \qquad (3.12)$$

The ratio P_{max}/T_{ad}, appearing in eqs (3.11) and (3.12), is equivalent to the ratio P_v/T_v. Actually, the value of the temperature T_v does not affect that much the fraction α injected, as becomes clear from figure 3.1 , showing the dependence of α with respect to T_v for a given set of conditions.

The variation of the injected fraction α as a function of the pressure in the reactor during injection (i.e. P_v) is illustrated on figure 3.2 for a given ratio $P_{max}/T_{ad} = P_v/T_v$.

+ + +

Experimental determination of the injection duration and rate.

The mean flow rate (D_i) through the injection nozzle and the duration of the injection (defined as the time, $t_{95\%}$, required to introduce 95% of the total injected volume) have been determined as a function of the pressure in the main reactor in an experimental way.

The main reactor being filled with air at ambient temperature and an initial pressure $P_{r,o}$, pure air is introduced into the injection cylinder at normal pressure and temperature, then compressed to a pressure $P_{i,o}$ in an isothermal way. Opening the solenoid valve between the injection cylinder and the reactor,, injection is started at t=0 and the pressure evolution in the reactor is recorded on the cathode ray oscilloscope.

Both injected gas and reactor gas being at the same temperature T_o, equation (3.5) now simplifies as follows:

$$P_r = P_{r,o} + \alpha_t P_o v_i/v_r \qquad (3.13)$$

The volume injected at a given time t after the start of the injection, is thus obtained as :

$$v_i \alpha_t = v_r (P_r - P_{r,o})/P_o \qquad (3.14)$$

The instantaneous flow rate D_i , measured over a small span of time $(t_2 - t_1) = t$, is then given by :

$$D_i = v_i(\alpha_{t2} - \alpha_{t1})/(t_2 - t_1) = v_r(P_{r2} - P_{r1})/(t_2 - t_1)P_o \qquad (3.15)$$

Integration of eq.(3.15) over the time, offers an alternative method to calculate $v_i \alpha_t$.

During injection, the instantaneous value of the pressure (P_i) inside the injection cylinder is given by :

$$P_i = P_{i,o}(1 - \alpha_t) \qquad (3.16)$$

At the end of the injection, α_t becomes α and the pressures P_r and P_i are identical; from the identity of eqs(3.13) and (3.16) one then obtains the value of α as :

$$\alpha = (P_{i,o} - P_{r,o}) / \left[P_{i,o} + (P_o\ v_i/v_r)\right] \qquad (3.17)$$

The value of α calculated according to eq.(3.17) is shown on figure 3.3 as a function of $P_{r,o}$. Upon comparing figures 3.2 and 3.4 it may be seen that the values calculated in the cases of cold reactor gases and of hot reactor gases (respectively by equations 3.17 and 3.9) are not that much different.

The relative fractional part injected at a given time t after the injection started , α_t/α , is obtained from eq.(3.14):

$$\alpha_t/\alpha = (P_r - P_{r,o})/(P_{r,e} - P_{r,o}) \qquad (3.18)$$

and may thus be calculated as a function of time from the measured values of the reactor pressure at the start, during and at the end ($P_{r,e}$) of the injection; the ratio α_t/α is independent of the volumes v_i and v_r and of the pressure $P_{i,o}$.

Values of α obtained from the experimental values of $P_{r,o}$ and $P_{r,e}$ by the relationship (see equation 3.14)

$$\alpha = v_r(P_{r,e} - P_{r,o})/\ P_o\ v_i \qquad (3.19)$$

for different values of $P_{r,o}$, are compared to values of α calculated from values of $P_{r,o}$ and $P_{i,o}$ (according to equation

3.17) on figure 3.3. The experimental values of $P_{r,o}$, P_r and $P_{r,e}$ used for these calculations are shown on figure 3.4.

Figure 3.3 also shows the experimental values of the injection duration ($t_{95\%}$) as a function of $P_{r,o}$, the duration decreasing as expected when the injected fraction α.

On figure 3.5 the evolution of the experimental values of the injection rates D_i (as obtained from equation 3.15) is plotted versus the time for two different values of $P_{r,o}$. The section of the injection nozzle utilised in these experiments being equal to 0.159 cm^2 , the initial injection velocities are rather large (100 to 130 $m\ s^{-1}$). The penetration of the jet may therefore be relatively important. Only optical visualization would enable one to check that.

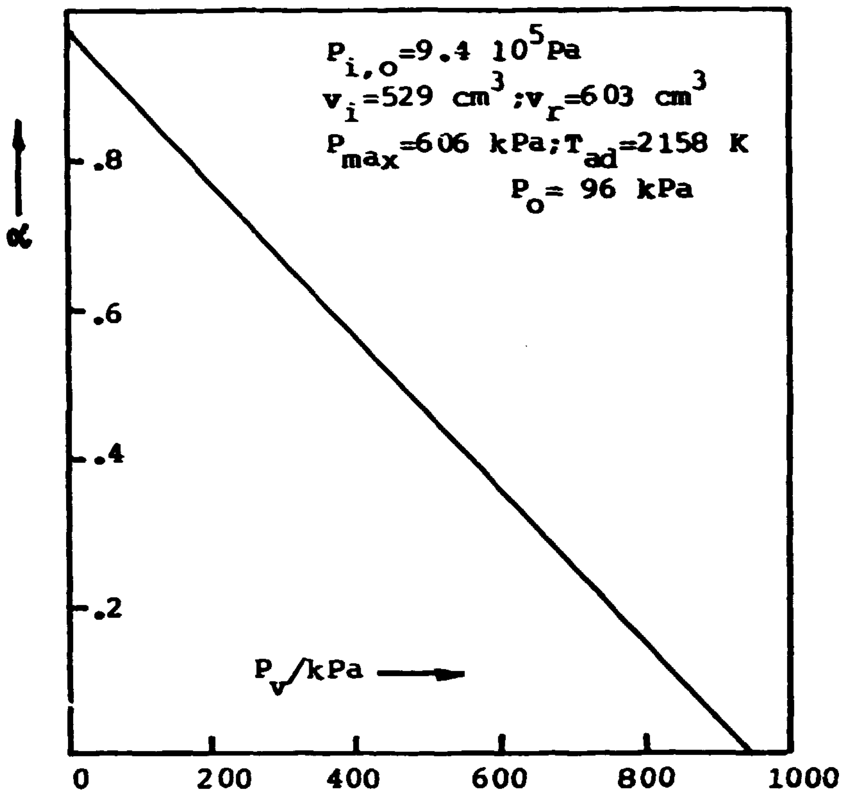
The experimental measurements just described also allow the determination of the injection cylinder volume (v_i) from the experimental values of v_r, $P_{r,o}$, $P_{r,e}$ and $P_{i,o}$; indeed, from the identity of eqs (3.17) and (3.19) it follows :

$$v_i = v_r\ P_{i,o}(P_{r,e} - P_{r,o})/(P_{i,o} - P_{r,e})P_o \qquad (3.20)$$

+⁺+

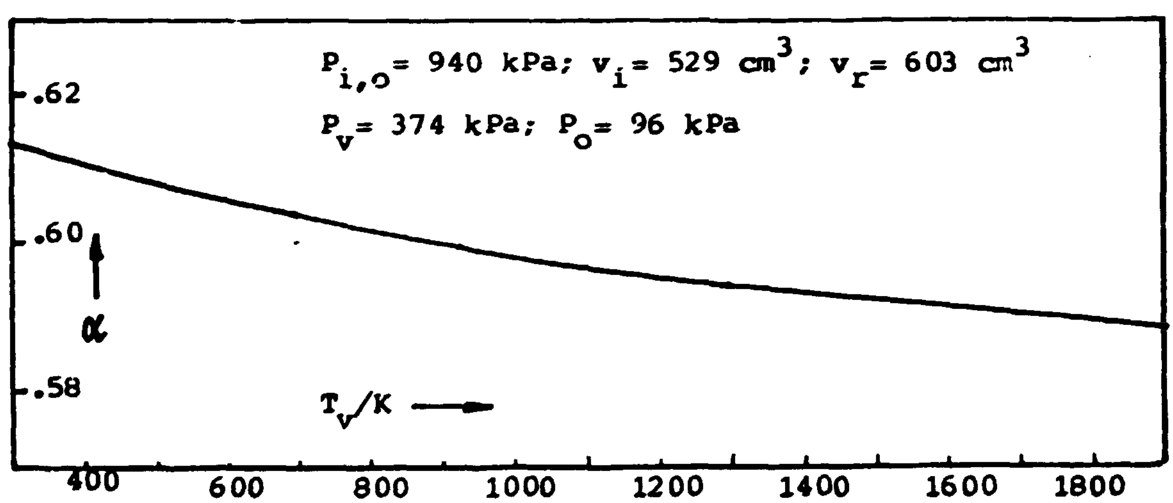
In many cases it may be useful to shorten the duration of the injection by closing the solenoid injection valve at a preset time t^* after the start of the injection. The fraction $\alpha_t{}^*$ injected may then be calculated by either eq.(3.13) or eq.(3.18). Figure 3.6 shows the values of $\alpha_t{}^*$ as a function of the initial pressure $P_{r,o}$ (initial = at the beginning of the injection) for different injection durations t^*. The calculation uses the experimental values of ($P_r - P_{r,o}$) shown on figure 3.4.

Fig.3.2



P_{i,o}=9.4 10^5 Pa
v_i=529 cm^3;v_r=603 cm^3
P_max=606 kPa;T_ad=2158 K
P_o= 96 kPa
α
.8
.6
.4
.2
P_v/kPa
0
200
400
600
800
1000

Fig.3.1



P_{i,o}= 940 kPa; v_i= 529 cm^3; v_r= 603 cm^3
P_v= 374 kPa; P_o= 96 kPa
.62
.60
α
.58
T_v/K
400
600
800
1000
1200
1400
1600
1800

Fig. 3.3

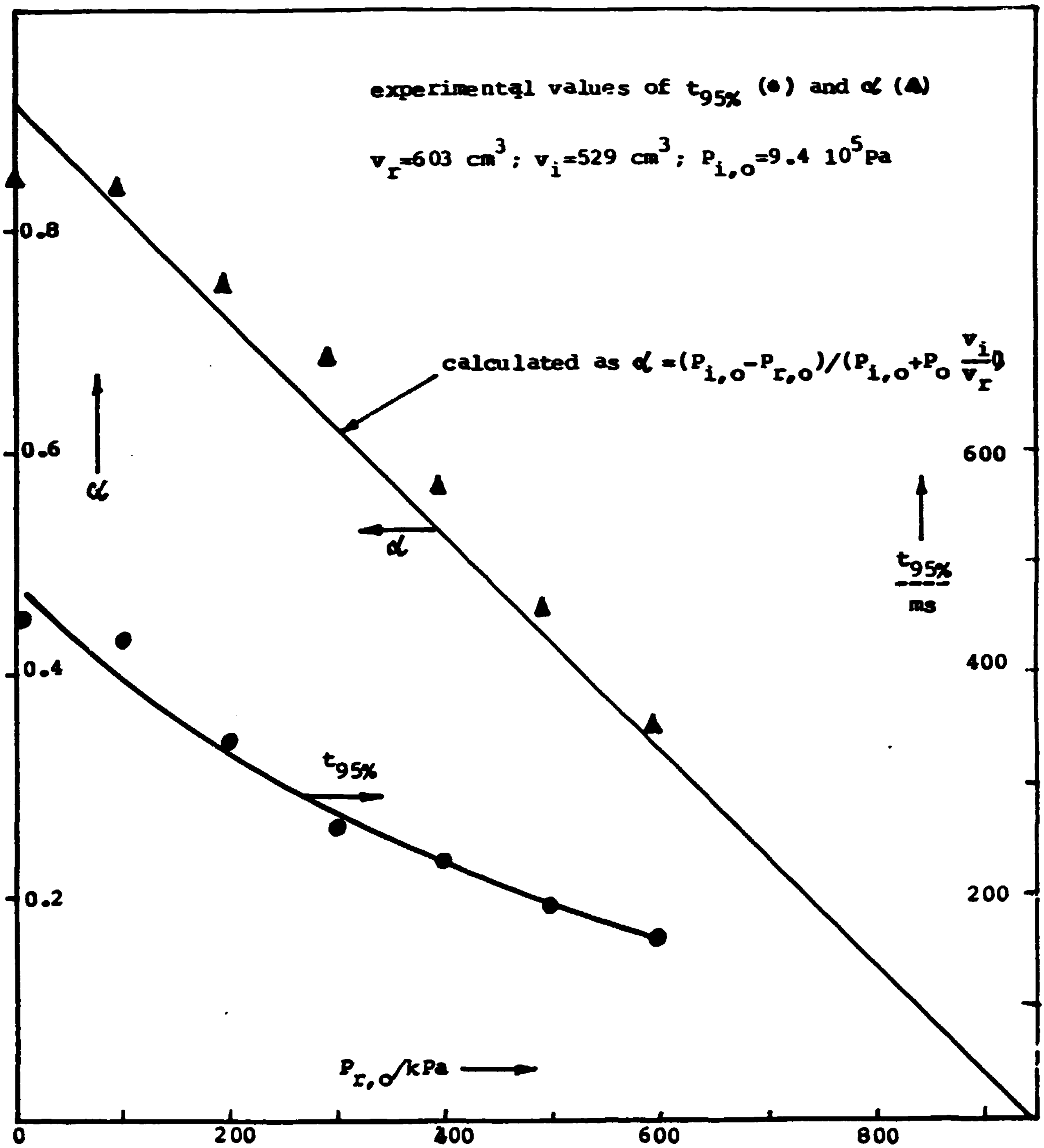

experimental values of t95% (•) and α (▲)
vr=603 cm3; vi=529 cm3; Pi,o=9.4 10^5Pa
calculated as α =(Pi,o-Pr,o)/(Pi,o+Po vi/vr)
α
t95%
t95% / ms
Pr,o/kPa
0.8
0.6
0.4
0.2
600
400
200
0
200
400
600
800

Fig. 3.4

$v_r = 603\ cm^3;\ P_{i,o} = 9.4\ 10^5 Pa;\ v_i = 529\ cm^3$

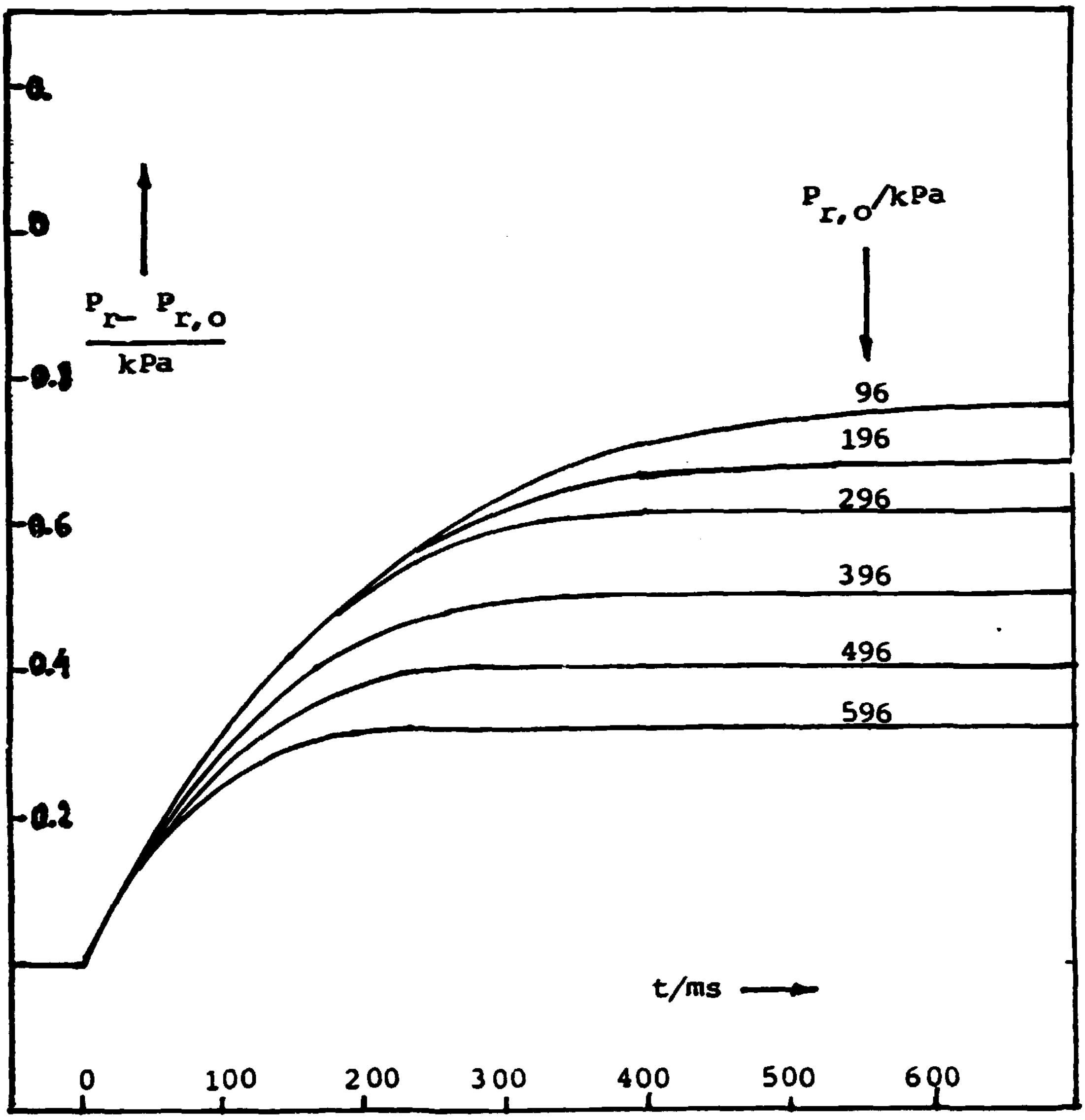


Fig. 3.5

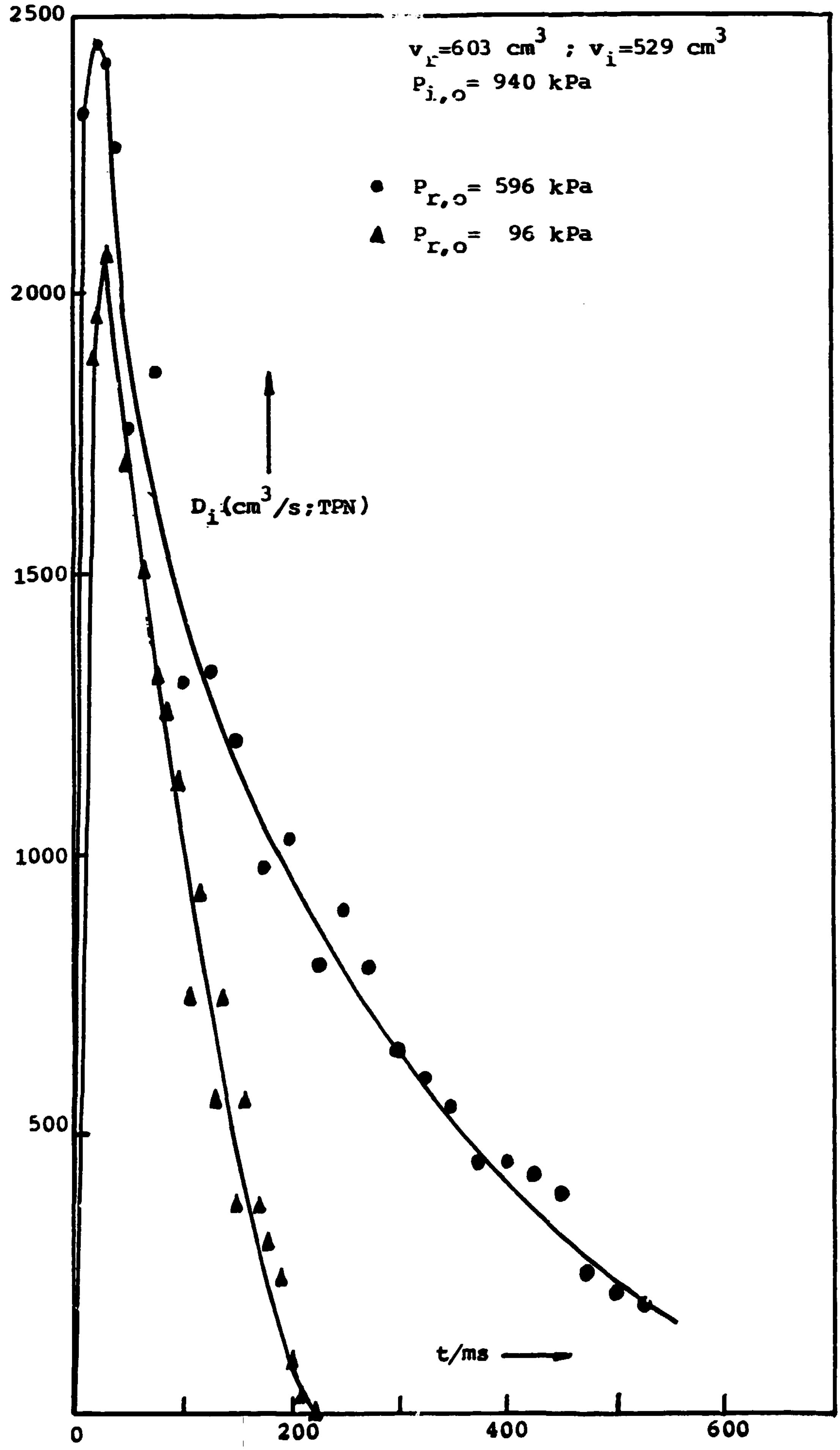
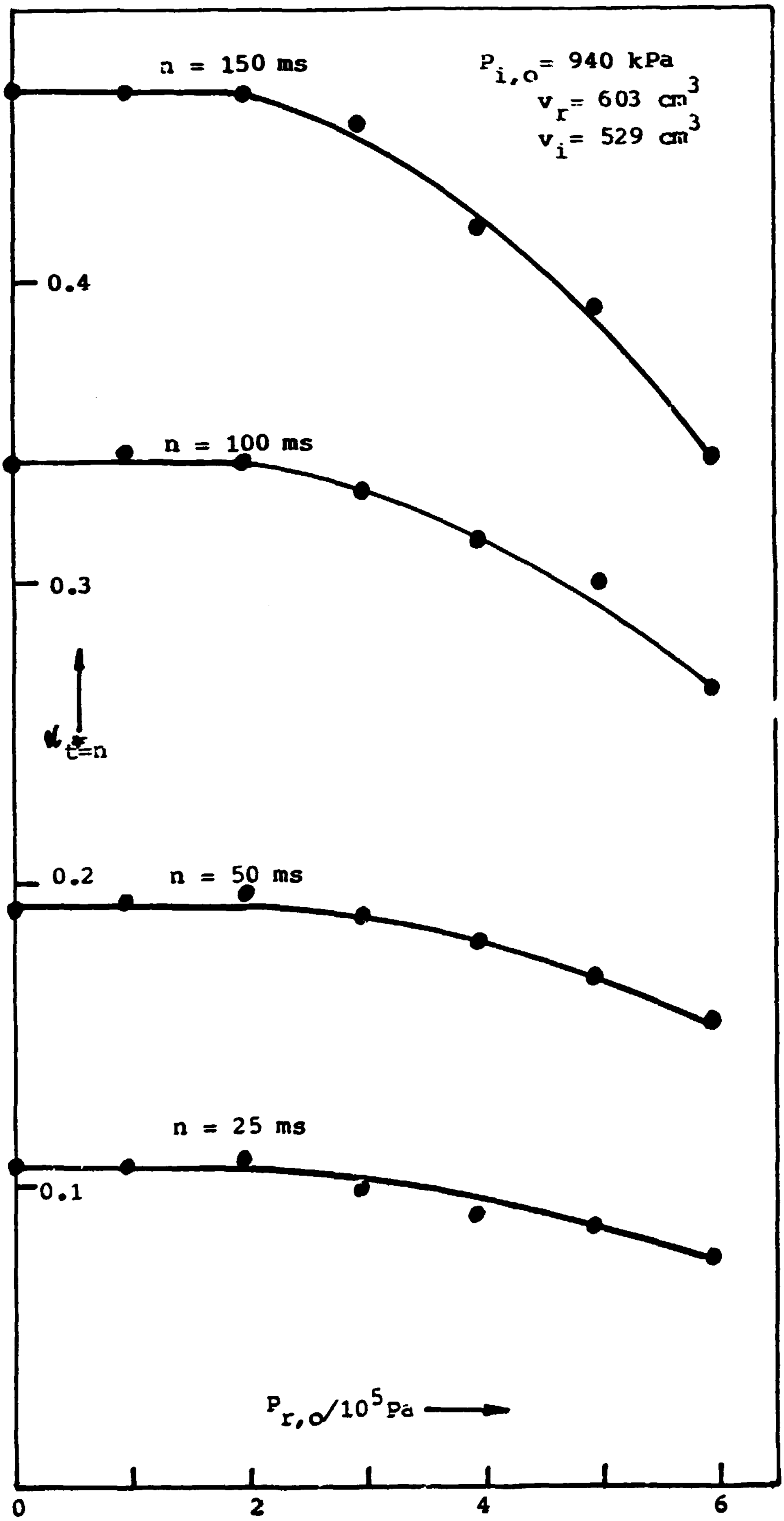

2500
2000
1500
1000
500
0
200
400
600
v_r=603 cm^3 ; v_i=529 cm^3
$P_{i,o}$= 940 kPa
● $P_{r,o}$= 596 kPa
▲ $P_{r,o}$= 96 kPa
D_i(cm^3/s;TPN)
t/ms

Fig.3.6



n = 150 ms
$P_{i,o}$ = 940 kPa
v_r = 603 cm^3
v_i = 529 cm^3
n = 100 ms
n = 50 ms
n = 25 ms
0.4
0.3
0.2
0.1
$\alpha_{t=n}$
$P_{r,o}/10^5 Pa$
0
2
4
6

ANNEX 4

Tentative Research Programme for the execution of Part II of the experimental study : Spark assisted ignition of liquid methanol sprays

A. Calibrations

Most of the calibration work (such as : calibration of the sonical nozzles and pressure transducers) has already been effectuated in Part I of the study (see reference 2, Annex 3,A).

Some new calibrations are specific for the second part of the study , mainly:

* determination of the high energy (H.E.) spark characteristics, and
* the characteristics of the methanol injector.

A.1. Characteristics of the H.E.sparks (high energy sparks)

For different setting of the electrical circuitry, the effective energy (E_s) released in the spark and its duration (θ_s) should be determined.

The spark circuit used in that study is of the type: high voltage charged capacitor discharged without intermediate inductance coil. In this case the energy effectively released in the spark is close to the one calculated from the capacity (C) and charge voltage (V) :

$$E_s = C\,V^2/2 \qquad (4.1)$$

The energy E_s may be directly measured upon displaying the current (i) and voltage (v) variation in the spark on a cathode ray oscilloscope as a function of time . The voltage v is measured over a high resistance bypass; the current i is measured by a Hall-effect probe ore more simply over a non coiled resistor placed in series with the spark gap. E_s is obtained as :

$$E_s = \int^{\theta_s} v.i.dt \qquad (4.2)$$

A.2. Characteristics of the liquid methanol injector

Owing to the volume of the main reactor utilized, and in order to obtain a range of overall equivalence ratios situated between 0.2 and 1, a pump should be selected that allows the injection of about 20 to 100 mg methanol per stroke.

Since the amount of methanol injected constitutes one of the parameters of the present study, the injector should be calibrated for different positions of the injection pump plunger.

The corresponding injection durations (θ_i) is to be determined as a function of the pressure (P) in the reactor. This may be done for example using a light beam passing to the methanol jet at the nose of the injection nozzle, impinging on a photoresistor, the output of which indicating the duration of the spray.

Boundaries and penetration of the liquid spray may be estimated from shadow-cinematography pictures.

It also might be worthwhile to check the droplet size distribution, using the (already existent) Malvern technique, especially in the case where different injector types should be studied.

A.3. Determination of various time lags

As indicated in reference 1, Annex 3, B.1., the scenario of a typical trial comprises the following consecutive steps (see figure 4.1) :

(1) At t(time) = 0, the low energy spark (=LE spark) circuitry is actuated ; this actuation triggers the following events:

a- the release of the low energy spark (LE spark), igniting the hydrogen-oxygen/nitrogen mixture, the combustion of which will produce the "synthetic air".

b- the cathode ray storage oscilloscope which, coupled to an x/y recorder, will make records of the P/t and light emission/t curves (the former from the pressure transducer, the latter from the photo multiplier PM).

c- over a variable delay (τ_c), obtained from channel 1 of a delayed pulse generator (=D.P.G.), the shadowgraphy camera is triggered.

d- channel 2 of the D.P.G. which, after a selected delay δ_1, will provide a pulse.

(2) at $t = \delta_1$, the pulse delivered by channel 2 of the D.P.G. triggers the following events :

a- the start of the methanol injection, by actuating an electromagnetic plunger driving the injection pump;

b- channel 3 of the D.P.G. which, after a variable preset delay δ_2, will provide a pulse.

(3) at $t = \delta_1 + \delta_2$, the pulse delivered by channel 3 of the D.P.G. triggers the high energy (=HE) spark circuit, assisting the methanol ignition and combustion.

The different delays appearing in that scenario, comprise the preset delays of the D.P.G. as well as the reponse times of the repective actuated devices. The latter should be determined in order to correct the preset values of τ_c , δ_1 and δ_2.

It is recommended to superimpose on the oscilloscope record the pulses delivered from channels 1, 2, and 3 of the D.P.G.

B.Compositions of the "synthetic air"

As already explained in reference 1, Annex %, A,4,1, the previous combustion of hydrogen/oxygen/nitrogen mixture aims at the obtention of hot combustion products containing 21% oxygen, the remainder 79% being dilution products (nitrogen and water vapor). Hence one has to deal with lean hydrogen/oxygen/nitrogen mixtures allowing for the condition :

$$(X_{O2})_p = 0.21 \qquad (4.3)$$

Defining the reactant molar fractions by :

$$a = (X_{H2})_r \ ; \quad b = (X_{O2})_r ; \quad c = (X_{N2})_r$$

The global combustion reaction of lean mixtures (neglecting the dissociation products) may be written as :

$$a\ H2 + bO2 + c\ N2 \longrightarrow a\ H2O + (b - \frac{a}{2})\ O2 + c\ N2 \qquad (4.4)$$

From eq.(4.4) the mole fractions of the combustion products are given by :

$$(X_{O2})_p = (b - \frac{a}{2})/(1 - \frac{a}{2}) \equiv 0.21 \qquad (4.5)$$

$$(X_{H2O})_p = a/(1 - \frac{a}{2}) \qquad (4.6)$$

$$(X_{N2})_p = c/(1 - \frac{a}{2}) \qquad (4.7)$$

The ratio of number of moles respectively in the products and in the reactants is given by :

$$N_p/N_r = 1 - \frac{a}{2} \qquad (4.8)$$

From eq.(4.5) one has the following relationship between the hydrogen and oxygen consentrations in the reactants :

$$(X_{O2})_r = 0.21 + 0.395\ (X_{H2})_r \qquad (4.9)$$

By definition one has the equality :

$$(X_{H2})_r + (X_{O2})_r + (X_{N2})_r = 1 \qquad (4.10)$$

Comparison of eqs (4.9) and (4.10) yields the following relationship between the oxygen and nitrogen concentrations in the reactants :

$$(X_{O2})_r = \left[0.605 - 0.395\ (X_{N2})_r\right] / 1.395 \qquad (4.11)$$

Relationships (4.9) and (4.11) allow the determination of the different reactant mixtures the combustion of which will yield the so called "synthetic air". Figure 4.2 shows the composition of all the possible "synthetic air" generating mixtures, together with teir adiabatic combustion temperature (calculated for reactants at normal pressure and ambient temperature) according to reference 3. The equivalence ratio of these mixtures passes through the lean flammability limit and through the lean detonability limit, as indicated on that figure. Numerical values of reactant and product compositions are presented on Table 4.I for some selected mixtures.

TABLE 4.I

$[(X_{O2})_p = \text{constant} = 0.21]$

N^o	Reactants composition				Products		T_{ad}(K)
	$(X_{N2})_r$	$(X_{O2})_r$	$(X_{H2})_r$	Eq.Rat.	$(X_{H2O})_p$	$(X_{N2})_p$	
1	0	0.4337	0.5663	0.6529	0.7900	0	2980
2	0.1	0.4054	0.4946	0.6100	0.6571	0.1329	2890
3	0.2	0.3771	0.4229	0.5608	0.5363	0.2537	2780
4	0.3	0.3487	0.3513	0.5037	0.4262	0.3638	2630
5	0.4	0.3204	0.2796	0.4363	0.3250	0.4650	2390
6	0.5	0.2921	0.2079	0.3558	0.2320	0.5580	2120
7 (a)	0.5690	0.2678	0.1632	0.3047	0.1777	0.6123	1920
8	0.6	0.2638	0.1362	0.2582	0.1462	0.6438	1780
9	0.7	0.2355	0.0645	0.1369	0.0666	0.7234	1280
10 (b)	0.7519	0.2191	0.0289	0.0661	0.0293	0.7607	

(a) lean detonation limit at atmospheric pressure
(b) lean flammability limit at atmospheric pressure

C. Outline of a tentative research programme

C.1. Preliminary remarks

a - The here proposed research programme presents a tentative character, in that, during its execution, we might well come across either practical difficulties imposing changes of the experimental scenario, or findings which may suggest to focuss on parameters which "a priori" were believed to present minor importance.

b - The outline of the research programme is dictated by (1) the purpose of the study itself and (2) the different parameters on which the phenomena may depend.

(1) Purpose of the study is to determine the occasional improvement of liquid methanol spray ignition by highly energetical sparks. That improvement may present different aspects such as :

* the possibility to ignite the spray at lower gas-temperatures and/or pressures
* the decrease of the ignition delay and/or of the duration of the combustion
* a better combustion quality (e.g. in terms of unburnt hydrocarbons or CO/CO2 ratio in the products).

(2) The parameters to be varied are mainly :

* pressure (P) and temperature (T) of the air in which the methanol spray is injected
* specification of the spray (droplet size distribution droplet density distribution in the aerosol, etc; the investigation of these parameters is provisoriously not foreseen in the present study)
* mass (m_i) of methanol injected (i.e. overall equivalence ratio), geometry, duration and flow rate of injected fuel (it is not foreseen to vary m_i and θ_i independently)
* Characteristics of the high energy spark, especially the released energy and the duration
* Location of the spark plug with respect to the injection nozzle (axial distance will be kept constant; radial distance will be varied)
* Spark timing (δ_2) with respect to the start of methanol injection.

A comparison with high energy spark effects obtained on hydrocarbon spray ignition would usefully be made.

C.2. Measurements to be made for each trial

C.2.1. During the trial

a- Pressure/time evolution in the reactor, recorded over a calibrated pressure transducer, linked to its charge amplifier, the output of which is displayed on the oscilloscope prior to being recorded on the x/y plotter, providing thus permanent documents.
The signal from the photo multiplier is also displayed on the scope and recorded.
An approximate Temperature/time curve will be derived from the pressure/time track by the relationship

$$T = T_{ad} \; P/P_{max} \qquad (4.12)$$

where P_{max} is the maximum value of P corresponding to the end of the combustion of the nitrogen/oxygen/hydrogen mixture. The adiabatic combustion temperature will be calculated by an appropriate computerprogramme (the values given on Table 4.I have been calculated at constant pressure (atmospheric) and therefore provide but a rough indication.

If visible from the pressure/time track or from the Photo Multiplier output/time track, the physico-chemical ignition delay (d_i , see figure 4.1) should be noted.

b- Using an appropriate setting of the delay τ_c (see A.3,1) and of the framing speed, a shadowgraphic movie track of the whole sequence of events will be recorded.

This two dimensional visualization of the phenomena is important for the qualitative understanding of tem, especially the effect of the distance between spark and symetry axis of the injector. For this reason, a radial displacement of the spark electrodes should be made possible. We designate by r and x the radial, respectively the axial distance of the spark with respect to the nose of the injector.

C.2.2. After the trial

The volumes of CO and CO_2 (repectively : v_{CO} and v_{CO2}) are to be determined . The procedure is identical to that described in reference 2 , Annex 3, B.2.5,g. An occasional sudden drop in the fraction of methanol burnt will provide supplementary indications of the limiting conditions of the efficiency of the high energy spark. The fraction of carbon burnt is given by the expression :

$$F_b = D_{N2}\, M \int_0^{t_d} (X_{CO} + X_{CO2})dt \;/\; v\, v_M\, \rho \tag{4.13}$$

where D_{N2} is the flow rate of nitrogen conveying the combustion products to the analysers; v, ρ and M are the volume, respectively the volumic mass and the molar mass of the injected liquid methanol; v_M is the mo;ar gas volume at standard pressure and temperature ; t_d is the moment where X_{CO} and X_{CO2} drop to zero during the analysis.

C.3. Trial series to be performed

C.3.1. Trials with methanol injection

As a rule, for each trial series (except for the preliminary ones) are indicated :

* the parameters to be kept constant
* the parameters to be varied
* occasionally, some remarks with respect to the choice of the parameters and the execution of the trials.

SERIES 1 : Preliminary trials

The purpose of these preliminary trials is tb check the ignition possibility of the liquid methanol sprays WITHOUT spark assistance. . As already stated earlier, the high energy spark assistance, at a given temperature and pressure, may show different effects :

* either provoke the ignition where it would fail without spark assistance
* or improve the ignition, which would already exist without spark assistance, e.g. in making it faster (decrease of ignition delay) or more efficient with respect to the completeness of the subsequent combustion (unburnt fuels and CO/CO_2 in the products).

Logically therefore, some trials without high energy sparks should be performed to check the possibility of hot gas ignition of the liquid methanol sprays.

The reactor will be operated with "synthetic air" , starting with a hydrogen/oxygen/nitrogen mixture that gives the highest possible temperature (but still being safe with respect to detonation, therefore, avoid using the five or six first mixtures of Table 4.I) and selecting the smallest possible value of δ_1. Repeat these trials for different values of m_i (mass of injected methanol).

Whenever one of these tests, run under the most favorable conditions for selfignition, provokes ignition of the injected methanol, then, AS A RULE, and for all the following trial series mentioned below, this type of test (i.e. without spark) should be performed to yield a baseline trial for comparison. Selfignition delay (d_i) as well as fraction of methanol burnt (F_b) should also be determined for these baseline trials.

Changing the hydrogen mixture composition and the delay of injection (δ_1) , note the values of T and P for which autoignition without spark starts to fail, in order to use these conditions in the later mentioned series as reference conditions.

SERIES 2 : Effect of temperature (and pressure)

a- Constant parameters:

* spark location (x,r) and timing (δ_2)

  Select a value of "r" so that the spark is fired close to the spray boundary; select a value of δ_2 of the order of the injection duration or slightly smaller than θ_i.

* Spark energy (and duration) : select a value of E_s as large as possible
* Injected mass of methanol : select a value of m_i corresponding approximately to an overall equivalence ratio of 0.5

b- Variable parameters : Temperature (and pressure) of the (synthetic) air.

c- Remarks

1.Start with the reactor being filled with pure"natural" air at room temperature.

* If no ignition occurs (check by determining P_b), even after eventual adjustment of r and/or m_i and δ_2, then go to point 2.
* If ignition occurs, note d_i and P_b and go to point 2.

2.Switch to the use of "synthetic air"
From Table 4.I, select the mixture corresponding to the highest dilution by nitrogen, but still being flammable (for example mixture N° 9) and go to point 3.

3.With the largest possible value of injection delay δ_1, run the trial and check whether or not there was ignition (using the Photomultiplier record, the value of P_b and the shadowgraphic pictures made during the trial).

* If ignition occurs, note the values of d_i and P_b and and go to point 4.
* if no ignition occurs, then decrease progressively the injection delay δ_1 and start again point 3.
If ignition fails even for the smallest possible value of δ_1, then go to point 4.

4.Select from table 4.I a much less diluted hydrogen/oxygen/nitrogen mixture and repeat the procedure of point 3.

Important note : For the conditions where ignition has been obtained without spark (see SERIES 1), run baseline trials without spark for comparison.

<u>SERIES 3</u> : Effects of the spark energy

a- Constant parameters :

* spark location and timing (δ_2) } same as for SERIES 2
* mass m_i methanol injected }
* Temperature and pressure :
select <u>three</u> different combinations of H"/O"/N" mixture composition and delay δ_1 having given different ignition delays and F_b values (but preferentially not giving ignition without spark)

b- Variable parameter : spark energy (E_s)

c- Remarks
For each of the three mixture/δ_1 chosen, run a series of trials with decreasing values of E_s . Note the critical values,where ignition fails to happen, as $(E_s)_c$.

<u>SERIES 4</u> : effect of spark timing

a- Constant parameters :

* Spark location (x,r) } same as for SERIES 2
* mass of methanol injected (m_i) }
* Temperature and pressure
select <u>two</u> combinations of hydrogen mixture and delay δ_1, one giving weak ignition, one giving strong ignition in SERIES 2.
* spark energy :
select <u>two</u> values of E_s of SERIES 3, one which , in combination with the previous parameter (pressure and temperature),gave strong ignition, another which yielded weak ignition.

b- Variable parameter : spark delay (δ_2)

c- Remarks :
For each of the retained constant parameter combinations, run a series of trials for progressively decreasing values of the spark delay (δ_2). Check the existence of ignition as well by shadowgraphy as by the values of d_i and F_b. Note the critical values of (δ_2)

SERIES 5 ; effect of injected mass of methanol

a- Constant parameters :

* spark location (x,r) : as in previous series
* spark energy (E_s)
* temperature and pressure
* spark timing (δ_2)

} chose two or three combinations having given ignition ranging from strong to weak

b- Variable parameter : injected mass of methanol (m_i)

c- Remarks :

For each of the two or three combinations of constant parameters, run a series of trials with increasing value of m_i. Note the critical values for which ignition starts to fail.

SERIES 6 : Effect of spark location

a- Constant parameters :

Select two combinations of E_s, m_i, δ_2, pressure and temperature , one having yielded strong, the other weak ignition in the former trials.

b- Variable parameter : spark gap location (r)

c- Remarks :

Run a series of trials for which the radial distance "r" between spark and injector symetry axis is progressively varied, between the two extreme possible positions r=0 and r = radius of main reactor. Note the limiting values of r where, occasionally, , ignition starts to fail.

C.3.2. Trials with liquid hydrocarbon injection.

Hydrocarbons mostly show quite different ignition behaviours than alcohols. Therefore it is suggested to perform some relevant comparative trials, in which a liquid hydrocarbon (e.g. heptane or decane) is injected instead of methanol.

Fig. 4.1

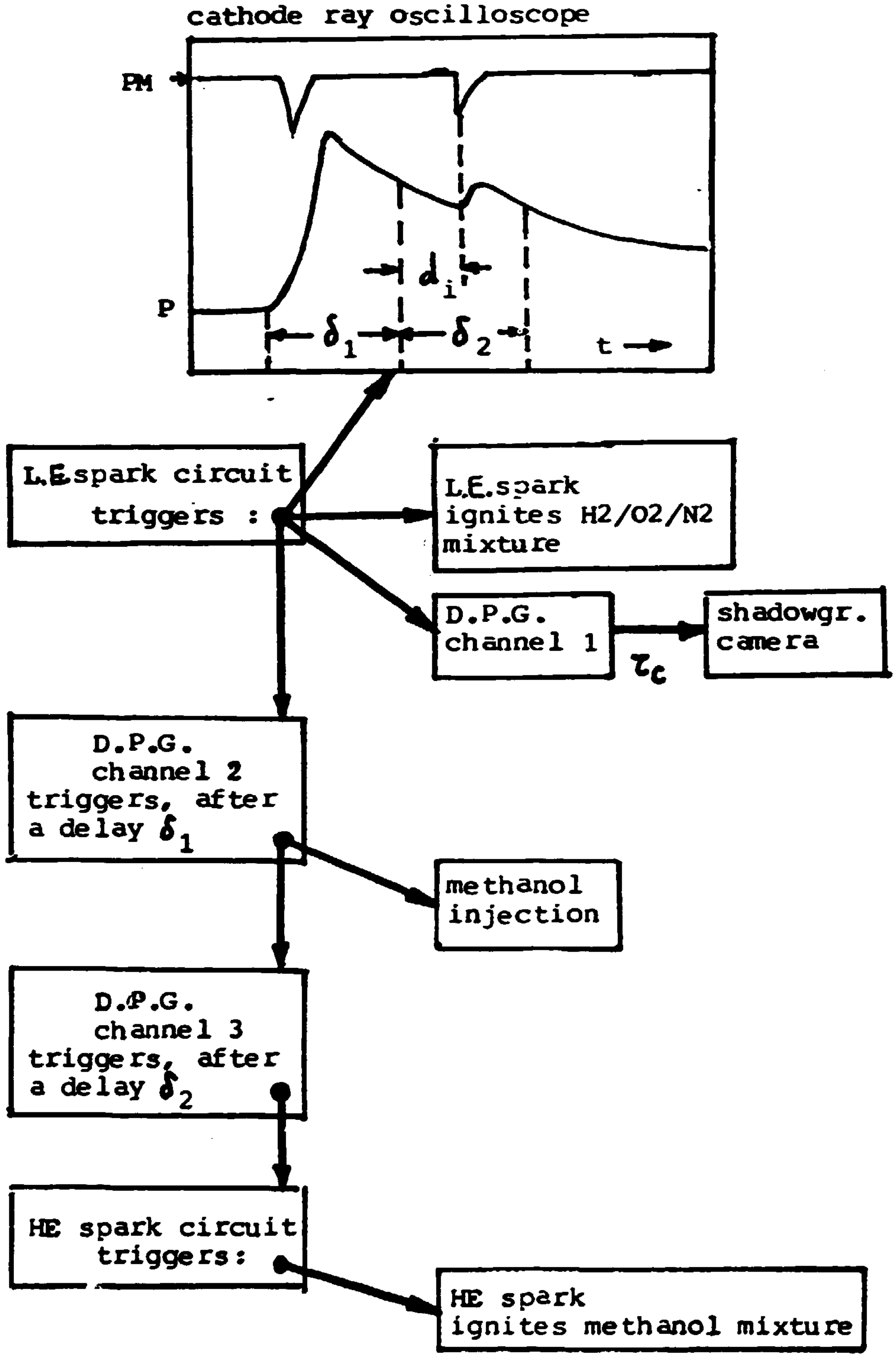
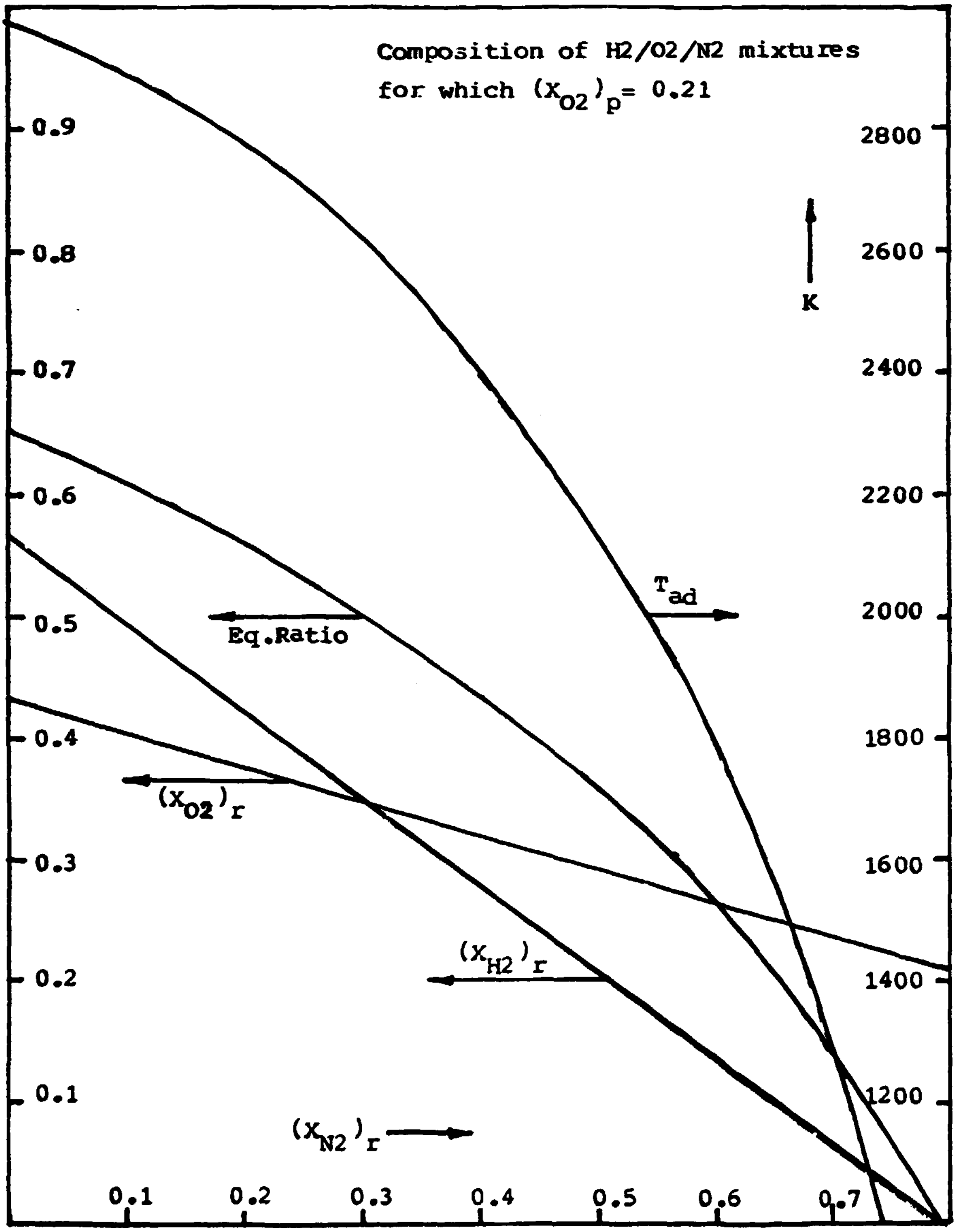

cathode ray oscilloscope
PM
P
d_i
δ1
δ2
t
L.E.spark circuit triggers :
L.E.spark ignites H2/O2/N2 mixture
D.P.G. channel 1
τc
shadowgr. camera
D.P.G. channel 2 triggers, after a delay δ1
methanol injection
D.P.G. channel 3 triggers, after a delay δ2
HE spark circuit triggers:
HE spark ignites methanol mixture

Fig.4.2


Composition of H2/O2/N2 mixtures
for which $(X_{O2})_p = 0.21$
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
2800
2600
2400
2200
2000
1800
1600
1400
1200
K
T_{ad}
Eq.Ratio
$(X_{O2})_r$
$(X_{H2})_r$
$(X_{N2})_r$
0.1
0.2
0.3
0.4
0.5
0.6
0.7