SOLID FUEL COMBUSTION CHAMBER
PROGRESS REPORT XI

Tenth Phase, January-June 1987

H. Wittenberg
P.A.O.G. Kortings
T. Wijchers
P.J.M. Elands
F. Dijkstra
R.P. van den Berg
J. van den Brand

Delft/Rijswijk, The Netherlands

November 1987
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# CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Introduction</td>
<td>2</td>
</tr>
<tr>
<td>2. Financial support</td>
<td>3</td>
</tr>
<tr>
<td>3. Expenditures</td>
<td>4</td>
</tr>
<tr>
<td>4. Project management</td>
<td>5</td>
</tr>
<tr>
<td>5. List of persons involved in the VBVK project during the periode January-June 1987</td>
<td>6</td>
</tr>
<tr>
<td>6. Theoretical developments</td>
<td>8</td>
</tr>
<tr>
<td>6.1. Introduction</td>
<td>8</td>
</tr>
<tr>
<td>6.2. Time dependent version of COPPEF</td>
<td>8</td>
</tr>
<tr>
<td>6.3. Investigation of the differences between the turbulent diffusion flame model and the finite chemical kinetics model</td>
<td>10</td>
</tr>
<tr>
<td>6.4. Implementation of the single-sided sudden expansion configuration in the COPPEF computer program</td>
<td>11</td>
</tr>
<tr>
<td>7. Experiments</td>
<td>14</td>
</tr>
<tr>
<td>8. Optical equipment and experiments</td>
<td>18</td>
</tr>
<tr>
<td>8.1. The particle generator</td>
<td>18</td>
</tr>
<tr>
<td>8.2. The formation of soot; absolute emission coefficient</td>
<td>18</td>
</tr>
<tr>
<td>8.3. The two colour pyrometer</td>
<td>18</td>
</tr>
<tr>
<td>9. Utilization</td>
<td>21</td>
</tr>
<tr>
<td>10. Users committee</td>
<td>22</td>
</tr>
<tr>
<td>11. Contacts</td>
<td>23</td>
</tr>
<tr>
<td>13. Planned program for the period July-December 1987</td>
<td>26</td>
</tr>
<tr>
<td>15. SFCC Publications</td>
<td>28</td>
</tr>
<tr>
<td>16. References</td>
<td>29</td>
</tr>
<tr>
<td>17. Acronyms</td>
<td>30</td>
</tr>
</tbody>
</table>
1 INTRODUCTION

The tenth phase (January-June 1987) of the Solid Fuel Combustion Chamber Project, DLR 15.0120 is described.

The primary aim of the project is to gain a thorough understanding of the flow and combustion processes as they occur in solid fuel grains, which will be achieved by a combination of experimental and theoretical research. The project has been extensively described elsewhere [1] and the scope of the project has remained the same since this publication.

The SFCC project is carried out jointly by the Prins Maurits Laboratory TNO and the Faculty of Aerospace Engineering of Delft University of Technology and is partly supported by the Technology Foundation (Stichting voor de Technische Wetenschappen), the Organization for Applied Scientific Research (TNO) and Delft University of Technology (DUT).

In this report also the planned activities for the next half year period (July-December 1987) are given in detail, while also a long term planning up to and including 1990 is presented.
2  FINANCIAL SUPPORT

By June 1987, the Technology Foundation informed the project group that she will support the SFCC project for another two years starting from January 1987.

Furthermore, the Organization for Applied Scientific Research decided to provide the project with additional funding to ensure continuation of this research.

Because of this joint support, Dr. T. Wijchers and mr. J. van den Brand can be hired until January 1989, while a position for a research assistant for a three years period is also made available.

The joint support resulted into kfl 125 for materials, small equipment and domestic travel, while kfl 175 may be used for the purchase of LDV equipment.

Apart from this, FAEDUT has released fundings for an assisting engineer for a three years period.
3 EXPENDITURES

During the period January-June 1987, the following expenditures have been charged to STW,

small equipment, gases and fuels

kfl 28.3
During the period January-June 1987, the project group consisted of:
- Prof.ir. H. Wittenberg (principal investigator FAEDUT, project manager)
- Ir. P.A.O.G. Korting (principal investigator PMLTNO)
- Dr. C.W.M. van der Geld (senior scientist FAEDUT, assistant project manager)
- Dr. T. Wijchers (senior scientist STW)
- Ir. J.B. Vos (research assistant STW)
- Ir. P.J.M. Elands (research assistant PMLTNO)
- Ing. F. Dijkstra (assisting engineer FAEDUT)
- Ing. R.P.M. van den Berg (assisting engineer PMLTNO)
- J. van den Brand (assistant to experimental work TNO/STW)

On May 1, 1987, Dr. C.W.M. van der Geld left the project group to return to Eindhoven University of Technology. He will be succeeded by Ir. B.T.C. Zandbergen who will start his activities by September 14, 1987.

For the newly available positions of research assistant and assisting engineer announcements appeared in Intermediair. As a research assistant, Ir. J.P. de Wilde was selected. He will start working on fuel surface and subsurface processes by September 1, 1987. Ing. F. Dijkstra has been appointed as assisting engineer and has started working by June 1, 1987.

On April 23, Ir. J.B. Vos received his Ph.D. degree for his work on calculation of turbulent reacting flows with a combustion model based on finite chemical kinetics. After leaving the project group on January 15, he started his new job at the Technical University of Lausanne by March 1. However, as an adviser he will remain involved in the SFCC project. As his successor, Ir. P.J.M. Elands was selected per January 1, 1987.
5 LIST OF PERSONS INVOLVED IN THE SFCC PROJECT DURING THE PERIOD JANUARY-JUNE 1987

In addition to staff members assigned to the project by FAEDUT, PMLTNO and STW, the following persons have contributed to the project:

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution</th>
<th>Dates</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>J. van Egmond</td>
<td>Apprentice Hogeschool Haarlem</td>
<td>1-12-1986 until 1-3-1987</td>
<td>Calibration CH₄-SCMC, vitiator exp.</td>
</tr>
<tr>
<td>G. Heppe</td>
<td>Apprentice Hogeschool Haarlem</td>
<td>1-3-1987 until 15-6-1987</td>
<td>Calibration report SCMC's, testing.</td>
</tr>
<tr>
<td>R.G. Veraar</td>
<td>Student Hogeschool Haarlem</td>
<td></td>
<td>Thesis work: Modelling of the flow through a single sided sudden expansion.</td>
</tr>
<tr>
<td>J.P. de Wilde</td>
<td>Student FAEDUT</td>
<td></td>
<td>Thesis work: Pyrolysis in connection with the SFCC.</td>
</tr>
<tr>
<td>E. de la Rambelje</td>
<td>Student FAEDUT</td>
<td></td>
<td>Thesis work: Design manufacture and testing of a N₂O₄/PE hybrid rocket motor system.</td>
</tr>
<tr>
<td>R. Koolen</td>
<td>Student FAEDUT</td>
<td></td>
<td>Third year assignment: Boron combustion models.</td>
</tr>
<tr>
<td>W.J.A.M. Aarts</td>
<td>Student FAEDUT</td>
<td>26-3-1986 until 1-2-1987</td>
<td>Design and development of a third pyrometer.</td>
</tr>
</tbody>
</table>
J.A.M.A. Mies
Student FAEDUT
1-1-1987 until 1-4-1987
Calculation of temperature profile in solid fuel grains.

G.C. Klein Lebbink
Student assistant FAEDUT
Data reduction and engineering thesis on the effect of surface discontinuities on channel flow with blowing.
6 THEORETICAL DEVELOPMENTS

6.1. Introduction

In the period of January-June 1987, theoretical work concentrated on the following topics:
- an analytical study of laminar channel flows;
- computational modelling of flow and combustion, employing algebraic finite volume methods (COPPEF);
- computational modelling of build-up and shedding of large vortex structures, employing Lagrangian vortex methods (VORTEX);
- computational modelling of the transient temperature behaviour of cylindrical bodies under a variety of boundary conditions;
- pyrolysis study.

The analytical study, in cooperation with the group of prof. Steketee was completed in this period. A report has been published.

Ir. P.J.M. Elands continued the work of dr.ir. J.B. Vos with COPPEF. Some results are discussed below.

The vortex modelling was terminated, due to the leave of dr. C.W.M. van der Geld. A report is in preparation.

The modelling of temperature prediction in fuel grains was completed in this period. A report has been published.

The MSc study on pyrolysis was completed. A report is in preparation.

6.2 Time dependent version of COPPEF

The general differential equation used in the COPPEF computer program [3] can be written in the following form:

\[
\frac{\partial}{\partial t} (\rho \phi) + \frac{\partial}{\partial x} (\rho u \phi) + \frac{\partial}{\partial y} (\rho v \phi) - \frac{\partial}{\partial x} (\Gamma \frac{\partial \phi}{\partial x}) - \frac{\partial}{\partial y} (\Gamma \frac{\partial \phi}{\partial y}) = S_\phi
\] (1)
Integration of the first term of this equation over the control volume yields

\[
\int_{j}^{j+1} \int_{y}^{y+1} \int_{x}^{x+1} (\rho \Phi) \, d\theta \, dx \, dy = \frac{\rho \text{Vol}}{\Delta t} (\Phi_p - \Phi_p^0) \tag{2}
\]

where \( \Phi_p^0 \) denotes the old time level and \( \Phi_p \) the new time level.

This term can be added to the steady state algebraic difference equation [3] in two manners.

The first manner is to split this term, yielding for the algebraic difference equation

\[
(a_p + \frac{\rho \text{Vol}}{\Delta t}) \Phi_p = \sum_j a_{j,j} \Phi_j + S_u \text{Vol} \frac{\rho \text{Vol}}{\Delta t} \Phi_p^0
\]

The term \( \rho \text{Vol}/\Delta t \) is added to the \( S \) component of the source term and the term \( (\rho \text{Vol}/\Delta t) \Phi_p^0 \) is added to the \( S_p \) component of the source term.

The advantage of this method is that it is not necessary to store two time levels of the dependent variable \( \Phi \), because \( S_p \) is connected with the new time level. This method however is not completely exact, because in the pressure equation at two different time levels the same temperature \( T \) is employed for the \( dp/\Delta t \) term, which is written as \( d(p/p) T/\Delta t \). Another severe limitation of this method is that errors can accumulate [2].

With this method it was possible to calculate a flow without combustion, yielding the same result at \( t \) is infinity as the steady state version of COPPEF.

For a flow with combustion however a convergent solution could not be obtained. In that case the residuals of the equations did accumulate.

The second method of handling the time term in Eq. 2 is to store all the dependent variables \( \Phi \) at two time levels. In the pressure equation [3] the \( dp/\Delta t \) term can be calculated exactly now. Because of employing this method, errors will not accumulate when \( t \) goes to infinity.

Furthermore it becomes possible to perform iterations on the equations within one time level, which is benificial especially when large gradients occur. For the flow with combustion however the boundary conditions for the process of starting up are difficult to prescribe and results of calculations for flows with combustion could still not be obtained.
Therefore it was decided to do two things. First the coupling of the heat flux from the main flow to the wall with the fuel injection velocity is to be made and secondly as initial conditions for the calculations with the time-dependent version of COPPEF a fully developed flowfield will be taken. In that way the difficulties of the process of starting up will be avoided. These difficulties occurred mostly with the turbulence equations and the energy equation.

6.3 Investigation of the differences between the turbulent diffusion flame model and the finite chemical kinetics model

In the COPPEF computer program three combustion models are incorporated. Two models are based on the diffusion flame concept, one is based on finite rate chemical kinetics [3]. Here the turbulent diffusion flame model and the finite rate chemical kinetics model are compared.

The turbulent diffusion flame model has included the effect of turbulence on the combustion process by means of a probability density function. The dissociation of species at high temperatures is not included. The finite rate chemical kinetics model has not included the effect of turbulence on the combustion process, but the dissociation of species is accounted for [1,3].

Calculations were carried out to compare the results obtained with both models. Polyethylene was taken as a fuel and air as oxidizer. It was tried to choose conditions in such a way that the temperature did not go beyond the level of significant dissociation.

In that way from the results of both calculations, from the differences in the temperature and the mass fractions, the effect of turbulence on the combustion process can be extracted.

However, from the calculations with the finite rate chemical kinetics combustion model it appeared that it is not possible - at least for this combination of fuel, oxidizer and conditions - to achieve a desired solution. Or the flame extinguished or the combustion process was sustained but in the latter case temperatures were significantly higher than the no-dissociation level.
6.4 Implementation of the single-sided sudden expansion configuration in the COPPEF computer program

The single-sided sudden expansion configuration, also called the backward facing step configuration, could not yet be calculated with the COPPEF computer program. This configuration however has been widely used for experiments and calculations [4]. Therefore it was decided to incorporate this configuration in the COPPEF computer program and to compare the results of calculations with theoretical and experimental data from the literature.

The main difference with the geometries which were used previously is that this is an asymmetric configuration, see Figure 6.1.

![Fig. 6.1. The single-sided sudden expansion configuration.](image)

Here to the grid system had to be adapted, especially near the northern solid wall. At this time also wall functions had to be employed. A description of this modification is given by Veraar [4].

From the calculations carried out with this configuration follows that the flow is very sensitive to the inlet conditions, i.e. the inlet turbulence level and the inlet velocity profile. Figure 6.2 illustrates this by showing the reattachment length/stepheight ratio as a function of the inlet turbulence intensity.

To show the influence of the inlet velocity, the difference between a fully developed inlet velocity profile and an uniform velocity profile for the same mass flow rate is illustrated in Figure 6.3, where a turbulent kinetic energy profile in radial direction is given. The differences in turbulent kinetic energy lead to different flowfields.
Fig. 6.2. Reattachment length as a function of the inlet turbulence intensity.

Other calculations show the effect of the gridsize on the accuracy of the solution, the effect of variation of the expansion ratio, the effect of variation of the Reynolds number and the effect of changing the computational domain [4].

Furthermore calculations were carried out to compare the results with experimental and numerical data from the literature.

These calculations show that the results obtained with the COPPEF computer program are in reasonable agreement with experimental data [4]. The calculated reattachment length is in close agreement with reattachment lengths obtained with other computer codes which also use the k-ε turbulence closure model.

This configuration will be made suitable to calculate flows with combustion.
Fig. 6.3. Comparison of normalized turbulent kinetic energy profiles obtained with and without a fully developed inlet velocity profile at $x/stepheight = 1.64$, where $x$ is the coordinate in axial direction ($x = 0$ at the inlet).
During the period January-June 1987, several experiments with PMMA, PS and PE were performed and analysed.

Experiments with heated air showed an increase in regression rate (determined by weight loss of the fuel) with air inlet temperature for all fuels tested (Fig. 7.1). At ambient temperature, the regression rates of PE and PMMA are about the same, while the regression rate of PS is about 40% higher. At higher temperatures though, the differences get larger, as can be seen in Fig. 7.1. The effect of air inlet temperature on the regression rate of PMMA at various pressures is shown in Fig. 7.2. Fig. 7.3 summarizes the performance of the three different fuels at elevated temperatures. The Figure clearly indicates the high potential of PS.

Besides experiments with heated air, some additional experiments with PE at ambient temperature have been performed to further evaluate the influence of mass flow and pressure on regression rate. Results are shown in Figs. 7.4 through 7.6.

In the framework of the pyrolysis study, several experiments with PMMA have been carried out to determine the surface temperature and the composition of the pyrolyzing fuel. It was found that apart from the monomer MMA also methane is formed and that the methane/MMA ratio increases with chamber pressure. Surface temperatures were found to be in the range of 750-850 K.

The regression rate in a burning solid fuel combustion chamber can also be measured with the aid of a pulse echo technique. With this technique, the time interval between emission and (after reflection) reception of an acoustical pulse is measured. The product of this time interval with the speed of sound in the material employed, is equal to two times the wall thickness. However, the speed of sound in grain materials, used for the SFCC, is temperature dependend. Although the speed of sound is known as a function of temperature for various materials, reliable measurements can be carried out only when the temperature profile inside the grain wall is known.
Fig. 7.1
PMMA / AIR
Mar=250 g/s L=300 mm H/Dpo=0.29 Dpo=60 mm
+ P=3.6-6.3  ▲ P=7.5-8.3  ● P=9.4-11.4
(bar)         (bar)         (bar)

Regression rate (mm/s)

35
30
25
20
15
10

Air inlet temperature (K)

300 400 500 600 700 800

Fig. 7.2
PE/AR and PS/AIR : L=300 mm : Dpo=40 mm
Mar=150 g/s : h/Dpo=0.3125
▲ PE
P=6,3-8,8bar
● PS
P=6,8-7,7bar

Regression rate (mm/s)

0.60
0.50
0.40
0.30
0.20
0.10

Air inlet temperature (K)

250 350 450 550 650 750

Fig. 7.3
HYDROCARBON PERFORMANCE
Tair=500 K  Pc=8 bar

HEAT FLUX (MJ/m²s)

20
10

PMMA PE PS

FUEL
Fig. 7.4
PE/AIR effect of pressure
$D_{op}=40\text{mm} \quad h_{op}=0.3125 \quad L=300\text{mm} \quad T_{ambient}$
$\Delta M_e=150\text{g/s}$

Regression rate (mm/s)

Pressure (MPa)

0.40
0.35
0.30
0.25
0.20
0.15
0.10
0 0.50 1 1.50 2 2.50

Fig. 7.5
PE/AIR effect of pressure
$D_{op}=40\text{mm} \quad h_{op}=0.3125 \quad L=300\text{mm} \quad T_{ambient}$
$\Delta M_e=150\text{g/s}$

Efficiency

Pressure (MPa)

0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0 0.50 1 1.50 2 2.50

Fig. 7.6
PE/AIR Effect mass flux
$D_{op}=40\text{mm} \quad h_{op}=0.3125 \quad L=300\text{mm} \quad T_{ambient}$
$\Delta p=0.45-0.51 \quad \Delta p=0.84-1.0 \quad \bullet p=1.3-1.4$

Regression rate (mm/s)

Mass flux (kg/m2s)

0.50
0.40
0.30
0.20
0.10
50 100 150 200 250
After the development of a special mounting technique, thermocouples were mounted at specific distances from the inner surface of a poly-ethylene grain at various locations along the axis.

During combustion, the thermocouple signals were recorded. Hence these signals gave the temperatures at various distances from the burning inner surface at any moment as far as the thermocouples had not been burned away.

From these results, the distance from the burning surface to the thermocouples as well as the temperatures, and hence the temperature profile, are obtained. Figure 7.7 shows such profiles at 300 mm from the SFCC entrance as a function of time.

This research was carried out in cooperation with DFVLR in Germany within the framework of a DEA.

![Graph showing temperature profiles](image)

**Fig. 7.7. Temperature profiles as a function of time after ignition.**
8 OPTICAL EQUIPMENT AND EXPERIMENTS

8.1 The particle generator

The particle generator, being discussed in [5], has been constructed and installed. The generator is filled with a mixture of 94% MgO (being the particle material), 3% A10 and 3% Aerosil. The two additives care for electrical neutralisation and prevention of clogging respectively. Initial experiments, where the scattered light from a laserbeam was measured, showed a useful density of particles. This density depended on the pressure in the air supply line, on the air massflow and on the adjustment of the taps between the generator and the air supply line.

8.2 The formation of soot; absolute emission coefficient

In connection with calculations on the influence of soot formation on the regression rate [5], an absolute value of the emission coefficient must be known.

To determine this quantity, absolute values of the spectral intensities of the spectra from the SFCC have been carried out at various temperatures with the aid of a calibrated tungsten ribbon lamp. Correcting for the emission coefficient of tungsten, an absolute scale could be established in the graph of Fig. 9.1 in [5]. It turned out that the absolute value of the logarithm of the emission coefficient can be obtained by subtracting the value 6.3 from the numbers along the vertical axis in the above mentioned graph. Values greater than zero, which have no physical meaning, mainly arise from errors in the determination of the temperature.

8.3 The two colour pyrometer

A large number of temperature determinations has been carried out on SFCC experiments with the aid of the two colour pyrometer in the last period. As a result of experience, obtained that way, the following modifications on the pyrometer were applied:

- A so called monitor channel was added and calibrated to measure the emission coefficient at a wavelength of 830 nm (infra-red) and to check the pyrometer
on reliable output. The monitor output in volts is equal to the logarithm of the ratio of 10 micro amp. and the (infra-)red detector current, plus a calibrated constant voltage.

- A power supply was built in, which prevents pick-up of disturbing signals at the highly sensitive blue (green light detection) channel.
- Offset voltages were adjusted to allow for a wider calibration and measurement range.

Test experiments pointed out that

1. a homogeneous reduction of the spectral intensity (caused by soot formation) by a factor of about 100 did not cause to change the temperature determined by more than about 15 K,
2. the signals from the pyrometer as well as the monitor vary only about 3 mV in an ambient temperature range of -50°C to 300°C. This variation in output corresponds to a variation of 2-6 K in determined temperature.

The reproducibility of the temperature signal from the calibration lamp over a period of at least four months was about 8 K at temperatures lower than 1600 K and about 5 K at temperatures higher than 1600 K.

The accuracy of the pyrometer is ≤ 20 K.

Fig. 8.1 shows a typical result of the pyrometer- and monitor output.
Fig. 8.1. Typical pyrometer and monitor output results.
9 UTILIZATION

- Sonic Control and Measuring Choke (SCMC)

In the previous report the interest of UNILEVER Research in SCMC's for the measurement and control of gas flows was already pointed out. Apart from some development work that has to be done with respect to a servo mechanism to actuate the pintle of the SCMC, also production of the SCMC has to be guaranteed. Therefore, contacts have been re-established with the company DINFA in 's-Gravenzande. Earlier, this company had already expressed its interest in the production of the SCMC, provided a serious customer would appear.
The Users Committee convened for the tenth meeting on Thursday, June 18, 1987 at PML. The next convention date is planned on Tuesday, December 15, 1987 at PML.

The following persons were present:

**SPCC PROJECT GROUP**

- H. Wittenberg (project leader, principal investigator)
- P.A.O.G. Korting (principal investigator)
- T. Wijchers (spectroscopy, pyrometry)
- P.J.M. Elands (combustion modelling)
- R.P. van den Berg (data acquisition)
- F. Dijkstra (experimental work)

**USERS COMMITTEE**

- PMLTNO
  - H.J. Reitsma
- STW
  - F.C.H.D. van den Beemt
- TNO
  - Cdr. b.d. R.H. Kerkhoven
- FAEDUT
  - J.A. Steketee
- Eindhoven University
  - C.W.J. van Koppen
- ESTEC
  - H.F.R. Schöyer
- TNO MT
  - A. Verbeek
- NLR
  - J.P.F. Lindhout

The following topics were presented:

- Status and planning of the project: H. Wittenberg
- Theoretical modelling: P.J.M. Elands
- General experimental progress: P.A.O.G. Korting

Furthermore the possible applications of the SFCC were discussed. The aim of the project group concerning the future research is given in Section 14.
11 CONTACTS

For this period the following contacts can be listed:

<table>
<thead>
<tr>
<th>Institute</th>
<th>Persons</th>
<th>Subject</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEP, France</td>
<td>Th. Delaporte</td>
<td>Flow and combustion modelling HM7</td>
</tr>
<tr>
<td>SRC, Belgium</td>
<td>Flemming</td>
<td>Solid Fuel Ramjets</td>
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<tr>
<td>NEOM</td>
<td>Van Melick</td>
<td>Combustion research</td>
</tr>
<tr>
<td>Fokker Hoogevan</td>
<td>De Jong</td>
<td>Gasgenerators</td>
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<tr>
<td>NWC, USA</td>
<td>K. Schadow</td>
<td>DEA USA-NLR</td>
</tr>
<tr>
<td>TUD, Energy Supply</td>
<td>Boersma</td>
<td>Combustion research</td>
</tr>
<tr>
<td>IMI, Summerfield</td>
<td>G. Owen, P. Boszko</td>
<td>Ducted Rocket Motor Testing</td>
</tr>
<tr>
<td>FAEDUT</td>
<td>H. Bos</td>
<td>Theoretical flow modelling by analytical means</td>
</tr>
<tr>
<td>Subject</td>
<td>Status</td>
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<tr>
<td>------------------------------------------------------------------------</td>
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<td></td>
</tr>
<tr>
<td>1 Experiments with</td>
<td>Many experiments performed on PMMA, PS and PE. HTPB grain manufactured and burnt successfully</td>
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</tr>
<tr>
<td>- PMMA, PS, PE</td>
<td></td>
<td></td>
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<tr>
<td>- Other materials (waste materials, HTPB)</td>
<td></td>
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<tr>
<td>2 Study on local, accurate temp/species determination from fluorescence spectra</td>
<td>Temperature measurements performed</td>
<td></td>
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<tr>
<td>3 Feasibility study with LDV set up</td>
<td>Seeding equipment installed</td>
<td></td>
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<tr>
<td>4 Extension of software for data analysis</td>
<td>Continuous effort</td>
<td></td>
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<tr>
<td>5 Small modifications of experimental system</td>
<td>New $O_2$ SCMC installed and calibrated, safety membranes installed</td>
<td></td>
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<tr>
<td>6 Theoretical work</td>
<td>MSc thesis completed and reported</td>
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<tr>
<td>Study on fuel pyrolysis in connection with SFCC combustion (MSc thesis)</td>
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<tr>
<td>7 Theoretical work (COPPEF):</td>
<td>Time dependent version for cold flow now available</td>
<td></td>
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<tr>
<td>Extensions (time-dependent version; ignition problems etc.)</td>
<td>Single sided sudden expansion configuration implemented in COPPEF</td>
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<tr>
<td></td>
<td>Theoretical work (Vortex)</td>
<td>Preliminary study completed and reported study on vortex shedding</td>
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<td>9</td>
<td>Theoretical work: Analytical</td>
<td>MSc Thesis completed and to be reported study of laminar channel flow</td>
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</table>
| 10 | Reports/presentations | - 5 reports published  
- 4 presentations prepared, one presentation given  
- Ph.D. thesis J.B. Vos  
- Preparation work for RO Summerfield  
- Contacts with SEP |
### PLANNED PROGRAM FOR THE PERIOD JULY-DECEMBER 1987

<table>
<thead>
<tr>
<th>Subject</th>
<th>July</th>
<th>Aug</th>
<th>Sept</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
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<tbody>
<tr>
<td><strong>1</strong> Experimental</td>
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<tr>
<td>Combustion behaviour of polymers</td>
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<tr>
<td>Combustion behaviour of HTPB + additives</td>
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<tr>
<td>Fuel pyrolysis</td>
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<tr>
<td>Initiating LDV-exp.</td>
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<tr>
<td><strong>2</strong> Theoretical</td>
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<tr>
<td>COPPEF</td>
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<tr>
<td>Fuel pyrolysis</td>
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<tr>
<td><strong>3</strong> Application study</td>
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<tr>
<td>Formation study group</td>
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<td><strong>4</strong> Other activities.</td>
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<td>Hiring of personnel</td>
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<tr>
<td>Contacts (DEA's)</td>
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<tr>
<td>Reporting/presentations</td>
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</table>
14 ANTICIPATED RESEARCH 1987-1990

1 Combustion behaviour of various polymers, including HTPB + additives.

2 Fuel pyrolysis

   Manpower: STW
   - Experimental part assisted by PML

3 Vortex shedding

   Experimentally (cold flow, LDV)

4 Theoretical modeling

   4.1 Time dependent version of COPPEF, regression rate modelling
       Manpower: TNO

   4.2 Interaction turbulence/combustion
       Manpower: ZWO-proposal

   4.3 Vortex shedding
       Theoretically (DUT?)

5 Application study

   Airbreathing propulsion of launchers.
   Project group to be formed by FDO, DUT, PML and possibly NLR.
15 SFCC PUBLICATIONS

1
SFCC nr. 41
M-564
C.W.M. van der Geld, J.A.M.A. Mies, R. Ramaprabhu
Numerical solutions of heat transfer problems in cylindrical geometries.

2
SFCC nr. 44
LR-517
G.C. Klein Lebbink
Theoretical analysis of laminar incompressible flow in slender channels.

3
SFCC nr. 45
LR-523
R.G. Veraar
Calculation of the flow through a single-sided sudden expansion with the COPPEF computer program.

In addition, the following papers were presented at the VDI Fachausschuss at Hannover, Germany and at the 23rd AIAA Joint Propulsion Conference in San Diego, U.S.A. respectively:

1. C.W.M. van der Geld
Vortex shedding; Numerical simulation and impact on solid fuel combustors.

2. J.B. Vos
Simulating an Ignition Pulse in Turbulent Reacting Flows Calculated with a Finite Chemical Kinetics Combustion Model.
AIAA-87-1979

3. P.J.M. Elands
AIAA-87-1702
16 REFERENCES

1. Wittenberg, H. et al.

2. A.E.P. Veldman,
Numerieke Stromingsleer B (lecture notes); Delft University of Technology, Faculty of Mathematics, August 1986.

3. J.B. Vos,

4. R.G. Veraar,

5. Wittenberg, H. et.al.
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>COPPEF</td>
<td>Computer Program for Calculation of 2D Parabolic and Elliptic Flows</td>
</tr>
<tr>
<td>DEA</td>
<td>Data Exchange Agreement</td>
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<tr>
<td>DFVLR</td>
<td>Deutsche Forschungs und Versuchsanstalt für Luft- und Raumfahrt</td>
</tr>
<tr>
<td>DUT</td>
<td>Delft University of Technology</td>
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<tr>
<td>ESTEC</td>
<td>European Space Research and Technology Centre</td>
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<tr>
<td>FAEDUT</td>
<td>Faculty of Aerospace Engineering, DUT</td>
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<tr>
<td>FDO</td>
<td>Fysisch Dynamisch Onderzoek</td>
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<tr>
<td>HTPB</td>
<td>Hydroxy Terminated Poly Butadiene</td>
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<tr>
<td>IMI</td>
<td>Imperial Materials Industries</td>
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<tr>
<td>LDV</td>
<td>Laser Doppler Velocimetry</td>
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<tr>
<td>MT</td>
<td>Maatschappelijke Technologie</td>
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<td>NEOM</td>
<td>Nederlandse Energie Ontwikkelings Maatschappij</td>
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<td>NLR</td>
<td>National Aerospace Laboratory</td>
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<td>NWC</td>
<td>Naval Weapons Center</td>
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<tr>
<td>PE</td>
<td>Poly Ethylene</td>
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<td>PMMA</td>
<td>Poly Methyl Methacrylate</td>
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<tr>
<td>PS</td>
<td>Poly Styrene</td>
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<td>PMLTNO</td>
<td>Prins Maurits Laboratory, TNO</td>
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<td>SCMC</td>
<td>Sonic Control and Measuring Choke</td>
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<td>SEP</td>
<td>Société Européenne de Propulsion</td>
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<td>SFCC</td>
<td>Solid Fuel Combustion Chamber</td>
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<td>SRC</td>
<td>Space Research Corporation</td>
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<td>STW</td>
<td>Stichting voor de Technische Wetenschappen (Technology Foundation)</td>
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<tr>
<td>TNO</td>
<td>Organization for Applied Scientific Research</td>
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<tr>
<td>VORTEX</td>
<td>Computer programme for direct simulation of vortex shedding</td>
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<tr>
<td>ZWO</td>
<td>Nederlandse Organisatie voor Zuiver Wetenschappelijk Onderzoek</td>
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