ON THE USE OF AN ULTRASONIC PULSE—ECHO TECHNIQUE FOR REGRESSION RATE ANALYSIS

PART II: SOME EXPERIMENTAL RESULTS

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NOMENCLATURE

List of symbols

D	inner grain diameter (m)
d_{po}	initial port diameter (m)
m_{air}	air mass flow rate (kg/s)
P	pressure (P_a)
$P_c = \bar{p}_c$	mean combustion pressure in aft mixing chamber (P_a)
r	regression rate (m/s)
s	second
κ	thermal heat diffusivity (m^2/s)

Acronyms

FAEDUT	Faculty of Aerospace Engineering of DUT
DUT	Delft University of Technology
PMMA	polymethylmethacrylate
PML-TNO	Prins Maurits Laboratory of TNO
SFCC	solid fuel combustion chamber
TNO	Dutch organisation for pure and applied scientific research

SUMMARY

Knowledge of the instantaneous regression rate of solid fuels that are used in solid fuel combustion chambers, SFCC's, is important for two reasons:

- First, there is a strong interaction between the local fuel regression rate and the combustion process. A thorough understanding of the latter is therefore intimately connected to knowledge of the regression rate, and vise versa.

- Secondly, the regression rate after all is a prime performance determining parameter. For solid fuel ramjets, energy conversion installations, or other applications of SFCC's, the regression rate in combination with mass flux, pressure and inlet temperature ultimately determines the performance. The measurement of local and instantaneous regression rate helps in disentangling the relationships between these parameters, and hence in improving our designing methods.

In this report, experimental results are presented for the instantaneous regression rate as measured by an ultrasonic pulse echo technique in combustion of polymethylmethacrylate with pure oxygen or mixures of oxygen and nitrogen.
It is demonstrated that the ultrasonic regression rate analyzer, URRA, is a useful tool in examining locally and instantaneously relationships that have already been well-established in terms of time- and space averaged parameters. It is also shown that the accuracy of URRA results can be increased by improving our knowledge of temperatures and heat fluxes in the pyrolyzing surface.

1   INTRODUCTION

In hybrid rocket motors and solid fuel combustion chambers the solid fuel pyrolizer at the inner grain surface. The induced regression of the surface is strongly dependent on the flow and combustion process in the chamber. Hence precise knowledge of the regression rate helps to better understand the combustion characteristics. In addition the performance of a solid fuel combustion chamber is dependent, amongst others, on the fuel mass flow rate.

To date, most regression rate data concern time and space averaged values. Instationary effects are seldomly traced, although it has been observed that the regression rate may depend on the burning time. Therefore one has to be careful when using time-averaged regression rate data.
Knowledge of the relations between local and instantaneous regression rates and parameters such as chamber pressure, inlet mass flux and possible others elucidates some mechanisms behind pyrolysis in a combustion chamber [1,2,3].

The first attempts to measure the instantaneous regressive rate in hybrid rocket motors have been made optically by the NLR [4]. This technique was only applicable to non-curved two-dimensional grains whereas data reduction was very time consuming.

The ultrasonic technique that is presently discussed was developed to measure in situ the local instantaneous regression rate in hybrid rocket motors and solid fuel combustion chambers. The measurement technique has been described extensively elsewhere [5].

This report presents regression rate data as obtained by means of the ultrasonic pulse echo method in a number of combustion experiments with polymethylmethacrylate (PMMA) as a fuel and pure oxygen or mixtures of oxygen and nitrogen as oxidizer. Subsequently, the relation between this locally measured, instantaneous regression rate, and various parameters such as oxidizer mass flux, oxidizer composition, the presence of a rearward facing step, pressure and pressure oscillations are discussed. These experiments have mainly been performed to investigate the usefulness of this method.

A description of the experimental set-up is given in Chapter 2, while a brief description of the data reduction technique is presented in Chapter 3. The

experimental results are discussed in Chapter 4, while conclusions are given in Chapter 5.

2 EXPERIMENTAL SET-UP

The solid fuel combustion chamber consists of a cylindrical PMMA fuel grain: length ~ 300 mm, outer diameter ~ 70 mm and inner diameter between 19 and 35 mm. The grain is mounted between an injection chamber and an aft mixing chamber. A variety of oxidizing gases (oxygen with nitrogen, oxygen content varying from 20 to 100%) can be forced to move through the grain at various speeds. Ignition is achieved by the injection of a small quantity of hydrogen and oxygen ignited by a spark plug. Use can be made of a variety of rearward facing steps as a flame stabilizer and a variety of nozzles. Locally the fuel grain is flattened at its outside to accomodate for the ultrasonic probe. Pressure is measured at the injection chamber and at the aft mixing chamber. Figure 2.1 shows the experimental arrangement.
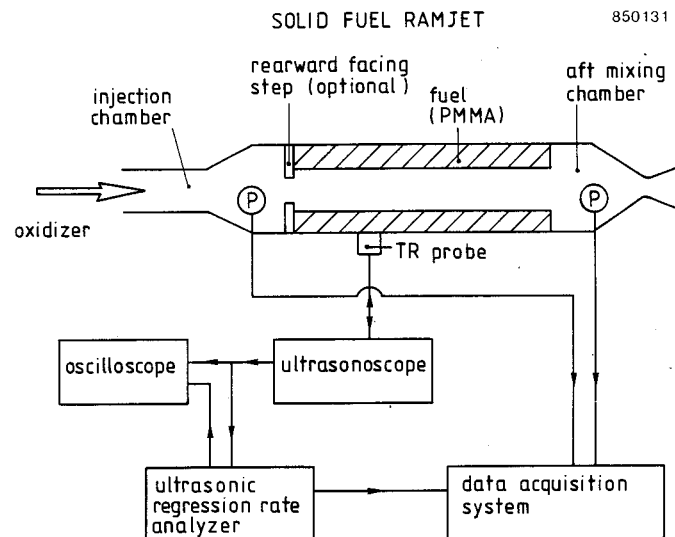

Figure 2.1. Schematic of the experimental system to determine the instantaneous local regression rate by means of the ultrasonic pulse-echo technique.

The emitted pulses are generated by an ultrasonoscope. The ultrasonic probe uses a 5 MHz carrier signal. The duration of each pulse is about 6 μs while the pulse is repeated every 1 ms. The time lapse between the emitted and received sound pulse is converted by the Ultrasonic Regression Rate Analyzer (URRA) into an output voltage that is sent to the data acquisition system. An oscilloscope is used to adjust experimental settings and to verify proper functioning of the URRA.

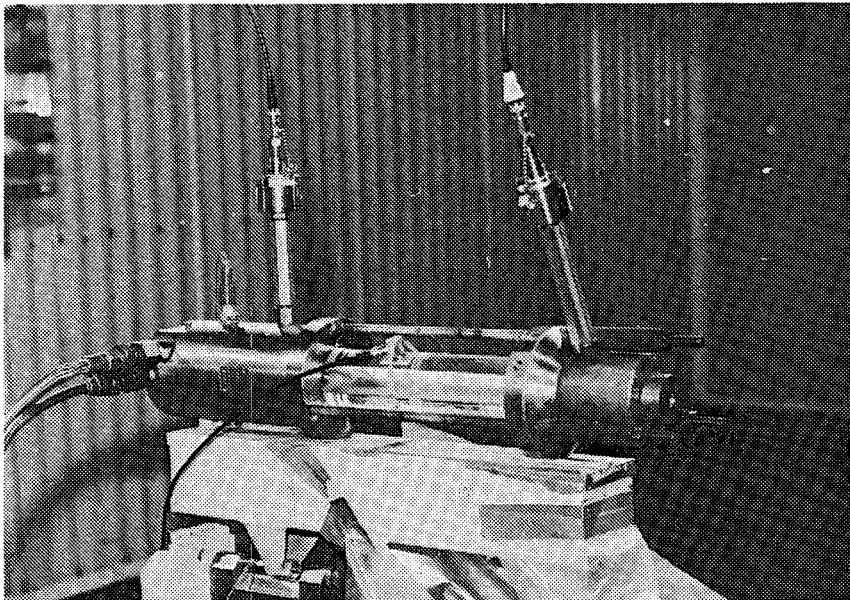Figure 2.2 provides an impression of the experimental set-up.

Figure 2.2. View on solid fuel combustion chamber with ultrasonic probe and
pressure transducers.

3 DETERMINATION OF REGRESSION RATE

An extensive discussion of the problems associated with the determination of the instantaneous regression rate from ultrasound measurements has been given in a previous report [5]. It is noted that the speed of sound depends strongly on temperature, whence the temperatures in the fuel grain have to be evaluated. Since the main purpose of the present investigation is the demonstrating of the usefulness of the measuring strategy, and since knowledge of the fuel grain temperature profile is intimately connected with knowledge of heat transfer at the boundary and hence all the complicated flow and combustion processes in the chamber, no attempt was made to develop a sophisticated calculation method for this temperature profile. The temperature dependancy of transport properties is therefore neglected. Furthermore it is assumed that immediately after ignition the surface temperature, T_s, reaches a constant value. This assumption is more or less validated by the presence of a melting layer at the surface of the fuel grain. The induced errors are not large, since large deviations from the mean temperature, and hence from the mean velocity of sound, only occur in a very small region adjacent to the inner grain surface. If the cylindrical wall is considered as an infinitely long slab, the temperature profile is described by [6]:

$$T(x) = T_i + \frac{1}{2}(T_s - T_i)\left[\text{erfc}\left(\frac{-x-rt}{2\sqrt{\kappa t}}\right) + \exp\left(\frac{-rx}{\kappa}\right)\text{erfc}\left(\frac{-x+rt}{2\sqrt{\kappa t}}\right)\right] \qquad (3.1)$$

where the origin of the coordinate system is located in the burning surface. In this equation $T(x)$ is the local temperature, T_i is the initial temperature and κ the thermal diffusivity of the solid.
The regression rate is denoted by r, and has to be known in advance.

In the above calculation procedure the actual temperature profile in the grain is fitted by a profile described by Eq. (3.1) by varying the parameter r. This procedure is fairly accurate, since large deviations from the mean temperature only occur in a very small region adjacent to the inner grain surface. Therefore induced errors in the time of flight of an echo pulse are small and more or less systematic, i.e. for calculations of the regression rate at different times not essentially different. Relative values of the regression rate are therefore even more accurate. For the analyses described in this report no higher accuracy is demanded.

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        ┌─────────────────────┐
        │  ASSUME REGRESSION  │
        │        RATE         │
        └──────────┬──────────┘
                   │
        ┌──────────▼──────────┐◄─────────────────┐
        │ CALCULATE THERMAL   │                  │
        │      PROFILE        │                  │
        └──────────┬──────────┘                  │
                   │                             │
        ┌──────────▼──────────┐                  │
        │ CALCULATE TIME LAPSE│                  │
        │ BETWEEN EMITTED AND │                  │
        │  RECEIVED PULSE,    │                  │
        │        ΔTth         │                  │
        └──────────┬──────────┘                  │
                   │                   ┌──────────┴──────────┐
        ◄──────────▼──────────►  NO    │  ADJUST REGRESSION  │
        ◄  ΔTth = ΔTmeasured   ►───────►│        RATE         │
        ◄─────────────────────►        └─────────────────────┘
                   │ YES
        ┌──────────▼──────────┐
        │  REGRESSION RATE    │
        │       KNOWN         │
        └─────────────────────┘
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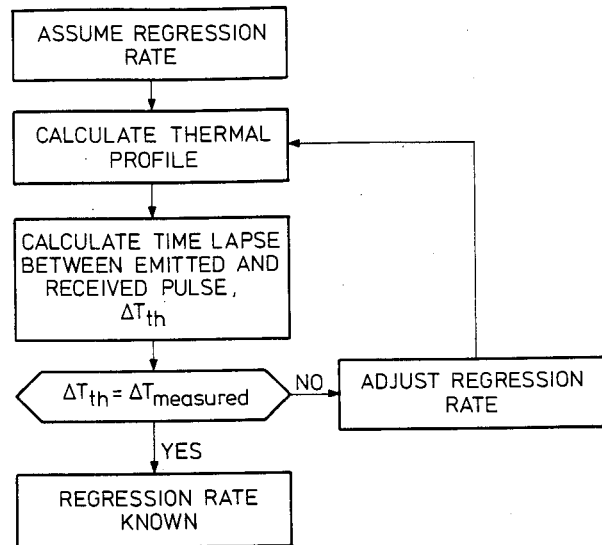
Figure 3.1. Flow chart of the iterative procedure to calculate the regression rate in a burning solid from ultrasound measurement.

It is noted that currently a numerical method is being developed [7], that takes into account

- the time dependency of the regression rate;
- the cylindrical shape of the fuel grain;
- the temperature dependency of the diffusivity of PMMA.

However, a time dependent regression rate is strongly connected to time dependent heat fluxes and hence time dependent boundary conditions. A calculation method that assumes a constant temperature at the fuel grain surface may therefore be quite unrealistic. Independent measurements are therefore planned with the sole objective of investigating this surface temperature with varying regression rate and other system parameters. Only if all the outcomes can be combined with the numerical method just mentioned, a substantial improvement of the accuracy of the pulse echo technique can be obtained.

4   EXPERIMENTS AND DISCUSSION

4.1   Testing of macroscopic laws on a microscale

Studies by the authors and other investigators [3], have shown that the mean regression rate of solid fuels in hybrid rocket motors and solid fuel ramjets strongly depends upon oxidizer mass flux and pressure. Usually the following, empirical relationship between regression rate, r, the oxidizer mass flux, G_{ox}, and the combustion pressure, p_c, is employed:

$$r = a \, G_{ox}^m \, p_c^n \tag{4.1}$$

Other parameters such as the dimensions of the rearward facing step, step size, length to diameter ratio and possible other factors have shown to play an important role in the regression rate behaviour [3]. However, for a given motor-configuration, the coefficient a and the exponents m and n in Eq. (4.1) depend only on the oxidizer and fuel type.

In the following subsections, the on a global scale verified relation (4.1) will be applied to and compared with local and instantaneous measurements of the regression rate as obtained with the ultrasonic technique. It will be seen that the URRA is a useful tool for testing Eq. (4.1) on a local and instantaneous scale, and the results will indicate that Eq. (4.1) is likely to hold on such a scale under prescribed conditions.

Some general features of URRA measurements are first elucidated in this section.

Figure 4.1 shows a typical pressure history and the corresponding regression rate history for an experiment with PMMA as fuel and a mixture of 62,5% oxygen and 37,5% nitrogen as oxidizer. In this case no flame stabilizer was used. The corresponding oxidizer mass flow history is given in Figure 4.2.

Figure 4.1 shows that the local regression rate was very high during the first seconds of the testrun. This phenomenon has been observed in all testruns. As to the explanation of this phenomenon we are still left with a many questions.
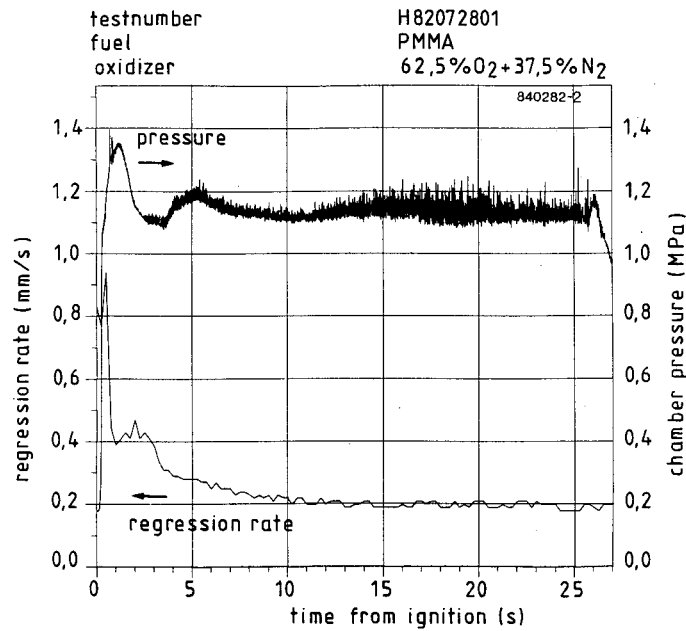
Figure 4.1. Specimens of histories of pressure and regression rate
(see also Figure 4.2).

Although we introduce non-stationary effects by igniting the fuel with an H_2-O_2 mixture during about 0.6 s, it is difficult to accept that the short presence of hydrogen would have such a long duration effect.
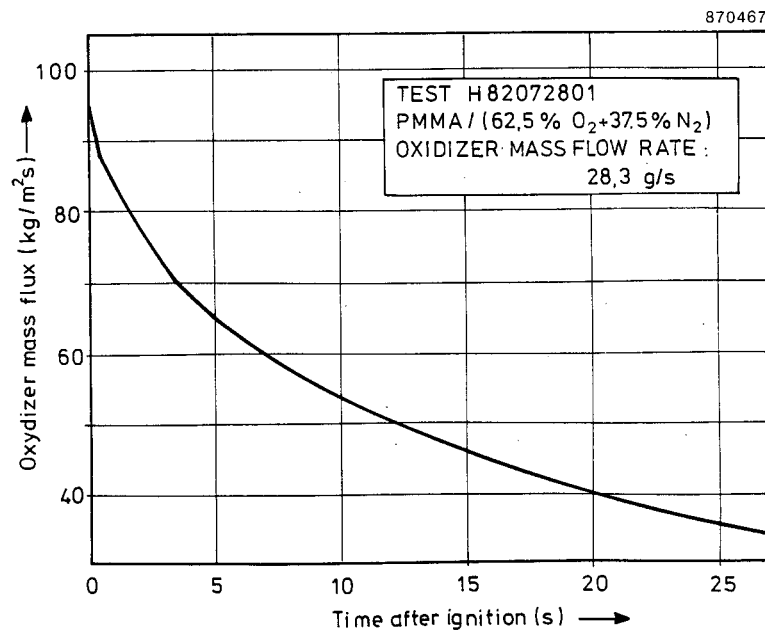

Figure 4.2. Mass flow history corresponding to figure 4.1.

A second cause might be associated with the development of a melt layer near the burning surface.

A third cause may be the data reduction method. In the computer programme it is assumed that immediately after ignition a constant surface temperature has been achieved. This will initially cause some discrepancies between computed results and reality.

However, at present there is no certainty about the cause of this high initial regression rate. Non of the above mentioned effects by itself seems to provide a sufficient explanation.

The existance of high regression rates during the first 5-10 s is also supported by other experimental data [3]. These experiments concern short duration test-runs up to 5 s. Similar experiments with a duration of 20 s or more, systemati-cally yielded a substantially smaller mean regression rate, based upon weight loss. A typical example is shown in Figure 4.3 for experiments with PMMA as fuel and oxygen as oxidizer. An initially high regression rate seems therefore very realistic.
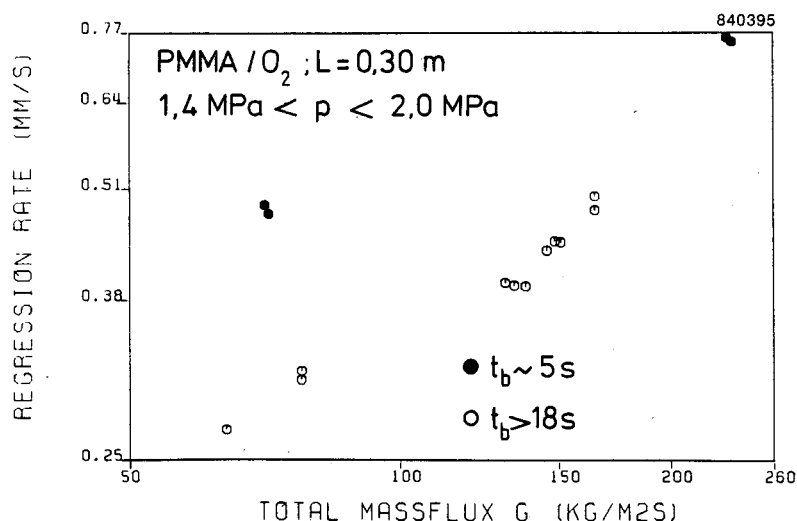

Figure 4.3. PMMA/O_2 experiments indicating initially high regression. Average regression rate based on weight loss (ref. 3).

From Figure 4.1 is it observed that after about 3 s a roughly experimentally decreasing regression rate develops.

Although the mass flow rate, m_{air}, is constant, the bore diameter increases because of the consumption of fuel. Hence the mass flux decreases, and in view of Eq. (4.1) the regression rate should also decrease. Which indeed is the case.

This is the first example of the testing and validating of a macroscopic law on a microscale with the help of the URRA.

Note that channel flow correlations for the heat transfer coefficient, α, are usually of the form

$$\alpha = \frac{\lambda}{D} [a + b \, Re^m \, Pr^n]$$

in which D denotes the tube diameter, λ the heat conduction coefficient, Pr Prandtl's number and Re Reynold's number

$$Re = m_{air}/(\mu \pi D)$$

If the fuel grain surface temperature and the temperature in the combustion chamber are hardly changing during combustion, the heat flux to the wall (W/m^2) is therefore roughly inversely proportional to D. This explains the decrease in regression rate with increasing tube diameter.
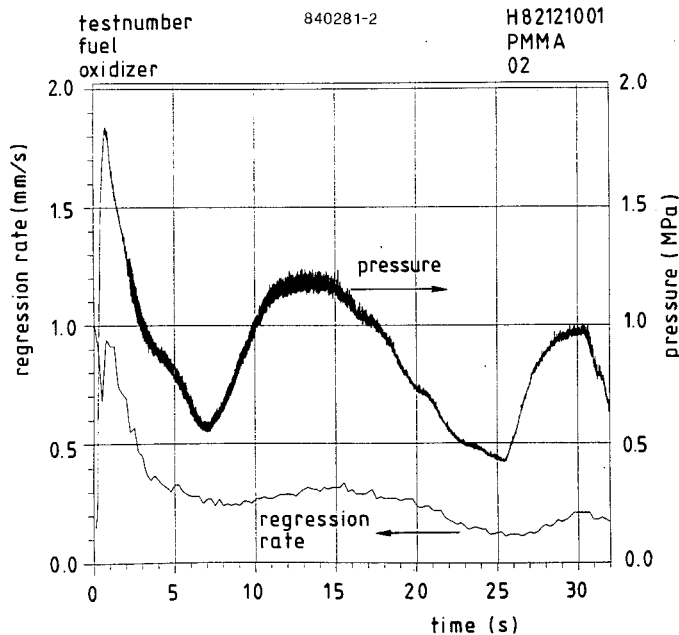

Figure 4.4. Pressure and regression rate simultaneously
affected by mass flow rate.

In order to save computer time, data reduction was performed at intervals of 0.25 s. Since the chamber pressure fluctuates at about 5 Hz some scatter in the calculated regression rate can be expected. This scatter is actually observed in Figure 4.1. This accounting for pressure fluctuations again amounts to testing of Eq. (4.1) on a microscale.

That the regression rate of PMMA really is affected by the combustion pressure is also seen in Figure 4.4. During this testrun the combustion pressure was varied. As no variable thrust area nozzle was available, the variation in combustion pressure was achieved by varying the mass flow rate. So in fact two effects are combined. It can be seen that indeed the regression rate follows the trend of the combustion pressure. In addition one notices that the regression rate peak shifts with about 2-3 s with respect to the pressure peak. This agrees well with the characteristic time, r^2/κ, for the adjustment of the thermal profile.

If the latter result would be confirmed by other experiments, it would imply that the relationship for time-averaged parameters

$$r = a\, G_{ox}^{m}\, P^{n} \tag{4.2}$$

in terms of local and instantaneous parameters takes the form

$$r = f\left(P, \frac{dP}{dt}, G_{ox}, \frac{dG_{ox}}{dt}\right) \tag{4.3}$$

This functional relationship explicitly may account for a phase difference between r and P or G_{ox}.

4.2 On the correlation between the instantaneous regression rate and the oxidizer mass flux

From integrated values of the local instantaneous regression rate as obtained by the ultrasonic pulse echo technique, the local instantaneous wall thickness may be calculated. When axisymmetric burning is assumed, the local instantaneous port area then easily follows. Once the local port area is known, the local oxidizer mass flux follows directly from the total mass flow rate. It is interesting to check whether indeed a relationship between the local regression rate and the local oxidizer mass flux of the following form holds, as employed by many investigators [8]

$$r = b \ G_{ox}^{m} \tag{4.4}$$

where

$$b = a \ \bar{p}_{c}^{-n} \tag{4.5}$$

This amounts to testing a well-established correlation on its universality or, to put it differently, on its applicability on a microscale (see also section 4.1).
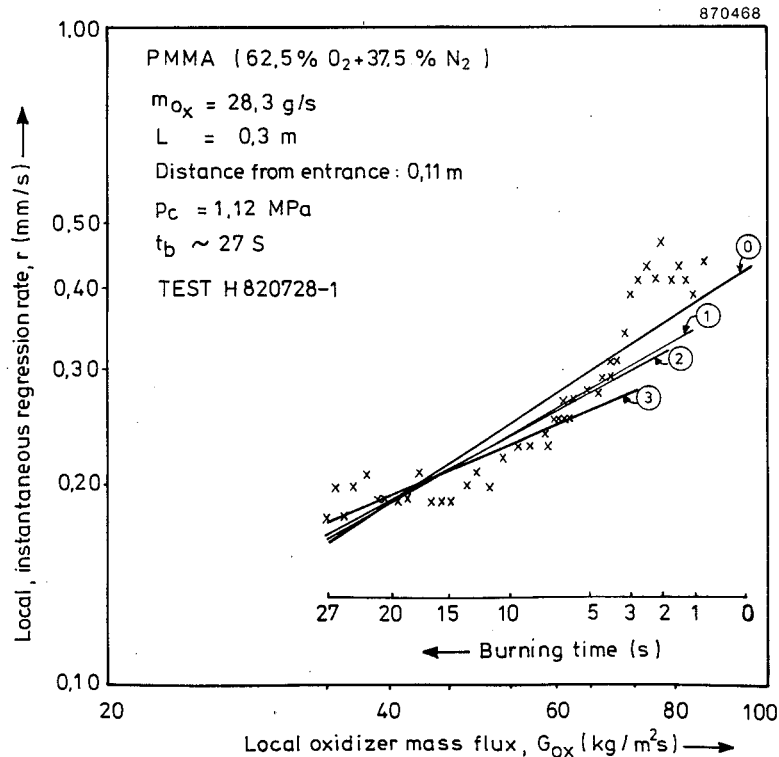

Figure 4.5. Instantaneous regression rate dependance on mass flux.
Linear fits of all data between 27 s and: 0 s : ⓪, 1 s : ①, 2 s : ②, 3 s : ③.

Figure 4.5 shows a typical plot of the regression rate versus the oxidizer mass flux during a single testrun. The four linear fits clearly indicate that data from the first two or three seconds should be discarded in order to obtain a fairly acceptable fit. In view of the conclusions of section 4.1 this hardly is a surprise. The correlation parameters are summarized in table 4.1.

Table 4.1. Regression rate coefficients and exponents for experimental H820728-1

Correlated data lay in the time interval between t = 27 s and t =	b[1])	m[1])
0 s	$5,8599.10^{-3}$	0,9431
1 s	$1,0402.10^{-2}$	0,7906
2 s	$1,1698.10^{-2}$	0,7607
3 s	$2,0906.10^{-2}$	0,6052

[1]) $r = b\, G_{ox}^{m}$, with r in mm/s and G_{ox} in (kg/m² s).

In the following sections, only data from three seconds after ignition onward will be correlated.

A physical explanation of the high initial regression rate might be based on the process of building a laminar sublayer. During the first few seconds this sublayer is incomplete, and heat transfer to the fuel surface is less hampered. The surplus in heat is consumed by pyrolyzing fuel, since this heat cannot diffuse into the fuel compound. A similar observation can and will be made with respect to an oscillating boundary layer (section 4.3).

All other experiments showed more or less the same trend as the one depicted in Figure 4.5. Since the chamber pressure, $\bar{P}_{c}$, was badly reproduced and regression rate depends on $\bar{P}_{c}$, it was no use in presenting all data in one single figure.

Although some scatter in the local and instantaneous regression rate remains, it is concluded that if dr/dt is less than 0,01.r/s per second, a correlation of the form (4.2) can be used to fit instantaneous regression rate data.

4.2.1 Mass fluxes of pure oxygen

Figure 4.6 shows the results of two experiments where pure oxygen has been used as oxidizer. No rearward facing step has been employed and it has been observed that the internal bore remained fairly cylindrical except for the forward end due to injection disturbances.
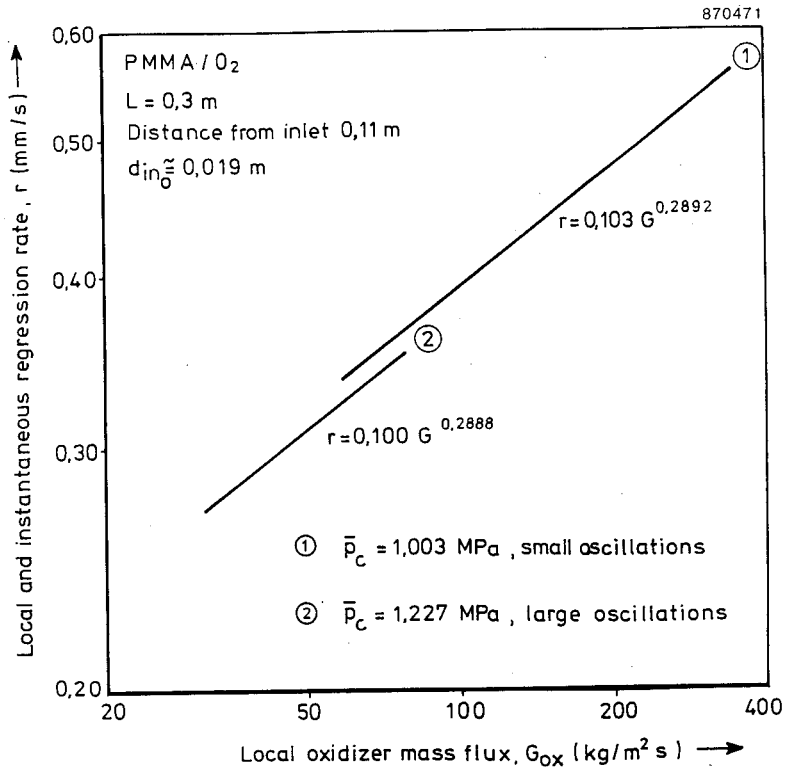

Figure 4.6. PMMA/O_2 dependance on mass flux of regression rate.

As the oxygen mass flow rates were different for the two testruns, while the initial port diameter was kept the same, this resulted in different regions for the oxidizer mass flux. The regression rate coefficient of the higher mass flux experiment is somewhat larger than the one for the lower mass flux testrun. This may be due to the appearance of chamber pressure oscillations (see Fig. 4.7). Such pressure oscillations increase the regression rate considerably. This phenomenon is discussed more fully is Section 4.3.
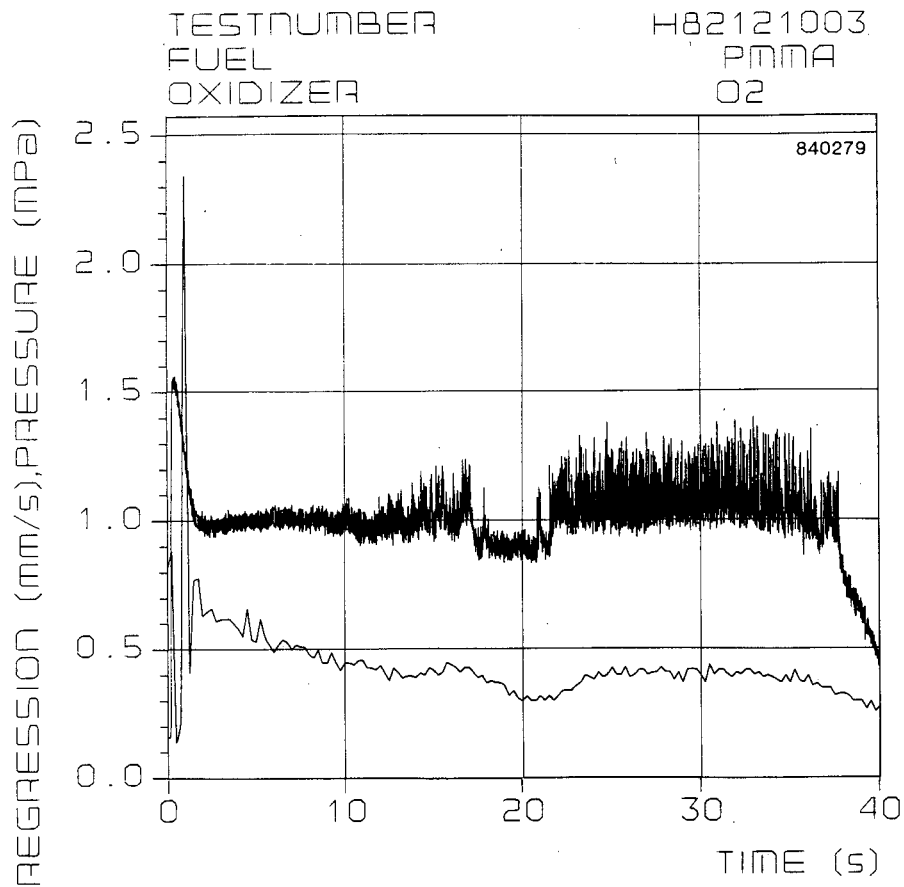
Figure 4.7. Pressure history and local regression rate history
during oscillatory combustion.

The mass flux exponents of about 0,29, observed during these experiments are considerably lower than the exponents reported in the literature [3,8]. These values vary between 0,4 and 0,8. However, these values apply to mean regression rates and mean oxidizer mass fluxes, while differences may also be caused by a different test configuration, different burning times etc.

4.2.2 Mass fluxes of mixtures of O_2 and N_2

Figure 4.8 shows linear curve fits of data obtained from experiments with PMMA where the oxygen content of the oxydizer was varied between 40 and 100%. Table 4.2 summarizes values of the parameters of the correlation $r = b\ G_{ox}^m$ with G in $kg/m^2 s$ and r in mm/s.
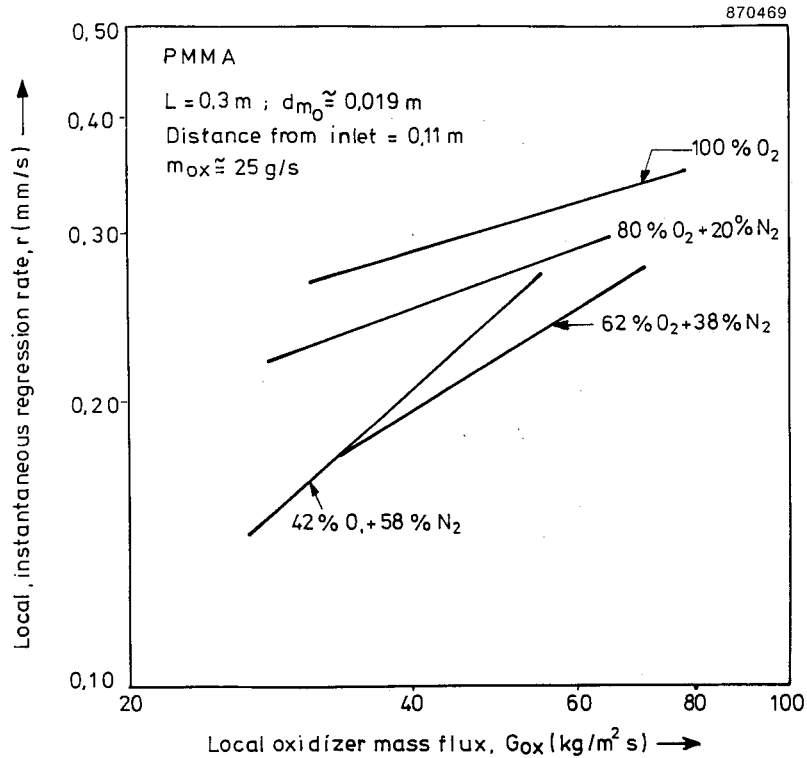
Figure 4.8. Effect of oxygen content on regression rate.

The following conclusions are drawn:

- In general, the regression rate decreases with decreasing oxygen content of the oxidizer. The testrun where a mixture of 42% O_2 and 58% N_2 as oxidizer was employed has a different overall mean equivalence ratio (see Table 6.3), indicating a fuel rich combustion environment.
  This is clearly connected to a relatively high regression rate whence this testrun is different from the others.
- The mass flux exponent increases with decreasing oxygen content in the oxidizer.

One experiment has been performed with PMMA and a mixture of 21% O_2 and 78% N_2 as oxidizer. To obtain sustained combustion a rearward facing step as a flame stabilizer was employed. As the use of a step dramatically affects the combustion behaviour of PMMA, see also section 4.3, this experiment cannot be compared with the previously discussed testruns.

Table 4.2. Regression rate coefficients and exponents for tests with PMMA and various oxidizers.

fuel	oxidizer	chamber pressure (MPa)	equivalence ratio (-)	b[1])	m[1])
PMMA	100% O_2	1,227	0,61	0,1000	0,2888
PMMA	80% O_2 + 20% N_2	1,255	0,78	0,0680	0,3554
PMMA	62% O_2 + 38% N_2	1,123	0,72	0,0209	0,6052
PMMA	42% O_2 + 58% N_2	0,823	1,23	0,0074	0,9027

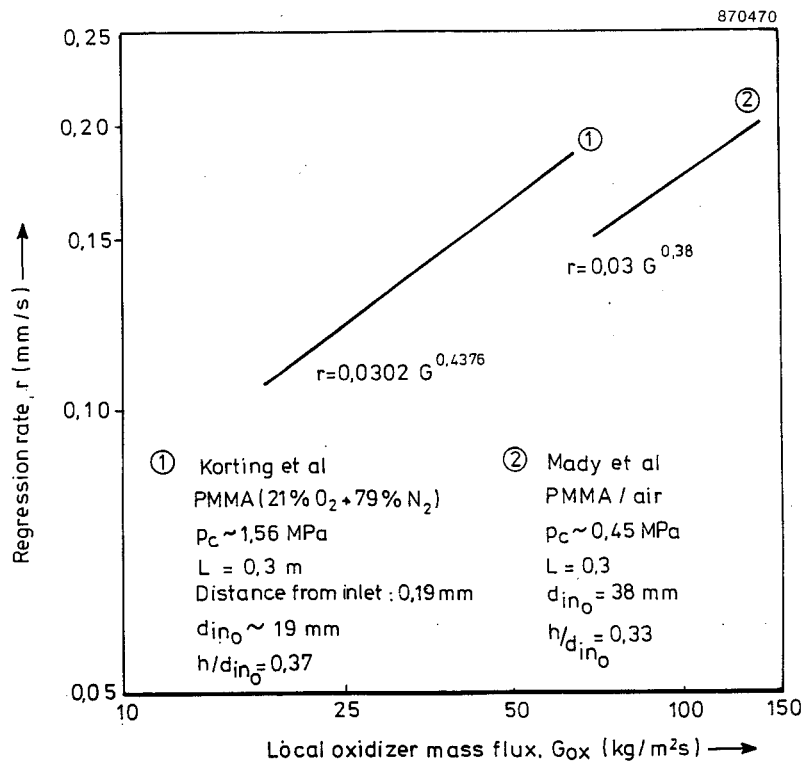[1]) $r = b\,G_{ox}^{m}$ with r in mm/s and G in kg/m^2 s.

Figure 4.9. Effect of mass flux on regression rate with flame stabilization. See also Mady et. al., ref. 9.

It is noted that for this experiment the ultrasonic probe was located at 190 mm from the forward end of the fuel grain. Therefore the regression rate data obtained are considered to be unaffected by the recirculation zone. The instantaneous regression rate data are plotted versus the instantaneous oxidizer mass flux data in Fig. 4.9. For comparison, the relationship between the regression rate and the oxidizer mass flux as obtained by the weight loss method by Mady et

al [9] is also plotted. Their relationship however was established at lower combustion pressure level. It is interesting to note that there is not much difference between the mass flux exponents of the two relationships. Probably the h/d_{in_o} ratio is more important than the value of d_{in_o} itself.

This comparison also indicates, that a relationship of the form $r = a\ G^b$ under some conditions can be applied to local and instantaneous values of regression rate and oxidizer mass flux.

4.2.3 Influence of the height of the rearward facing step

When cold air is used as an oxidizer no sustained combustion of PMMA can be obtained without using a suitable flame holder. A rearward facing step with an appropriate stepheight was employed succesfully as a flame stabilizer. For oxidizers with at least 40% oxygen content it has been established that no flame holder is required. However, so as to investigate the effect of a step on the regression rate, testruns with oxidizers containing 40 to 100% O_2 were also performed with an additional rearward facing step.
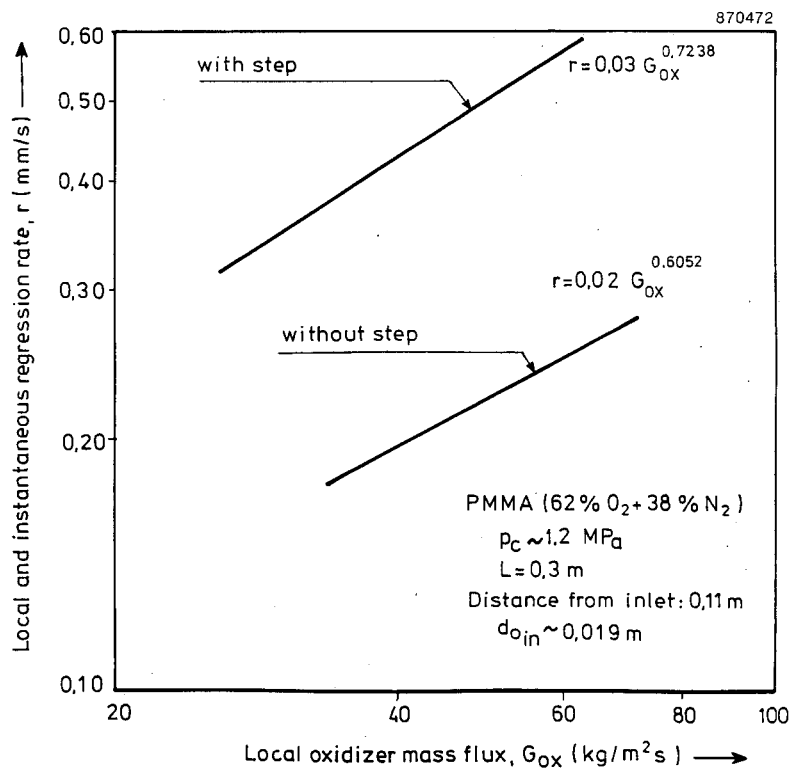

Figure 4.10. Effect of a rearward facing step on
regression rate behaviour.

Typical results are presented in Figs. 4.10 and 4.11. From both figures it is concluded that the presence of a step increases the regression rate tremendously. This applies to the regression rate along the entire fuel grain length. The regression rate is particularly high in that part of the fuel grain that is adjacent to the recirculation zone of the flow (Fig. 4.12). The occurrance of some pressure oscillations increases the regression rate even more, although these oscillations by themselves do not account for the large increase in the regression rate (see section 4.3).
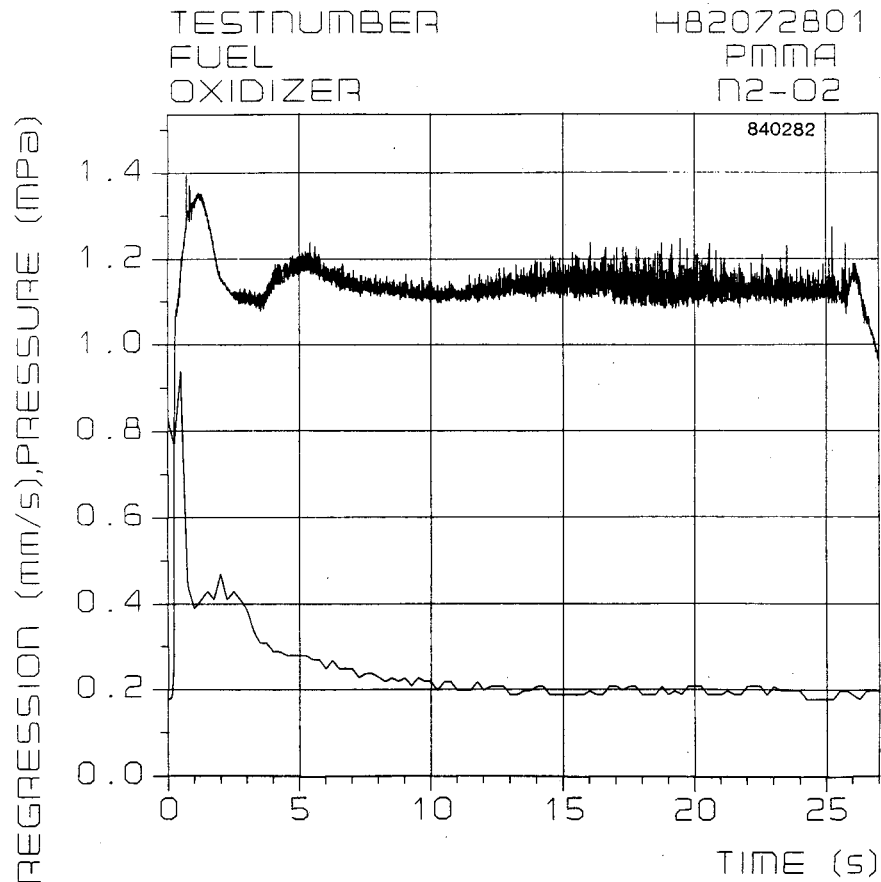

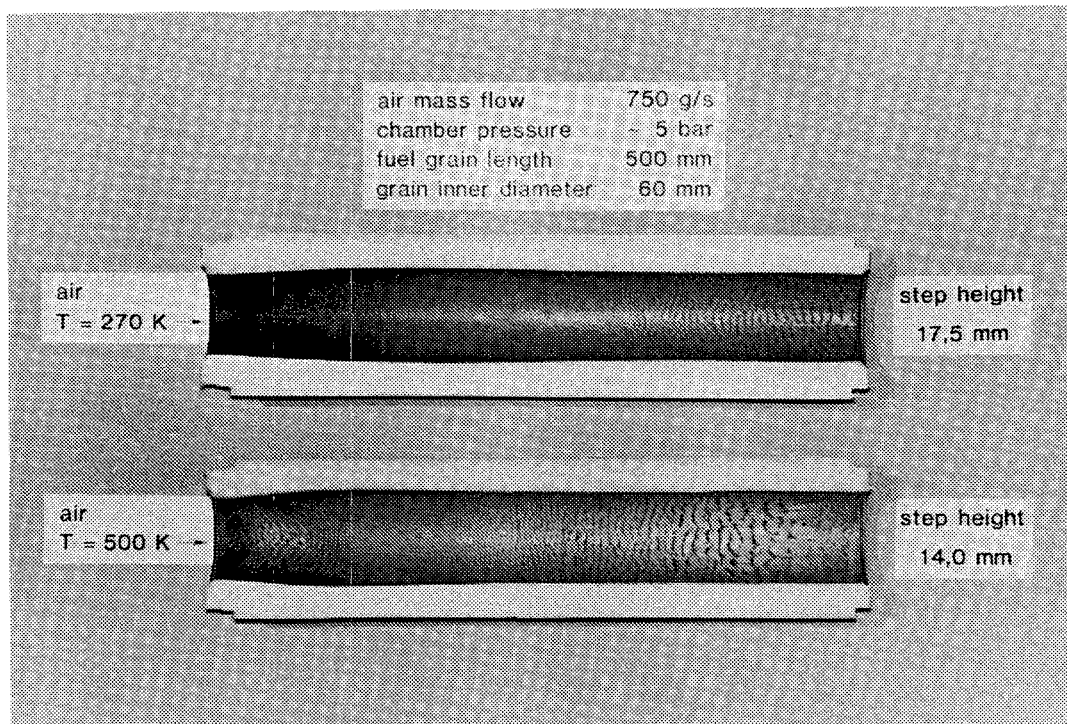Fig. 4.11. Effect of flame stabilisation on regression rate history.

Fig. 4.12. Grain profile after a combustion experiment during which a rearward facing step was employed. In the recirculation zone area the regression rate behaviour is more pronounced.

4.3 Pressure oscillations and regression rate

The occurrance of pressure oscillations enhances the regression rate. This phenomenon was already observed during two testruns in which severe chamber pressure oscillations occurred during combustion.

The first testrun which will be discussed is an experiment with PMMA and pure oxygen, see Fig. 4.7. For an unknown reason severe pressure oscillation took place, the frequency being about 800 Hz corresponding to the first acoustic mode of the motor. At about 12 s after ignition some oscillations start to develop which is suddenly followed by a dip of the mean pressure. At about 22 s severe oscillations develop which continue until burnout. It is noted that initially one our the slowly decreasing regression rate occurs that was discussed in section 4.1. Then, the regression rate is more or less constant or even increases, which corresponds to the developing oscillations.

The dip in the regression rate around 20 s corresponds to the dip in the pressure, clearly exhibiting the dependency of the regression rate on pressure and the phase shift between pressure and regression that was discussed in section 4.1. When severe oscillations develop the regression rate increases again. If no oscillations or variations in pressure would have taken place, a monotonely decreasing regression rate because of decreasing oxidizer mass flux would have been found (see section 4.1).
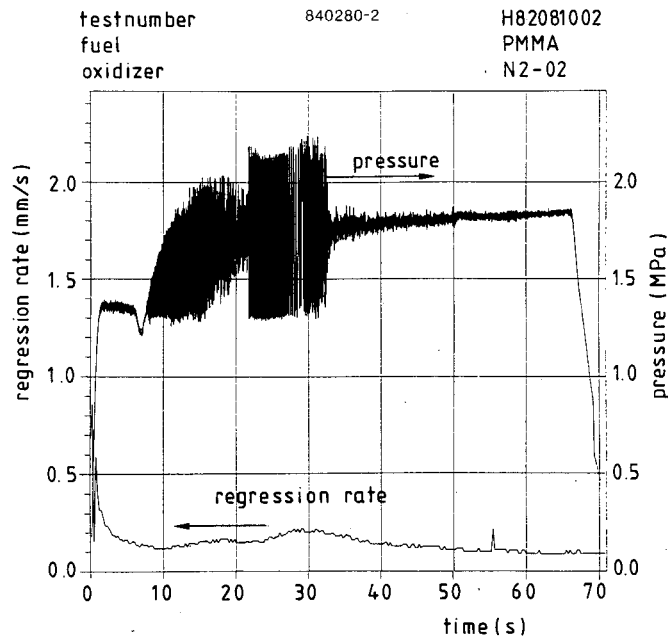

Figure 4.13. Increased regression rate due to oscillatory combustion.

A second example is a testrun with PMMA and a mixture of 21% O_2 and 79% N_2 (mass-based). The pressure history and the instantaneous regression rate are shown in Fig. 4.13. To achieve sustained combistion a flame holder was used. For ignition, hydrogen less been supplied during the first 7 seconds. Obviously the combustion had difficulty in achieving steady state conditions. The transient process is apparently associated with combustion oscillations. After about 32 s oscillations suddenly cease and steady combustion takes place.
Again it is evident that the strong pressure causes an increase in regression rate, and that the latter does not keep pace with pressure, but responds to changes after a certain time.

It is obvious from the above and other observations that the URRA is a useful tool in discovering time-dependent phenomena concerning regression rate. The

increase in regression rate due to oscillations was already known for averaged values [3]. We now have learned that this 'large-scale law' also applies to local and instantaneous regression, but that possibly the response to changes is not immediate.

5 CONCLUSIONS

With the aid of the URRA, an ultrasonic pulse echo technique, information was obtained about the instantaneous and local regression rate in solid fuel combustion chambers. This technique is a very promising tool for combustion diagnostics.

Well-established correlations in terms of time- and space averaged quantities were re-examined with the locally and instantaneously measured quantities as obtained with the URRA. The relationships proved to be applicable to the latter quantities if transient phenomena occurred relatively smoothly.

During combustion a melt layer is built up at the fuel surface. This building up process is not accounted for in the data analysis applied. If at all times the temperature and heat flux in the melt layer would be known, the data analysis would benefit and URRA results would become extremely accurate. At present the URRA, if applied at times larger than about five seconds after ignition, is fairly accurate.

6 REFERENCES

1 P.A.O.G. Korting, 'Onderzoek naar het stromings- en verbrandingsgedrag in een VBVK, inclusief meetprogramma's'. FAEDUT/PMLTNO, Report LR-460/PML 1985-C9, SFCC publication 26, Delft/Rijswijk (in Dutch).

2 P.A.O.G. Korting, H.F.R. Schöyer, 'Solid Fuel Combustion Chamber Research in the Netherlands'. FAEDUT/PMLTNO, Report LR-444/PML 1984-C74, SFCC publication 20, Delft/Rijswijk, September 1984.

3 Y.M. Timnat, P.A.O.G. Korting, 'Hybrid Rocket Motor Experiments'. FAEDUT/ PMLTNO, Report LR-453/PML 1984-C04, SFCC publication 23, Delft/Rijswijk, February 1985.

4 C.C. Groothoff, 'Ervaringen bij het NLR omtrent het hybriede verbrandings-proces', NLR Report CC 58.2, May 1967 (in Dutch).

5 P.A.O.G. Korting, E.H. den Hertog, H.F.R. Schöyer, 'Determination of the regression rate of solid fuels in solid fuel combustion chambers by means of the ultrasonic pulse-echo technique. Part I. The measurement technique'. FAEDUT/PMLTNO, Report LR-453-I/PML 1985-C5, SFCC publication 18, Delft/ Rijswijk.

6 H.S. Carlslaw and J.C. Jaeger, 'Conduction of heat in solids'. Oxford Univ. Press, London, 1959.

7 C.W.M. van der Geld, J. Mies, R. Ramaprabhu, 'Numerical solutions of heat transfer problems in cylindrical geometries'. Memorandum M-465, Report PMLTNO 1987-C18, SFCC publication 42, Delft University of Technology, 1987.

8 R.J. Muzzy, 'Applied Hybrid Combustion Theory'. AIAA paper no. 72-1143, November/December, 1972.

9 C.J. Mady, P.J. Hickey, D.W. Netzer, 'Combustion behaviour of solid fuel ramjets'. Journal of Spacecraft and Rockets, Vol. 15, nr. 3, May-June 1978.