SOLID FUEL COMBUSTION CHAMBER

PROGRESS REPORT X

Ninth phase, July - December 1986

H. Wittenberg
P.A.O.G. Korting
C.W.M. van der Geld
J.B. Vos
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Delft/Rijswijk, The Netherlands  April 1987
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1 INTRODUCTION

The ninth phase (July-December 1986) of the Solid Fuel Combustion Chamber Project (SFCC), DLR 15.0120/PBE 90743.140 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. SFCC's have a potential for aerospace propulsion (ramjets), energy conversion systems, hot gas generation, 'clean' combustion of waste and possibly others.

The SFCC project is sponsored by the Technology Foundation (Stichting voor de Technische Wetenschappen, STW) and the Project Office for Energy Research (Projectbeheer Energie Onderzoek). In addition, money and manpower have been made available in the past four years by a special funding from DUT (Beleidsruimte), while manpower and computer facilities are provided by FAEDUT and PMLTNO. Also PMLTNO provides the project with funding.

At the end of this report the planned activities for the next half year period (January-June 1987) are outlined.
2 FINANCIAL SUPPORT

The decision by the board of STW concerning continuation of financial support of this project after the eighth phase was positive but because of a temporarily stop of funding by STW no funds could be made available yet. Further support of STW can only be expected some time after January 1987.

STW was able to finance the appointment of dr. T. Wijchers (spectroscopist) until 1-1-1988, and provided some extra funds for travelling.

FAEDUT put forward funds to continue the position of ir. J.B. Vos (theoretical work) until 1-1-1987, and for the position of an assisting engineer if funding of the project by STW or other sources are assured to continue the project.

DUT has announced the ending of DUT special funding for research (Beleidsruijte) and FAEDUT acknowledged the need to avoid a financial disbalance between PMLTNO and FAEDUT because of that. For 1986 FAEDUT granted kfl. 12,5. PMLTNO released fundings for the appointment of ir. P.J.M. Elands (theoretical work) for two years, starting 15-11-1986.

TNO will provide additional financial support of kfl. 100,-- for small equipment, fuels etc. for experiments in 1987.

The research group took actions to ensure the continuation of the project in consultation with STW, TNO and DUT.
3 FINANCES

During the period July-December 1986 the following expenditures have been charged to STW:

- large investments: fl. 11,837,--
- small equipment, component for the test stand, gases and fuels: fl. 50,660,--
- foreign travel expenses: fl. 14,134,--

FAEDUT made the following expenses:

- nozzles, small optical equipment: fl. 6,500,--
4 PROJECT MANAGEMENT

Mr. J. van den Brand has started his activities on maintenance of the test installation in February 1986. In 1987 he will be employed by PMLTNO, but partly charged to the SFCC budget. From September 1986 to 1-1-1987 he was partly charged to the Department of Labour and Social Affairs.

The employments of dr. T. Wijchers, ir. J.B. Vos, ir. P.J.M. Elands were discussed in section 2 of this report. FAEDUT will release fundings for an assisting engineer as soon as ir. Elands will be appointed.

Dr. Ramaprabhu from India (Univ. of Madras) joined the group in this period.
5 LIST OF PERSONS INVOLVED IN THE SFCC PROJECT IN THE PERIOD JULY-DECEMBER 1986

In addition to staff members assigned to the project by DAEDUT, PMLTNO and STW, the following persons have attributed to the project.

W. van Duuren
Apprentice HTS-Haarlem.
15-8-1986 until 1-12-1986.
Calibration CH₄-SCMC, vitiator experiments.

J. van Egmond
Apprentice HTS-Haarlem.
1-12-1986 until 1-3-1987.
Calibration O₂-SCMC, experiments with SFCC.

G.C. Klein Lebbink
Student assistant FAEDUT.
Data reduction of experiments at FAEDUT. Also engineering thesis on the effect of surface discontinuities on channel flow with blowing. Co-coaching by dr. H. Bos.

P.J.M. Elands
Student FAEDUT.

J.P. de Wilde
Student FAEDUT.
Thesis work: Pyrolysis in connection with the solid fuel combustion chamber.

G. Vermij
Student FAEDUT.

W.J.A.M. Aarts
Student FAEDUT.
Design and development of third pyrometer.
P. Sukmawanto
Student FAEDUT.
Study of solid fuel ramjets to improvement of launch vehicles?.

W.K. Tang
Student FAEDUT.
Thesis work: temperature measurements in SFCC and some additional topics.

D. Jansen
Student FAEDUT.
Fourth year assignment and thesis work in cooperation with ESTEC. Hybrid rocket motor design.

I. Silverman
Student Technion IIT Haifa.
Faculty Aerospace/Mechanical Engineering.
IAESTE student exchange.
3 months stay at FAEDUT.
Computation of streamlines for VORTEX (see section 6.4).
6 THEORETICAL DEVELOPMENTS

6.1 Introduction

Just like in the eighth period, theoretical work concentrated on three topics [1]:

- An analytical study of laminar channel flows;
- Computational modelling of flow and combustion, employing algebraic finite element methods (COPPEF);
- Computational modelling of built-up and shedding of large vortex structures, employing Lagrangian vortex methods (VORTEX).

The analytical study, in cooperation with the group of prof. Steketee, made substantial progress during this period. A report is in preparation, and some results are discussed below.

Ir. J.B. Vos completed some calculations on ignition problems with COPPEF, and finished his Ph.D. thesis work during this period.

Some results of the diffusion flame model in COPPEF have already been discussed in the progress report of the eighth period [1]. A review of the implementation of this model was presented by Mr. P. Elands at the meeting of the Users Committee in December 1986; this review and some results are discussed below.

Two different versions of VORTEX were completed during this period, while wall and viscosity effects were carefully studied. A report is in preparation, and some results will be discussed below.
6.2 Analytical solutions of laminar channel flows with blowing or suction
(G.C. Klein Lebbink)

In cooperation with the group of Prof. Steketee laminar flows with blowing in
axisymmetric channels with varying cross section were analytically studied.
Upon introduction of the Stokes streamfunction ($\psi$), the equations of motion
yielded one partial nonlinear differential equation for $\psi$. This equation was
rewritten in a nondimensional form using nondimensional coordinates and para-
eters representing slenderness and mass-inflow. The problem of determining the
flow field in a channel with blowing and varying cross section was solved in two
steps.

1. The flow field in a channel with constant cross section and with blowing was
determined by expanding the nondimensional streamfunction in a power series
of $n$, a nondimensional transverse coordinate. Typical results for several
values of the mass-inflow parameter ($\lambda$) are given in Figure 6.1.
Figure 6.2. Velocity profiles for slowly varying channels.

\[ \lambda = \frac{2M}{\partial z} \quad \text{Re} = 100 \]

Wave length is 100 \( \times \) channel length
Wave amplitude is 0.25\% of radius

a: disturbances at \( z = 0 \)
b: disturbances at \( z = 0.5 \, L \)
c: disturbances at \( z = L \)

Radial profile of axial velocity disturbances for long waves.

Axial profile of axial velocity disturbances for long waves.
\[ \lambda = \frac{3M}{5z} \]

Re = 100

Wave length is 100 times channel length

Wave amplitude is 0.25\% of radius

a: disturbances at \( z=0 \)
b: disturbances at \( z=0.5 \) \( L \)
c: disturbances at \( z=L \)

Radial profile of radial velocity disturbances for long waves.

Axial profile of radial velocity disturbances for long waves.
2. The flow field in a channel with varying cross sections was determined. The cross sections in this channel were assumed to differ only little from the cross sections of a channel with constant cross sections, and therefore the corresponding flow field was supposed to be a small perturbation of the flow field in a channel with constant cross sections. The wall disturbances were supposed to be wavelike (as observed in experiments). Both long and short waves were studied. For long waves, figure 6.2a, b, c and d give typical results for the velocity disturbances in axial and radial direction. Figures 6.3a through to 6.3d give typical velocity disturbances for short waves.

In the near future the pressure disturbances for long and short waves will be determined.

\[ \frac{\lambda^3}{\frac{M}{2}} \frac{\text{Re}}{\text{Re}} = 100 \]

- wave length is 0.314
- channel length
- wave amplitude is 0.125% of radius

a: disturbances at z=0
b: disturbances at z=0.079
c: disturbances at z=0.157
d: disturbances at z=0.236

Radial profile of axial velocity disturbances for short waves.

Figure 6.3. Velocity profiles for channels with a rapidly varying cross section area.
Axial profile of axial velocity disturbances for short waves.

\[ \lambda = \frac{3\lambda}{2z} \quad \text{Re} = 100 \]

wave length is 0.314 x channel length

duration amplitude is 0.125% of radius

\( a \): disturbances at \( r=0 \)
Axial profile of radial velocity disturbances for short waves.
\[ \lambda = \frac{3 \pi}{3 \lambda} \text{ Re} = 100 \]

wave length is 0.314 \times 
channel length
wave amplitude is \(0.125\% \) of radius

a: disturbances at
z=0

b: disturbances at
z=0.079

c: disturbances at
z=0.157

d: disturbances at
z=0.236

Radial profile of radial velocity disturbances for short waves.

This study of laminar channel flow aims at a better understanding of the effect of surface discontinuities such as the observed small ripples at the inner grain surface. The large-scale law

\[ r = a \times P^b \]

(a, b constants, P pressure, r regression rate) is supposed to be valid also at a small scale. This law is used to generate an axially inhomogeneous blowing velocity corresponding to an inhomogeneous pressure field caused by a surface discontinuity.

It might turn out that such discontinuities are self-eliminating under the influence of combustion (with the above pressure law). This equalisation of the surface has actually been observed in experiment.
6.3 Computational modelling of flow and combustion (COPPEP)
(P.J.M. Elands)

6.3.1 Combustion modelling
The implementation of the diffusion flame combustion model and the turbulent diffusion flame combustion model has been completed. Both combustion models are based on an infinitely fast reaction between oxidizer and fuel. The mixing of oxidizer and fuel is the flame controlling mechanism.

In the first model, the influence of turbulence on combustion is neglected, while in the second model this influence is taken into account by weighting the mass fractions with the beta probability density function. This beta probability density function can be expressed in terms of the mixture fraction $f$ and two variables $a$ and $b$, which are a function of $f$ and of $g$, the scalar fluctuation, yielding

$$P(f) = \frac{f^{a-1} (1-f)^{b-1}}{\int_0^1 f^{a-1} (1-f)^{b-1} \, df}$$

![Figure 6.4. Mass fraction distributions for two combustion models, for a combustion of $C_2H_4$ with $O_2$.](image)

Figure 6.4. Mass fraction distributions for two combustion models, for a combustion of $C_2H_4$ with $O_2$. 
With the diffusion flame model, oxidizer and fuel cannot exist together at the same time at the same place. With the turbulent diffusion flame model however, oxidizer and fuel can exist at the same place, their mass fraction distributions being a time-average of the instantaneous situation. In figure 6.4 the difference between the mass fraction distribution of oxidizer and fuel is clearly demonstrated for a calculation with \( \text{C}_2\text{H}_4 \) and \( \text{O}_2 \).

As can be seen there is an overlap of mass fractions of oxidizer and fuel for the turbulent diffusion flame model (IC = 3), which is not present for the diffusion flame model (IC = 2).

The difference between the two models can also be seen from the calculated temperature distributions in radial direction, see figure 6.5.

![Diagram showing temperature distributions for two combustion models.](image)

Figure 6.5. Temperature distributions for two combustion models.

For the diffusion flame model there is a sharp edge in the profile, while the curve for the turbulent diffusion flame model is more smooth. In figure 6.6 the flame zones for both combustion models are given.
Figure 6.6. Flame zones for two combustion models.

The flame zone is defined as the area where the temperature is not less than 99% of the maximum temperature in radial direction. Obviously, the flame zone for the turbulent diffusion flame model is thicker than that for the diffusion flame model, and it is located closer to the wall. It must be noted that maximum temperatures are larger for the diffusion flame model.

Figure 6.6 confirms what was to be expected. Since the turbulent diffusion flame model allows oxidizer and fuel to exist at the same location, being a time-average of the instantaneous situation, there is 'unmixedness'. A smaller amount of reactants will react, hence less heat is released from the chemical reaction and temperatures will be lower. Since fuel and oxidizer coexist within a certain volume there will be a thicker flame front than with the diffusion flame model, where fuel and oxidizer do not coexist at the same place.

Some results of calculations will be discussed. The effect of the stepheigh/diameter ratio on the reattachment length is investigated by varying the diameter, for flows without combustion and for flows with combustion, using both the diffusion flame combustion model and the turbulent diffusion flame combustion model.

The relation between the stepheigh/diameter ratio and the reattachment length/diameter ratio for the different calculations as well as derived from the literature values is given in Figure 6.7.
Figure 6.7. Reattachment length/diameter ratio as a function of stepheight/diameter ratio.

The main conclusion is that the reattachment length in a flow with combustion will be smaller than in a flow without combustion. This is due to the increase of turbulent shear stresses in the near wall region, due to a change in turbulent kinetic energy and in the dissipation of turbulent kinetic energy. These changes are resulted from the changes in density caused by the combustion process.

The influence of the oxidizer/fuel ratio on the reattachment length is also investigated. The oxidizer/fuel ratio is changed by changing the fuel injection velocity. The influence of the injection velocity of fuel on the reattachment length is given in figure 6.8.

From figure 6.8 it may be concluded that the injection of fuel decreases the reattachment length. This effect is large for low injection velocities. For increasing injection velocities the reattachment length goes asymptotically approaches a certain value.
The explanation of this effect is also found in the increase in turbulent shear stress caused by an increase in turbulent kinetic energy due to the injection of fuel.

More details are given by Elands [2].

Figure 6.8. Reattachment length as a function of fuel injection velocity.
Total channel length = 0.300 m.

6.3.2 Calculations with an extended chamber
In a normal Solid Fuel Combustion Chamber, fuel is pyrolyzed at the whole length of the fuel grain. This implicates that at the outlet unburnt fuel is leaving the channel. To determine whether combustion takes place until all fuel is burnt at an excess of oxidizer, a calculation has been made with an extension of the channel. At the wall of this extended channel no fuel is blown in. From the calculation it is found that the fuel is burnt almost completely at the exit of the nozzle, see figure 6.9.
Figure 6.9. Mass fraction distribution of fuel (C\textsubscript{2}H\textsubscript{4})
for a calculation with an extended nozzle.

6.3.3 Time dependent version of COPPEF
To be able to model regressing boundaries and the injection velocity of fuel as
a function of the heat transfer from the flow to the wall, it is necessary to
develop a time dependent version of the COPPEF Computer Program.
This problem has already been addressed by Mr. A.C. van den Berg from PMLTNO in
a different context; his modified version of COPPEF served as a basis for new
investigations.

The general differential equation of the form:

$$\frac{3}{3t} (\rho \psi) + \frac{3}{3x} (\rho u \psi) + \frac{3}{3y} (\rho v \psi) - \frac{3}{3x} (\Gamma \frac{\partial \psi}{\partial x}) - \frac{3}{3y} (\Gamma \frac{\partial \psi}{\partial y}) = S$$

can be written into an algebraic difference equation of the form:

$$\psi_p = \sum a_j \psi_j + S \cdot VOL + \rho \cdot \frac{VOL}{\Delta t} \psi_p^o$$

$$a_p = \frac{\rho \cdot VOL}{\Delta t}$$

where $\psi_p^o$ denotes the old time level and $\psi_p$ the new time level.

Problems are to be expected with obtaining cell-continuity.
Since the line continuity correction procedure cannot be used, as it disturbs
the flow, in the continuity equation also the $\partial \rho / \partial t$ term has to be incorporated.
In the energy equation the $\partial \rho / \partial t$ term has to be taken into account, although its
influence is expected to be minor.
Finally, problems are expected with the initial and boundary conditions.
6.4 Direct simulation of vortex shedding (VORTEX)
(C.W.M. van der Geld)

The phenomenon of the shedding of large coherent structures downstream of the sudden expansion has already been described in the previous progress report (1).

It was concluded from experiments that
- chemistry is not vital;
- the vortices are rotatory symmetric;
- inlet conditions affect frequency and regularity of the shedding.

During this period the monitoring of the calculations with the simulation programme 'VORTEX' became complete. It is now possible to visualize the flow by
1. calculating streamlines;
2. using emitted vortices as tracers;
3. calculating velocity vectors on nodal points of a grid.

The conditional stability of the Adams-Bashforth method for 1. proved to be better than that of Runge-Kutta methods.

The computation time was reduced by:
1. making the merging parameter inhomogeneous;
2. adapting this parameter in the course of time;
3. re-ordering the main routines;
4. optimizing the time step.

The effects of viscosity are not fully accounted for, since diffusion of individual vortices is not yet modelled. Hence resulting flow calculations are close to laminar (see figures 6.10 through 6.13). It is clearly seen that Von Karman street-like structures are built up in the wake of a circular section.

The effect of viscosity in the near wall region was further studied. To mimic the physics, vortices are generated in such a way that normal velocity components of direct wall points are equal to zero, while the total circulation around an object is preserved. On sharp edges this method proved to be better than the method of making the stream function a constant on the body surface.
Figure 6.10. Initial stage of vortex generation at sharp edges. Flow is from left. The length of a velocity vector is a measure for its value.

Figure 6.11. Intermediate stage of built-up of large vortex structures in the wake of the body.
Figure 6.12. Emitted vortices as flow tracers and calculated velocities on grid points. Notice the rescaling in the flow direction.
Figure 6.13. Continued floe evolution. The cores of the large vortex structures are clearly shifted with respect to each other.
Possible configurations of creation points were studied analytically, and most of them also computationally. Selective criterions for the best configuration were:
- vortex $i$ should originate basically from satisfying the boundary condition at the nearest wall point $i$;
- $\Sigma |\Gamma_i|$ should be as small as possible to effectuate smooth vortex generation. Here $\Gamma_i$ denotes the strength of emitted vortex $i$.

Future work will deal with the diffusion of individual vortices and the validation of the channel flow version (see ref. 1).
7 EXPERIMENTS

During the period July-December 1986 only few experiments could be performed, since PMLTNO needed the test room for other experiments, and STW had stopped the financing of the project.

Some of the experiments are described in section 9. Experiments with a long inlet tube (L/D > 30) in the context of the vortex shedding research (see section 6.4) showed a drastic decrease, almost 50%, of the shedding frequency. Choking of the flow at the lowest acoustical mode was observed directly. The frequency of this mode is about 20 times the vortex shedding frequency.
8 STATUS OF THE EXPERIMENTAL FACILITY

Only minor changes of the experimental facility have been pursued. The O₂ and CH₄ SCMC's have been recalibrated while a small testseries has been performed to determine the combustion behaviour of the vitiator at different conditions (high/low combustion pressure, high/low air mass flow, high/low air temperature).

Adaptations of the air inlet section were manufactured and tested in the context of the vortex shedding research (see section 6.4):
1. smooth, long inlet tube (L/D > 30);
2. swirl generators.

The latter form of flame stabilization could not be tested because of ignition problems. Fuel grains of a relatively large size were applied, and these grains - with or without swirl generators - could only be ignited if inlet temperature was sufficiently increased. Even then ignition was troublesome.
9 OPTICAL EQUIPMENT AND EXPERIMENTS

9.1 Acetylene detection in an SFCC flame

In literature, a strong correlation between the density of soot and the presence of acetylene in flames has been reported. Acetylene is assumed to be formed from the pyrolyses products. Therefore we attempted to detect acetylene in the SFCC flame close to the wall.

In order to record the spectrum of acetylene at 229 nm, the optical set up, which brings radiation from the SFCC to the spectrograph, was fitted with UV optics. The direction of observation was adjusted to make a shallow angle with the axis of the SFCC in order to detect radiation from the pyrolyzing grain surface.

Not any signal from acetylene was detected, although the background signal from soot at this wavelength and detector noise was practically zero. However, the absence of acetylene radiation may be caused by absorption of soot near the inlet of the SFCC.

Observation of the flame in radial direction will prevent this absorption. To achieve this, grains are to be provided with quartz windows and more experiments are planned.

9.2 Two colour pyrometer

The colour temperature of a radiator is defined as the real temperature of a black body, which emits radiation with the same spectral intensity ratio at specific wavelengths, as the radiator does.

A two-wavelength pyrometer has been constructed by W.J.A.M. Aarts. In this instrument, the spectral intensity of radiation at two different wavelengths, selected with the aid of interference filters, is measured. Built-in electronics transform both detector signals to the logarithm of the signal ratio. This log ratio signal of the pyrometer is fed to the data acquisition system. Signal temperature dependence, arising from detectors and electronics, is eliminated with help of a built-in temperature sensor. The pyrometer was calibrated against a calibrated tungsten ribbon lamp; the real temperature of this lamp was corrected to colour temperature. The temperatures, calculated from the output and the instrument parameters, agreed with about 1% with the lamp temperatures.
This pyrometer enables us to determine temperatures and with an accuracy of 10-20 K. The time resolution is deliberately limited to 0.01 s to allow for reliable measurements at minimum radiation intensities.

9.3 Particle generator

To measure gas velocities with LDA equipment, particles with dimensions of 1 to 5 microns must be added to the gas with the aid of so-called particle generator.

A design from the Delft University of Technology of such a device for low pressure gas, was adopted and modified for use at the inlet air pressures of the SFCC. At present the generator is under construction.

9.4 Soot formation

Experiments with the SFCC showed a positive correlation between soot radiation intensity and regression rate. This intensity is a function of soot density, temperature and soot particle dimension.

Neglecting the differences in particle dimensions at various flame conditions, relative soot densities were determined, assuming that

a. the spectral absorption coefficient at the wavelength of measurement is independent of the temperature,

b. the soot density at constant temperature is proportional to the spectral intensity of the radiation. This will be the case at low densities.

The relative soot density was obtained by dividing the measured spectral intensity (number of counts per exposure time at 380 nm) by the spectral radiance at 380 nm according to Planck's equation. The result is presented in figure 9.1, where the relative soot density is plotted against temperature $T$.

The dependence of the density on $T$ is striking.

At constant $T$, the density tends to increase with pressure. While the use of heated air has (hardly) any effect on the density, extra oxygen significantly reduces the formation of soot.

Comparing the spectral intensities, measured from the flame and from the calibration lamp at the same temperature, it can be concluded that the emissivity of the flame, observed radially through the axis, is unity at a temperature of about 1700 K and lower.
Figure 9.1. Relative emissivity versus temperature. The absolute emission coefficient is unity at about 1700 K.

10 UTILIZATION

1. Unilever Research has expressed its interest in a Sonic Control and Measuring Choke for measurement and control of hydrogen gas flows to reactor vessels. For this application, however, the SCMC needs to be equipped with a servo mechanism to actuate the pintle of the SCMC. Although such an extension is well feasible, no experience with this option is available. This implies that still some development work will be required for a proper device that can be
used by Unilever Research is available. This organisation is not interested in this development work, buying (as a general rule) only equipment from the shelf. Presently, there is no funding available for the project group to initiate this new development work.

2. Presently, Europe's launcher ARIANE III suffers from severe problems as far as the third stage engine is concerned. Some of these problems may be attributed to bad ignition conditions. Contacts have been established between the project group and CNES/SEP to inform them about the capabilities of the project group on flow and combustion modeling.
11 USERS COMMITTEE

The Users Committee convened for the ninth meeting on Friday, December 12, 1986 at PML. The next convention data is planned on Friday, June 12, 1987 at PMLTNO.

The following persons were present:

SFCC project group: H. Wittenberg
    P.J.M. Elands
    P.A.O.G. Korting
    R.P. van de Berg
    T. Wijchers
    J.B. Vos
    C.W.M. van der Geld

PMLTNO : H.J. Reitsma
    H.J. Pasman

STW : F.C.H.D. van den Beemt

TNO : Cdr. b.d. R.H. Kerkhoven

FDO : G. Troost

FAEDUT : J.A. Steketee

ESTEC : H.F.R. Schöyer

Eindhoven Univ. : C.W.J. van Koppen

The following topics were presented:

Status and planning of the project : H. Wittenberg
Spectroscopic experiments : T. Wijchers
Diffusion flame modelling in COPPEF: P.J.M. Elands
Vortex shedding modelling : C.W.M. van der Geld
12 CONTACTS

For this period the following contacts can be listed:

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<th>Persons</th>
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</tr>
</thead>
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<td>Unilever Research Laboratorium, Vlaardingen</td>
<td>G. Colen, Mehler</td>
<td>SCMC for $H_2$</td>
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<td>IMI Summerfield</td>
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<td>First trials ducted rocket motor</td>
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<td>Société Européenne de Propulsion, Vernon, France</td>
<td>Th. Delaporte, P. Baudart</td>
<td>Flows and combustion modeling ARIANE III (HM7 engine)</td>
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<td>Naval Weapons Center, China Lake, California</td>
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<tr>
<td>1 Experiments with SFCC with spectroscopic, ultrasonic regression rate and radiation equipment</td>
<td>15 experiments with polymethylmethacrylate</td>
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<tr>
<td>2 Implementation of spectroscopic techniques for colorimetry for soot temperature measurement</td>
<td>Time averaged technique available; Version for instantaneous measurements completed</td>
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<tr>
<td>3 Study of accurate and local species/temperature determination by fluorescence techniques</td>
<td>Study in progress</td>
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<tr>
<td>4 Study of laser doppler velocity measurements in an SFCC</td>
<td>Optical equipment for feasibility study manufactured. First test results were obtained visually and were promising. Particle generator conceived and designed</td>
<td></td>
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<tr>
<td>5 Extension of software for data analysis</td>
<td>FAEDUT: Main routines for data analysis available; special routines (frequency analysis) partly completed. Continuous effort</td>
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<tr>
<td>6 Small modifications of experimental system</td>
<td>PMLTNQ: Software for dataprocessing available; improvements continuous effort</td>
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<tr>
<td>7 Theoretical work. Study of fuel pyrolysis in connection with SFCC combustion</td>
<td>Thesis study started</td>
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<tr>
<td>8 Theoretical work</td>
<td>Two versions of the program 'VORTEX' com-</td>
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</table>
Study of vortex shedding in an SFCC

9 Theoretical work (COPPEF)
   - Ph.D. Thesis J.B. Vos
   - Time-dependent calculations with COPPEF at FAEDUT

10 Other activities
   - Hiring of personnel
     Position Ir. J.B. Vos continued until 1-1-1987
     Position dr. T. Wijchers continued until 1-1-1988
     Technician (LTS) from 1-2-1986 to 1-1-1988
   - Reporting and presentations
     6 reports published
     1 paper presented
   - Commercializing spin-offs
     Contact with various industries established, see section 12

completed. Wall influence studied and computation time reduced. See section 6.4.
14 PLANNED PROGRAM FOR THE PERIOD JANUARY-JUNE 1987

<table>
<thead>
<tr>
<th>SUBJECT</th>
<th>Jan</th>
<th>Febr</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
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<tbody>
<tr>
<td>1 Experiments with</td>
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<tr>
<td>- PMMA, PS, PE</td>
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<td>- Other materials (waste materials, HPTB)</td>
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<td>2 Study on local, accurate temp/species determination from fluorescence spectra</td>
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<td>3 Feasibility study with extended LDA set up</td>
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<tr>
<td>4 Extension of software for data analysis</td>
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<tr>
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<tr>
<td>Study on fuel pyrolysis in connection with SFCC combustion (MSc thesis)</td>
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<td>7 Theoretical work (COPPEF)</td>
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<td>Extensions (time-dependent version; ignition problems etc.)</td>
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<td>8 Theoretical work (Vortex)</td>
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<td>Study on vortex shedding</td>
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<tr>
<td>9 Other activities</td>
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<td>- Contacts and commercializing</td>
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<tr>
<td>2</td>
<td>P.A.O.G. Korting and J. Vermeulen</td>
<td>SFCC nr. 35</td>
<td>Een computerprogramma voor datareductie van metingen in de vaste brandstof verbrandingskamer.</td>
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<tr>
<td>3</td>
<td>P. Merkx and R.P. van den Berg</td>
<td>SFCC nr. 36</td>
<td>Instantaneous Solid Fuel regression rate measurements at more than 1 location - an ultrasonic pulse echo multiplex system.</td>
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<tr>
<td>4</td>
<td>P.J.M. Elands</td>
<td>SFCC nr. 37</td>
<td>Implementation of a Diffusion Flame Model and a Turbulent Diffusion Flame Model in the COPPEF Computer Program.</td>
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<tr>
<td>5</td>
<td>J.B. Vos</td>
<td>SFCC nr. 38</td>
<td>The calculation of Chemical Reacting Turbulent Boundary Layers Using the Cray-1 Supercomputer.</td>
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</tbody>
</table>
In addition the following abstracts were submitted for international symposia:

Vortex shedding: numerical simulation and impact on solid fuel combustors. C. van der Geld.

A theoretical investigation of the flow and combustion in a solid fuel combustion chamber. P.J.M. Elands, J.B. Vos.

Simulating an ignition pulse in turbulent reacting flows. J. Vos.


Also a paper was presented by J.B. Vos at the 2nd meeting of the working group on the Mathematical Modelling of Flames, organized by the International Flame Research Foundation on 30 September 1986 in Amsterdam: 'Theoretical investigation of a solid fuel combustion chamber'.
16 REFERENCES

Solid fuel combustion chamber progress report VIII; Eighth phase, January-
June 1986; Report LR-498; PML 1986-C73; FAEDUT/PMLTNO; Delft/Rijswijk,
September 1986.

[2] Elands, P.J.M.
Implementation of a diffusion flame model and a turbulent diffusion flame
model in the COPPEF computer program. Report LR-494; PML 1986-C65;
FAEDUT/PMLTNO; Delft/Rijswijk, August 1986.
ACRONYMS

COPPEF  Computer Program for Calculation of 2D Parabolic and Elliptic Flows
DEA    Data exchange agreement
ENR    Energie Centrum Nederland Rekencentrum
ESA    European Space Agency
ESTEC  European Science and Technology Centre
FAEDUT Faculty of Aerospace Engineering, Delft University of Technology
LDA    Laser Doppler Anemometry
PEO    Stichting Projektbeheersbureau Energie-Onderzoek
PMLTNO Prins Maurits Laboratory TNO
SCMC   Sonic Control and Measuring Choke
SFCC   Solid Fuel Combustion Chamber
STW    Stichting voor de Technische Wetenschappen (Technology Foundation)
TNO    Organization for Applied Scientific Research
URRA   Ultrasonic regression rate analyzer
VORTEX Computer programme for direct simulation of vortex shedding
ZWO    Nederlandse Organisatie voor Zuiver Wetenschappelijk Onderzoek