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CO-OPERATION BETWEEN ECN AND NPCC (CHINA) ON PULVERISED-FUEL COMBUSTION RESEARCH

Phase 1 - Design and commissioning of an ECN lab-scale combustion (and gasification) simulator at NPCC and initial experiments

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Preface

This report describes the accomplishments of the project entitled "Co-operation ECN-NPCC on PF Combustion Research". The project was executed in close co-operation between ECN and NPCC for Novem under contract number 971327-0240 within the framework of the Memorandum of Understanding on Clean Coal Technology Co-operation between the Directorate General for Energy of the Ministry of Economic Affairs of the Netherlands and the Department of High-Technology Development & Industrialisation of the Ministry of Science and Technology of the People's Republic of China. The ECN work has been performed under ECN project number 7.2163.

Abstract

The report describes the initial successful steps in establishing a durable co-operation between ECN and the State Engineering Technology Research Centre of Combustion of Power Plant (NPCC) in Shenyang, Liaoning province, China. NPCC has been selected by the Chinese government to play a major role in the optimisation of existing and new coal-fired power generation capacity in (Northeast) China. The initial steps towards a durable co-operation were taken within the framework of the Memorandum of Understanding on Clean Coal Technology Co-operation, concluded in 1998 between the Ministry of Economic Affairs of the Netherlands and the Ministry of Science and Technology of the People's Republic of China. The steps comprised of the training of NPCC personnel to maintain and operate a state-of-the-art lab-scale combustion simulator, as developed by ECN, the construction of such a combustion simulator at NPCC, and initial joint experiments within the framework of a Chinese research project on reburning. Furthermore, information on the possibilities of the simulator and the combined skills of NPCC and ECN in the field of pulverised-fuel combustion was disseminated to representatives of the Chinese power sector, boiler manufacturers, other research institutes and universities. For the future, there remains the challenge to build on these first successful steps and maintain a durable co-operation between ECN and NPCC through a continuous chain of joint R&D activities.

Keywords

coal, pulverised-coal combustion, lab-scale combustion simulator, Sino-Dutch co-operation, reburning, burnout

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SUMMARY

Coal is the main primary energy source in China. About 75% of the power production is based on coal and power consumption is expected to grow with approx. 9%/annum. Furthermore, the current status is that power is generated from coal with a rather low average efficiency of approx. 30% compared to common values of 38-40% in industrialised countries. Therefore, it is a major objective of the Chinese government to improve the R&D infrastructure on coal and coal conversion.

In Northeast China, the State Engineering Technology Research Centre of Combustion of Power Plant (NPCC) has been identified as one of the institutes, which should play a major role in upgrading coal-fired power plants. NPCC was established in 1993 in Shenyang, Liaoning province, by the Northeast China Electric Power Group Corporation (NEPGC) and in 1996 approved by the State Science and Technology Committee. Currently, NPCC is to support not only the NEPGC, but to conduct R&D in support of coal-fired power generation throughout China. Until 1998, the R&D focus at NPCC was mainly on hydrodynamic aspects of coal-fired power generation. In 1998, the decision was taken that NPCC should expand its activities onto combustion research. One of the first steps in this direction was the acquisition of a 150 kW single burner combustion furnace from Ontario Hydro Technology in Canada. In addition to experiments with this test boiler, a strong need for smaller-scale combustion facilities was identified and inventory studies and business trips were conducted to select most suitable small-scale experimental approaches and belonging equipment. This finally led to the selection of an experimental approach, as developed by the Energy research Centre of the Netherlands (ECN).

ECN has conducted coal conversion R&D since the late 1980’s, initially focusing mainly on combustion phenomena occurring in modern pulverised-coal-fired boilers. Later, during the 1990’s, the scope was broadened to include entrained-flow gasification and biomass co-firing as well. A major share of the coal combustion, entrained-flow gasification and co-firing R&D was, and still is, carried out in a laboratory-scale test facility, in which actual pulverised-fuel combustion and entrained-flow gasification conditions can be mimicked closely. The design of this facility is based on the notion that a similar experimental approach can be chosen to assess (mineral matter behaviour in) combustion and entrained-flow gasification. A key element in this approach is the adaptation of the staged flat flame burner concept. According to this concept, a laboratory-scale entrained-flow reactor is applied with an integrated, premixed and multi-stage flat flame gas burner. By feeding different gas mixtures to the different stages, the staged gas burner is used to simulate the high initial heating rates and temperatures, and the gaseous environment history that fuel particles experience in the actual process. An accurate simulation of these process parameters is known to be essential for obtaining realistic volatile matter yields and mineral matter transformations.

The ECN lab-scale combustion (and gasification) simulator, as it was available at ECN in 1998-1999, was recognised and selected by NPCC as most suitable in conjunction with their single burner combustion facility. In 1998, the Netherlands and China signed a Memorandum of Understanding on Clean Coal Technology Co-operation and in this framework, funding could be made available both in the Netherlands and China to initiate the current project aimed at establishing an “ECN-NPCC co-operation on pulverised-fuel (PF) combustion research”. Basically the project comprised:

- The realisation of a lab-scale simulator for coal combustion research according to an ECN design at the NPCC in China.
- Guidance to the purchasing and installation of supporting analytical equipment at NPCC (Simultaneous Thermal Analyser, Slag Viscometer, Ultimate Analyser).

- Transfer of know-how required for the construction and operation of the lab-scale facility from ECN to NPCC.
- The initiation of a joint research and exchange programme.

Overall, the project was successful, despite the longer time it took to completion. NPCC personnel received an extensive training to maintain and operate a state-of-the-art lab-scale combustion simulator, as developed by ECN, and the simulator was built at NPCC. Subsequently, initial experiments were conducted successfully in the framework of a Chinese research project on reburning, and information on the possibilities of the simulator and the combined skills of NPCC and ECN in the field of pulverised-fuel combustion was disseminated to representatives of the Chinese power sector, boiler manufacturers, other research institutes and universities.

Furthermore, it was experienced that long distance, cultural differences and differences in normal business practice between the Netherlands (or Western industrialised countries in general) and China make the preparatory phase of a co-operative project like the current one very time consuming and labour intensive. However, a solid preparation does pay out. Money transfer from China to the Netherlands and shipment of equipment from the Netherlands to China turned out to be much more complex and time consuming then initially anticipated. In this respect, it may help to involve an external organisation with experience in this field.

For the future, there remains the challenge to build on these first successful steps and maintain a durable co-operation between ECN and NPCC through a continuous chain of joint R&D activities.

1. INTRODUCTION

Coal is the main primary energy source in China. About 75% of the power production is based on coal and power consumption is expected to grow with approx. 9%/annum. This requires an increase in installed capacity of approx. 15-18 GW/annum, i.e. a yearly increase comparable to the current total installed power generating capacity in the Netherlands. Furthermore, the current status is that power is generated from coal with a rather low average efficiency of approx. 30% compared to common values of 38-40% in industrialised countries. Therefore, it is a major objective of the Chinese government to improve the R&D infrastructure on coal and coal conversion. This is even more important if one realises that the majority of the domestic coal reserves are of a rather poor quality in terms of low volatile matter, high ash and low ash fusion temperatures.

NPCC

In Northeast China, the State Engineering Technology Research Centre of Combustion of Power Plant (NPCC) has been identified as one of the institutes, which should play a major role in upgrading coal-fired power plants. NPCC was established in 1993 in Shenyang, Liaoning province, by the Northeast China Electric Power Group Corporation (NEPGC) and in 1996 approved by the State Science and Technology Committee. The NEPGC is a large utility in Northeast China with 48 power stations. The Northeast China Electric Power Network covers an area of 1.2 million km^2 and serves 100 million people. By the end of 1995, the network had an installed generating capacity of 27.6 GW and the installed generating capacity was expected to reach 38.8 GW by the year 2000. Currently, NPCC is to support not only the NEPGC, but to conduct R&D in support of coal-fired power generation throughout China.

Until 1998, the R&D focus at NPCC was mainly on hydrodynamic aspects of coal-fired power generation. To this purpose, the institute comprised, e.g., the following experimental facilities:

- aerodynamic test hall
- gas-solid two-phase flow test hall
- wind tunnel test hall
- supporting labs: hot-wire test lab, laser camera lab, wear-proof test lab, oil atomisation lab, blower system lab, combustion test lab.

Studies undertaken in the 1995-1998 timeframe comprised, for example:

- Study on the pulverised coal average distribution of direct-fired pulverised coal systems for 200, 300 and 600 MWe units.
- Study on the stable combustion of fan mill systems for 200 and 300 MWe units.
- Study on low-resistance flow of air-gas systems for fossil-fuel power plants.
- Study on the aerodynamic characteristics and furnace improvements for the 600 MWe unit of the Yuanbaoshan Power Plant.
- Development of a fuel computer management system for fossil-fuel power plants.
- Study on the computer management technology in fossil-fuel power plants.
- Development of a numerical simulator for a 600 MWe unit.

In 1998, the decision was taken that NPCC should expand its activities onto combustion research. One of the first steps in this direction was the acquisition of a 150 kW single burner combustion furnace from Ontario Hydro Technology in Canada. In support of experiments with this test boiler, a strong need for smaller-scale combustion facilities was identified and inventory studies and business trips were conducted to select most suitable small-scale experimental approaches and belonging equipment. This finally led to the selection of an experimental approach, as developed by the Energy research Centre of the Netherlands (ECN).

Coal combustion and gasification R&D at ECN

ECN has conducted coal conversion R&D since the late 1980's, initially focusing mainly on combustion phenomena occurring in modern pulverised-coal-fired boilers. Later, during the 1990's, the scope was broadened to include entrained-flow gasification and biomass co-firing as well. The topic of (oxygen-blown) entrained-flow gasification was taken up to support the operation of the 253 MWe Integrated Gasification Combined-Cycle (IGCC) plant in Buggenum. Biomass co-firing in coal-fired boilers came up in the Netherlands in the late 1990s as a means to limit net CO_2 emissions and to use renewable energy sources for power generation with a high efficiency.

At ECN, a major share of the coal combustion, entrained-flow gasification and co-firing R&D was, and still is, carried out in a laboratory-scale test facility, in which actual pulverised-fuel combustion and entrained-flow gasification conditions can be mimicked closely. The design of this facility is based on the notion that a similar experimental approach can be chosen to assess (mineral matter behaviour in) combustion and entrained-flow gasification. A key element in this approach is the adaptation of the staged flat flame burner concept. According to this concept, a laboratory-scale entrained-flow reactor is applied with an integrated, premixed and multi-stage flat flame gas burner. By feeding different gas mixtures to the different stages, the staged gas burner is used to simulate the high initial heating rates and temperatures, and the gaseous environment history that fuel particles experience in the actual process. An accurate simulation of these process parameters is known to be essential for obtaining realistic volatile matter yields and mineral matter transformations. Fuel particles are fed through the inner burner and undergo rapid heating ($> 10^5$ °C/s) up to the high temperature level of the near-burner zone. The gas/particle flow is confined in a reactor tube, which is surrounded by a controllable heating section to create the required temperature history for the particles. After having been subjected to the simulated process conditions, the particles can either be sampled using a particle collection probe or be deposited on a deposition probe. Both collected particles and deposits/slags can subsequently be analysed, *e.g.*, by using Scanning Electron Microscopy.

The ECN lab-scale combustion (and gasification) simulator, as it was available at ECN in 1998-1999, is described in more detail in Appendix A. At that time it was officially named the "Atmospheric Entrained-Flow Gasification and Combustion simulator (AEFGC-simulator)". It was this experimental approach that was recognised and selected by NPCC as most suitable in conjunction with their single burner combustion facility. At that time, ECN had conducted already a wide range of experimental studies with the simulator, including studies on mineral matter behaviour in pulverised-coal combustion [1-7], entrained-flow gasification of coal and biomass [8, 9], and the combustion behaviour of low-quality coals [10-12]. Since then, the scope was broadened even further to include studies on various aspects of biomass co-firing in pulverised-fuel boilers as well [13, 14]. For this purpose, the facility at ECN went through a major modification, in particular in order to enable longer particle residence times and therefore higher burnout. The new name of the facility at ECN is Lab-scale Combustion Simulator (LCS) and details of the modified set-up can be found elsewhere [14]. However, discussions on a potential co-operation between ECN and NPCC focused on the 1998/1999 design.

Sino-Dutch co-operation on Clean Coal Technology

1998/1999 soon appeared to be a good timeframe for the start of a co-operation between ECN and NPCC on coal combustion research, since in 1998 the Netherlands and China signed a Memorandum of Understanding on Clean Coal Technology Co-operation. In this framework, funding could be made available both in the Netherlands and China, and the current project aimed at establishing an "ECN-NPCC co-operation on pulverised-fuel (PF) combustion research" could be initiated. Basically this project comprised:

- The realisation of a lab-scale simulator for coal combustion research according to an ECN design at the NPCC in China.
- Guidance to the purchasing and installation of supporting analytical equipment at NPCC (Simultaneous Thermal Analyser, Slag Viscometer, Ultimate Analyser).

- Transfer of know-how required for the construction and operation of the lab-scale facility from ECN to NPCC.
- The initiation of a joint research and exchange programme.

In this report, first the project objectives and approach are summarised in Chapter 2. Then, in Chapter 3, activities concerning the transfer of know-how required for the detailed design, construction and operation of the simulator at NPCC are described. Actually, this comprised both the transfer of ECN expertise and experience to NPCC personnel, as well as activities to make ECN personnel more familiar with the specific conditions at NPCC. Subsequently, the actual realisation of the simulator at NPCC is sketched in Chapter 4. This includes the detailed design, the ordering and manufacturing of the equipment, the shipment of equipment from ECN to NPCC, the assembly of the simulator at NPCC and the commissioning. Following the commissioning, an initial experimental programme was conducted under the supervision of ECN, as described in Chapter 5. This experimental programme was accompanied by a workshop in which information on the possibilities of the simulator and the combined skills of NPCC and ECN in the field of pulverised-fuel combustion was disseminated to representatives of the Chinese power sector, boiler manufacturers, other research institutes and universities. Finally, the main conclusions are presented in Chapter 6.

2. OBJECTIVES AND APPROACH

The general objective of the Novem project was to establish a durable co-operation between ECN and the Northeast China Electric Power Combustion Research Centre (NPCC) in Shenyang (China) in the area of Pulverised Fuel (PF) Combustion through:

- making research facilities and expertise available to the NPCC, and
- initiating a joint research and exchange programme aimed at increasing the reliability and efficiency and lowering the environmental impact of coal-fired boilers in (Northeast) China.

At the start of the project in 1999, this general objective was based on the notions that:

- ECN has developed unique facilities and expertise in the field of (research on) ash behaviour in pf boilers. Fuel and ash behaviour in pulverised-coal-fired electricity generating processes has been for over a decade, and still is, one of the focal points in the ECN solid fuel research programme.
- NPCC has been identified by the Chinese government to play an important role in the optimisation of existing and new coal-fired power generation capacity in (Northeast) China. To fulfil this role, NPCC is expanding its activities in the field of combustion research. For the establishment of the required experimental facilities and expertise, it seeks co-operation with institutes with a large experience in this area. They have identified ECN as such an institute.

The specific aim of the project was to establish the durable co-operation through:

- The realisation of a lab-scale simulator for coal combustion (and gasification) research according to an ECN design at the NPCC in China. Coal and ash characterisation experiments in this simulator were considered to be a valuable addition to burner tests in a 150 kW combustion furnace, which NPCC had acquired from Ontario Hydro Technology in Canada.
- Transfer of know-how required for the construction and operation of this facility from ECN to NPCC.
- The initiation of a joint research and exchange programme.

3. INFORMATION EXCHANGE AND ENGINEER/OPERATOR TRAINING

During the first four months of 1999, i.e. the first four months of the project, the details and conditions of the co-operation between ECN and NPCC were further discussed and negotiated. In March 1999, this process was supported by a visit of a Chinese delegation to ECN, consisting of Prof. Shi Dinghuan, director general of the Department of High Technology Development & Industrialisation, and Mr. Li Baoshan, deputy director of the Energy & Transportation Division, both of the Chinese Ministry of Science and Technology, and Prof. Li Zhenzhong, deputy director of NPCC.

Finally the details and conditions of the co-operation were laid down in two agreements, one general agreement on the co-operation and one on the first project in the framework of the co-operation, entitled “Realisation of an AEFGC-simulator and supporting analytical equipment at the NPCC”. The project agreement is included as Appendix B and contains a detailed description of the first activities in the co-operation. The work programme of this first joint project comprised the following 6 tasks:

task 1 - Detailed design (incl. detailed construction work plan and cost estimate)
task 2 - Construction
task 3 - Engineer/operator training at ECN
task 4 - Commissioning
task 5 - After-care
task 6 - Guidance supporting analytical equipment

Although it took quite a while to arrive at the final text of both agreements, the process of drafting the agreements proved very worthwhile in order to get to know each other better and to avoid misunderstandings later on.

The two agreements were confirmed by the signing of a Memorandum on the joint construction of the lab-scale simulator during a visit of an ECN delegation to NPCC in April 1999 (Figure 3.1). Later that year, the ECN-NPCC co-operation was also confirmed in an Annex to the Memorandum of Understanding on Clean Coal Technology Co-operation concluded between the Directorate General for Energy of the Ministry of Economic Affairs of the Netherlands and the Department of High-Technology Development & Industrialisation of the Ministry of Science and Technology of the People’s Republic of China.

The first visit of an ECN delegation to NPCC was also used to make a detailed inventory of the local situation (fact finding) to facilitate the detailed design. The main findings were included in the Memorandum as well. In general, the visit gave a good impression of the existing experimental facilities at NPCC, including the single burner test facility from Ontario Hydro (see Figure 3.2) and the facilities for hydrodynamic studies (see Figure 3.3). In addition, the space available for the simulator was shown (Figure 3.3) and detailed discussions were held on the infrastructure requirements and limitations.

This formed the starting point for the detailed design at ECN of the simulator for NPCC, based on detailed documentation on the simulator available at ECN (design specs, layout, P&ID, component specs, etc.). In principle, the detailed design of the simulator at NPCC was to be equal to the existing one at ECN. However, adaptations were required to cope with the specific situation and possibilities at NPCC.

Figure 3.1 *Ceremony for the signing of the Memorandum on the joint construction of the lab-scale simulator at NPCC in April 1999.*

In this stage of the project, two NPCC representatives, viz. the NPCC project leader Prof. Zhang Jingwu and Prof. Li Chengzhi, and two delegates from Liaoning Province which is co-funding the NPCC-ECN co-operation, visited ECN (see Figure 3.4). This enabled the Chinese side to get more acquainted with the details and R&D possibilities of the simulator and to have further discussions on adaptations in the design for the NPCC simulator. During the visit, opportunity was given as well to Stork Thermeq to present their capabilities with respect to retrofitting existing coal-fired boilers, including the installation of low-NOx burners.

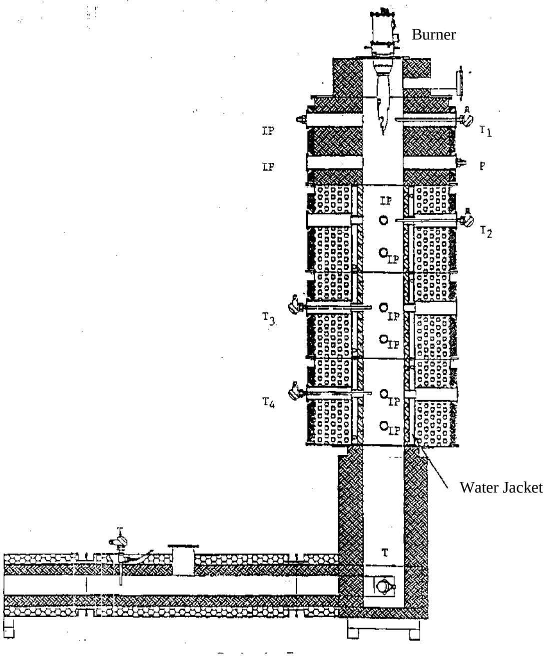

Figure 3.2 *Single burner combustion research facility at NPCC, as obtained from Ontario Hydro Technology in Canada.*

Figure 3.3 *Some of the experimental facilities for hydrodynamic studies (upper two photo's) and space available for the lab-scale simulator (bottom) at NPCC.*

Figure 3.4 *Visit of delegation from NPCC and Liaoning province to ECN (July 1999).*

Then, during the period of 15 September – 3 November 1999, two NPCC engineers (Wang Yang and Yun Yong) visited ECN for a two-month training period. In addition to getting familiar with the set-up and operation of ECN's combustion and gasification simulator, the training period also included extensive further discussions on the design and construction of the simulator for NPCC.

In summary, the training period comprised the following:

1. General introduction to ECN and to the ECN combustion and gasification simulator.
2. Joint definition and execution of a small experimental work plan aimed at gaining some experience with the operation of the ECN simulator and at obtaining experimental input for the detailed design of the simulator at NPCC. It was decided to conduct two experiments with two size fractions of a Chinese coal (Xingaoshan coal). The coal is the design coal of the Shuizong power plant, which is an 800 MWe plant based on a Russian design for an oil-fired boiler. The plant was under construction at that time (nearly completed). The experiments were focused on fouling under conventional firing conditions (4% excess oxygen in both inner and outer burner of the simulator) and consisted of high burnout experiments with both coal samples using the particle collection probe. Both the coal and the obtained char samples were subjected to different analyses, *viz.* Ultimate analysis, Proximate analysis, ICP-AES and SEM. In addition, some gas temperature measurements were conducted and the execution of gas composition measurements was explained and discussed in detail.
3. Introduction at ECN to the application of different sample analysis techniques, *viz.* Ultimate analysis, Proximate analysis, Inductive Coupled Plasma – Atomic Emission Spectroscopy (ICP-AES) and Scanning Electron Microscopy (SEM).
4. One-day introduction to the use of Mass Flow Controllers (MFC) at Bronkhorst (MFC-supplier) in Ruurlo.
5. One-day introduction to Amsterdam Valve & Fitting (AVF) at ECN (NPCC engineers obtained certificate for the use of AVF-fitting technology and received pipe-fitting tools).
6. Definition of the detailed design of the NPCC AEFGC-simulator (P&ID) and infrastructure requirements.
7. Preparation of several additional drawings (e.g. overview, frame, furnace protection cover, burner cooling system, control panel and 19'' rack).

At the end of the training period, a complete set of drawings and listings, as well as an extensive set of photos of various details of the simulator at ECN, were made available to NPCC. It was furthermore agreed that a limited number of components/key equipment would be ordered or manufactured by NPCC. This comprised the following:

- Frame + Table + Stairs
- Furnace protection cover (Reactor crust)
- Ventilation
- Controllers plate
- Water box (part of burner cooling system)

The remaining part of the key equipment was to be ordered by ECN and then shipped to NPCC.

As an overall conclusion, the traineeships largely contributed to the faith on both sides that the simulator could be constructed and operated at NPCC successfully.

During the visits and the traineeships, also guidance was given to NPCC with respect to the purchase of supporting analytical equipment. This concerned (micro-) Gas Chromatography for gas analysis, Thermo Gravimetric Analysis (e.g., to conduct proximate analyses on simulator samples) and analytical equipment for Ultimate Analysis and Bulk Ash Analysis.

Figure 3.5 *Traineeship of two NPCC employees, Yun Yong (2nd from the left) and Wang Yang (2nd from the right), at ECN (September-October 1999).*

4. REALISATION OF THE SIMULATOR AT NPCC

4.1 Ordering, manufacturing and shipment of equipment

The activities sketched in the previous chapter are summarised in Table 4.1, together with the activities in the second part of the project. By the end of 1999, the design of the NPCC simulator was almost completed and decisions had been taken with respect to who should order or manufacture the various pieces of equipment. It appeared that we could move forward quickly, aiming at getting the equipment within a few months at NPCC in order to start the assembly.

Table 4.1 *Historic overview of main project activities.*

Period	**Activity**
January - April 1999	Drafting of the co-operation agreement between ECN and NPCC
19-21 April 1999	Visit ECN delegation (Kiel, Eenkhoorn, Benneker) to NPCC to finalise the ECN-NPCC agreement and to make an inventory of the NPCC experimental facilities and possibilities
25-31 July 1999	Visit NPCC/Liaoning Province delegation (Zhang Jingwu, Li Chengzhi and two representatives of Liaoning Province) to ECN to get acquainted with the details of the lab-scale simulator
15 September - 3 November 1999	Training of an Engineer (Yun Yong) and an operator (Wang Yang) from NPCC at ECN + detailed discussions on the design of the simulator for NPCC
November 1999 - May 2001	Finalising the detailed design of the NPCC simulator, (defining the conditions for) ordering and manufacturing equipment by ECN (and NPCC) and shipment of equipment to NPCC
18-22 June 2001	Visit ECN delegation (Kiel, Heere) to unpack the equipment and initiate the assembly of the simulator at NPCC
June - November 2001	Assembly of the simulator by NPCC personnel
10-14 December 2001	Visit ECN delegation (Kiel, Heere, Ruiter) to NPCC to commission the simulator
January - October 2002	Simulator testing and building up operation experience by NPCC personnel
28-31 October 2002	Visit ECN delegation (Kiel, Heere) to NPCC to participate in the NPCC-ECN workshop on the simulator and the combined NPCC-ECN skills, and to conduct/supervise initial reburning experiments
November - December 2002	Collecting and discussing the results of the initial reburning experiments and finalising the project

Unfortunately, this proved to be very unrealistic. Before starting to order the equipment, ECN requested a 30% down payment and guarantees concerning the remaining part of the payment by NPCC. But, it then appeared that NPCC did not have the authority to do so. An intermediate trading firm, SFETA, had to be involved. It took until mid-October 2000 (9 months!) until finally all financial matters (contract between ECN and SFETA, 30% down payment, Letter of Credit for the remaining 70%) were arranged and the ordering could be started. The ordering, checking, testing, assembling of certain simulator parts and packaging then took until March 2001. Finally, shipment started on 23 March 2001, but due to some delays at Chinese customs the equipment arrived at NPCC only at the end of May 2001.

This led to a serious and unexpected delay in the project. On the one hand, part of this delay could have been avoided if both ECN and NPCC would have been experienced in the Netherlands-China trading procedures. For instance, the discussions with SFETA could have started in the second half of 1999. Therefore, on future occasions it is advised to involve an experienced trading organisation to deal with these aspects. However, on the other hand, these formalities will always take considerable time, which should be accounted for in future similar activities.

Figure 4.1 *Starting the assembly of the lab-scale simulator at NPCC (June 2001).*

4.2 Simulator assembly at NPCC

Following the arrival of the key equipment at NPCC, ECN personnel visited NPCC in the second half of June to unpack and inspect the components of the simulator, as well as to provide guidance at the start of the assembly phase. In general, the components were found to have arrived in good order and in accordance with the packing list. It was concluded that only some minor components were still missing or did not meet the specifications.

The assembly phase was initiated with the preparation and installation of the frame and the positioning of the oven, burner housing and axial probe transport system (see Figure 4.1). In general, this was completed successfully. However, it only appeared that the top section of the frame was still not rigid enough to get/keep the oven, burner housing and probe transport system in line. Thereupon, it was discussed how to increase the rigidity of the top section. Simultaneously, possibilities to apply the simulator in (joint) future projects were elaborated on through several discussions supported by ECN presentations.

Following this visit, NPCC formed a team to execute the further assembly/construction of the simulator. The team was headed by Yun Yong and Wang Yang, who received extensive training at ECN. ECN provided distant support through communication by e-mail and fax. The assembly/construction was completed by early November 2001.

4.3 Commissioning

With the assembly completed, technicians from ECN visited NPCC early December 2001 to:

1. check and test the various systems of the AEFGC-simulator (functional testing),
2. conduct the pre-oxidation of the oven,
3. provide guidance to eventual optimisation of the facility, and
4. perform and supervise the commissioning tests.

Within one week of hard work (see Figure 4.2), all this could be accomplished and the simulator was commissioned successfully by conducting an ash formation test.

Thus, although with some delay, the simulator was realised successfully at NPCC. Simultaneously, also supporting analytical facilities were up and running. So, in conclusion, the necessary conditions were fulfilled to allow for the start of experimental programmes.

Figure 4.2 *Commissioning of the lab-scale simulator at NPCC (December 2001).*

5. INITIAL EXPERIMENTS

5.1 Introduction

Although the simulator at NPCC was available for experimental work by the end of 2001, it took until the second half of 2002 before first real experiments could be started. In the meantime, NPCC personnel conducted several test runs to get more acquainted with the facility. This was even more necessary, because one of the trainees left NPCC and was replaced by a new main operator, Laura Liu.

The first half of 2002 was needed to get a new Chinese research project approved, in which application of the simulator was foreseen. Finally, this project entitled “Development of De-NOx combustion technology with micro-pulverised coal” was approved within the framework of the National 863 programme, initiated by Deng Xiao Ping to promote science and technology development in key areas, and first experiments could be planned.

The De-NOx project is co-ordinated by the Research Institute of Combustion Engineering of Harbin Institute of Technology (HIT), and involves besides NPCC the following partners:

- Harbin boiler works (largest boiler manufacturer in China, 90% market share in Northeast China),
- North-China Electric Power Institute.

The project concerns coal-over-coal reburning using the coarse fraction from a classifier as the main fuel, while the fine fraction (of the same coal) is being used as the reburn fuel. The main overall project objectives are:

- To develop a reburning technology with Superfine Pulverised Coal (SPC), which has the advantages of low NOx emissions, and low investment and operating cost, and which is aimed at the Chinese energy infrastructure with coal as the primary fuel.
- To complete the development, type selection and system design.
- To complete industrial demonstration in 200 MW and larger pf-boilers.
- To complete the whole set of technologies including their patent position and to realise industrial application.

As a first phase in the project, it was planned to use the lab-scale combustion simulator for obtaining basic data on coal performance in the different stages of a coal-over-coal reburning process. These basic data will then be used as input for pilot-plant (single burner) testing.

To initiate the experimental programme with the simulator, a workshop was held in October 2002. The workshop comprised extensive knowledge transfer by ECN to the project group, detailed discussions on the set up of the experimental programme, as well as the execution of the first experiments (see Figure 5.1). ECN personnel played a guiding role in the drafting of the experimental programme and supervised the first experiments.

Figure 5.1 *NPCC-ECN combustion simulator workshop (October 2002).*

5.2 Design of experiments in the combustion simulator

In the development of the reburning process, the phenomena that take place in the reburning zone and the burnout zone are of particular interest. Therefore, the simulator is to be applied mainly to clarify these phenomena. Basically, this includes not only the fate of the fuel particles (e.g. devolatilisation, N-release, burnout), but also the formation and reduction of NO_x. However, in this respect the design principles of the simulator, and the resulting limitations regarding the analysis of gas-phase processes, should be taken into account.

The simulator has been designed to create realistic conditions for the fuel particles. Realistic means similar to the conditions the particles observe in the full-scale process in terms of heating rate, and temperature and gaseous environment history. These realistic conditions are created by the staged gas burner at the top of the reactor tube in combination with the furnace surrounding the tube. The gas burner flow rates are at least two orders of magnitude higher than the coal flow rate to ensure proper, known and controllable conditions for the fuel particles. This implies that the simulator essentially is not a miniaturised coal-burner. Down-scaling of a coal burner to lab-scale will not lead to representative burning conditions, and translation of results from such a lab-scale burner to full-scale will be impossible or at least extremely difficult and unreliable. However, it also implies that analysis of gaseous species originating from the fuel will be very inaccurate or even impossible. The focus should essentially be on the solids phase. Nevertheless, some gas-phase changes can be assessed indirectly from analysing the solids-phase changes; e.g. the time-dependent N-release from the fuel particles will give rise to NO_x formation in the gas phase.

The principle of the coal-over-coal reburning process is shown schematically in Figure 5.2. At the exit of the primary combustion zone, the temperature level is approximately 1200-1300 °C and the oxygen content in the flue gas is approx. 2 vol.%. In the project, it is foreseen to use Superfine Pulverised Coal (SPC) with an average particle size of <20 µm as the reburn fuel.

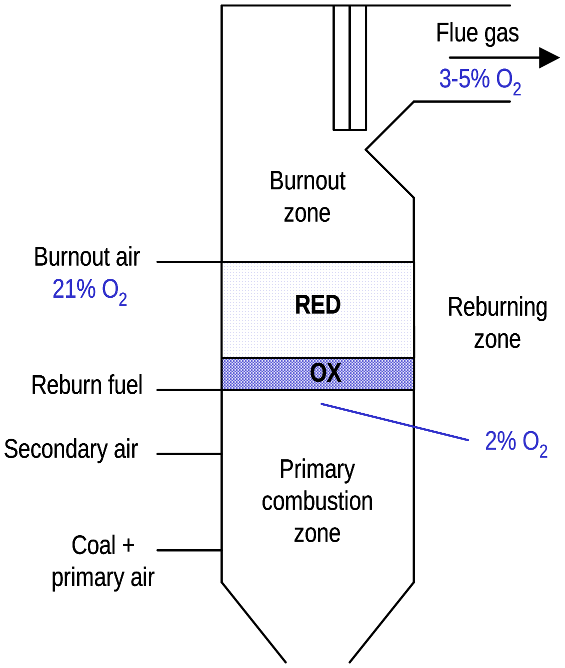

Figure 5.2 *Schematic of the reburning process.*

When these fine reburn fuel particles enter the boiler, they will rapidly devolatilise. Due to the small particle size, the volatile matter yield is expected to be relatively high compared to the volatile matter yield of pulverised coal particles of an average size (70 µm). The volatiles will partly react with the oxygen, but the excess volatiles will create a reducing atmosphere. In this reducing atmosphere, radicals and reducing species (including HCN and NH_3) from the coal will react with the NO_x formed in the primary combustion zone. In this reducing zone, no significant further conversion of the char after devolatilisation is expected, since there is no oxygen present and the temperature is too low for a significant contribution by the gasification reactions with CO_2 and H_2O. However, the char may/will have a catalytic effect on the NO_x reduction.

The further conversion of the char from both the primary pulverised coal and the SPC is envisaged to take place in the burnout zone, where extra air is introduced to complete the combustion process in order to reach low carbon-in-ash levels. The final oxygen concentration in the flue gas is expected to be 3-5 vol.%.

The expected conversion profile for the SPC is shown schematically in Figure 5.3. The devolatilisation of the particles takes first place in an oxidising atmosphere, while the second part takes place in a reducing atmosphere. In this respect, one may realise that the gaseous atmosphere surrounding the particles is not so important during devolatilisation, because the particles are then surrounded mainly by a cloud of their own volatiles. There may only be an effect on the devolatilisation process, if the presence of oxygen leads to the combustion of the cloud of volatiles close to the particles, and consequently the particle temperature increases.

After devolatilisation, no further conversion of the char particles takes place in the reducing zone. In the burnout zone, the conversion is completed through the reaction with the burnout air.

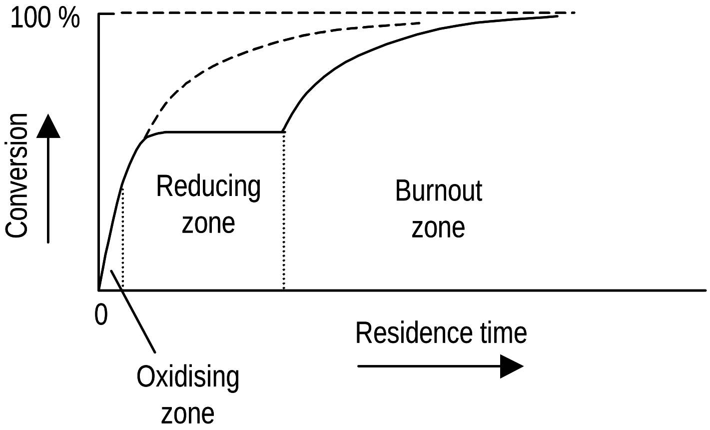

Figure 5.3 *Expected conversion of a Superfine Pulverised Coal (SPC) particle after being injected as reburn fuel.*

The dashed line indicates the expected conversion profile in the simulator experiment.

In the lab-scale combustion simulator, the three zones indicated in Figure 5.3 cannot be simulated as such. However, when one realises that no significant char conversion takes place in the reducing zone, this zone can be omitted in the simulator experiments. Furthermore, if the gaseous environment during devolatilisation is not critical, than for the gaseous environment in the simulator, attention can be focused on the burnout zone. In addition, the settings for the gas burner and the furnace should be such that the temperature level is 1200-1300 °C throughout the reactor (corresponding to the temperature level in the reburning and burnout zones, as indicated by Harbin Institute of Technology and NPCC). Finally, with respect to the char conversion in the burnout zone, the oxygen content is likely to be most important (more important than CO_2 and H_2O).

In a first approach, realising that NPCC still has to build up operating experience with the simulator and making optimum usage of the presence of ECN employees during the workshop, it was decided to use nearly the same settings, which were applied already in tests with the simulator at ECN (see Table 5.1). In the ECN facility, these settings resulted in a temperature profile as shown in Figure 5.4. Compared to the desired conditions for a proper reburning simulation, the overall temperature level is somewhat lower and the initial inner burner temperature (985 °C) is considerably lower. However, concerning the latter one may notice from Table 5.1, that the inner burner flow rate is very low, which results in a rapid mixing-in of the outer burner gases (within approx. 20 mm, see Figure 5.4). Furthermore, it may be expected that the temperature drop in the first 200 mm will be larger in the NPCC simulator due to differences in configuration (e.g. a larger distance between the burner and the top of the furnace)[1]. The oxygen level in the ECN settings is 4.5 vol.%, compared to a desired level of 6 vol.%. The 1.5 vol.% increase, however, can probably be accomplished without any problems and without any (major) adjustment of the other settings. Finally, the extra CO_2 in the outer burner will not be applied in the reburning experiments, because it was not readily available at NPCC during the workshop. In the ECN-experiments, the extra CO_2 was injected to increase the CO_2 content in the final\gas mixture. This would also be desirable in the reburning experiments since the CO_2 level at the entrance of the reburning zone is calculated to be 16.8 vol.%. However, as stated above, this CO_2 level will only have a very limited or even negligible impact on the char burnout. Therefore, omission of the CO_2 in the outer burner will not make the experiments significantly less representative.

In summary, the operating conditions as a result of the envisaged NPCC settings, presented in Figure 5.4 and Table 5.1, are expected to be fairly close to the desired ones.

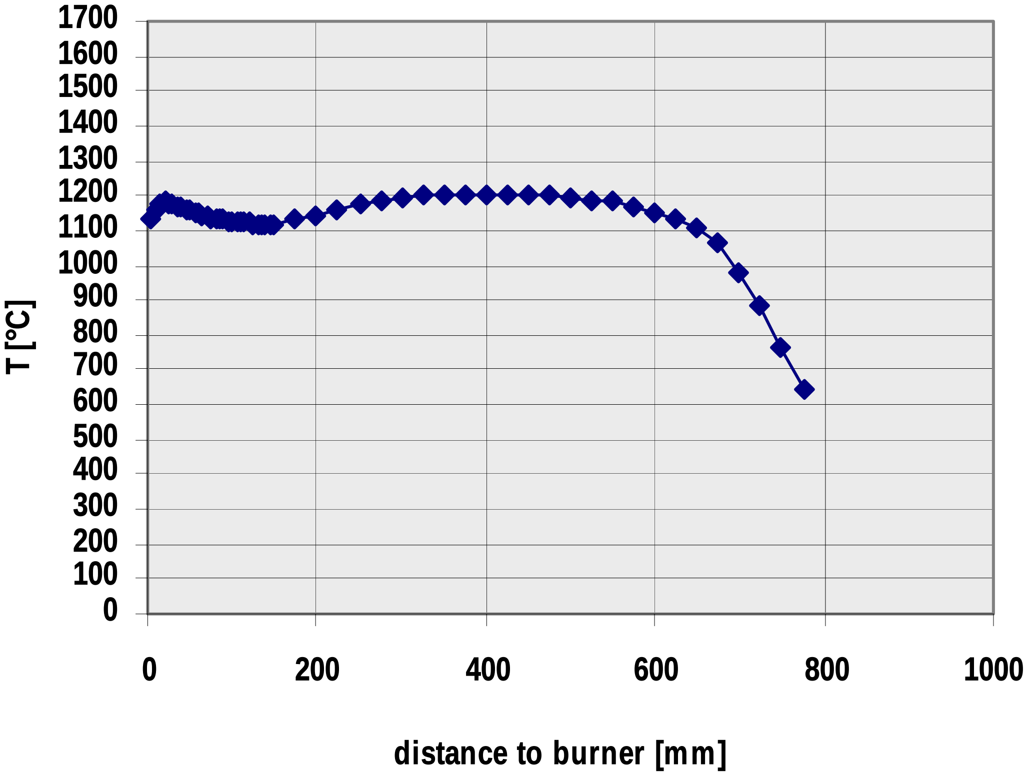

Figure 5.4 *Temperature profile as measured in the AEFGC-simulator at ECN for the set of operating conditions given in Table 2.*

Stoichiometric $CH_4/O_2/N_2$ mixture in inner burner with an adiabatic flame temperature of 985 °C; overstoichiometric $CH_4/O_2/N_2$ mixture in outer burner with an adiabatic flame temperature of 1219 °C and 4.5% excess O_2; furnace temperature 1200 °C.

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[1] In future, the furnace may be moved approx. 3 cm closer to the burner to decrease this temperature drop. The distance between the burner and the top of the heated zone of the furnace must not be smaller than 23 cm; otherwise the eriseal in the burner housing may become too hot. A way to go around this limitation is to install an extra external cooling around the eriseal, as it has been applied at ECN.

Table 5.1 *Settings for the gas burner and the furnace of the NPCC lab-scale simulator.*

	ECN settings	Envisaged NPCC settings	Final NPCC settings
Inner burner (l_n/min)			
CH_4	0.02	0.02	0.04
O_2	0.04	0.04	0.08
CO_2	-	-	-
N_2	0.45	0.45	0.97
Outer burner (l_n/min)			
CH_4	1.13	1.13	1.23
O_2	3.33	3.61	3.77
CO_2	1.44	-	-
N_2	15.61	15.61	14.03
Tertiary ring (l_n/min)			
N_2	1.67	1.67	1.67
Furnace (°C)	1200	1200	1200
Adiabatic flame temperature (°C)			
Inner burner	985	985	~985*
Outer burner	1219	~1230*	~1200-1300*
Gas composition after gas combustion and complete mixing (vol.%)			
O_2	4.5	6.0	6.0
CO_2	10.9	5.1	5.8
H_2O	9.7	10.2	11.6
N_2	74.9	78.7	76.6

* Estimated values, since at NPCC the Aspen+ software package to calculate the adiabatic flame temperature was not available. Later, at ECN, the adiabatic flame temperatures for the final NPCC settings were calculated to be 946 ^oC and 1496 ^oC for the inner and outer burner respectively.

5.3 Simulator testing

Before conducting the actual experiments, the performance of the simulator at NPCC was tested. This comprised the following:

1. *Perform a general check of all the components of the simulator*.
   It appeared that all components still functioned well, in agreement with the findings during the commissioning test conducted 10 months earlier.

2. *Test the performance of the staged gas burner for the* <u>*envisaged*</u> *NPCC settings given in Table 5.1* (with the quartz tube to allow good visibility of the flames).
   First, it was attempted to operate the outer burner on the envisaged settings. This appeared to be impossible. At the envisaged settings, the flame blows off. The reason for this is not clear (gas purity and mass flow controller calibration errors were ruled out). Therefore, starting from the settings for normal combustion conditions (which were known to give a good flame stability from previous tests with the NPCC simulator), the settings were gradually changed to approximate the envisaged settings. It appeared that the final settings given in Table 5.1 are the closest approximation. Thus it was decided to apply these.
   Then the inner burner was tested. Here the envisaged flow rates appeared to be too low. Approximately double flow rates are required to reach stable flame conditions. This may be partly due to the low CH_4 and O_2 flow rates, which requires the respective mass flow controllers to be operated in their 0-10 % range. This part of the operating window for the mass flow controllers is known to be inaccurate/non-linear.

3. *Test the feeding of the Superfine Pulverised Coal (SPC).*
   Feeding of the SPC appeared to be without problems during the first 30-45 min. Then, however, the honeycomb flow straightener in the inner burner became partly blocked (about half of the 1 mm^2 holes). This blocking could not be overcome by excitation of the burner or by temporarily increasing the nitrogen flow rate to the inner burner. Thereupon, it was decided to remove the honeycomb flow straightener. Normal practice then is to replace it by a ceramic cylinder (with the same open area as the honeycomb) to prevent preheating of the gases before they leave the burner-tip. But, since this ceramic cylinder was not available, it was decided to test a completely open inner burner tube[2].

   This test appeared to be very successful, enabling a stable operation of the (inner) burner in combination with a constant, well-distributed particle feeding. Although it was somewhat surprising that almost the same inner burner settings could be used as for the situation with the ceramic honeycomb, even though the open area of the honeycomb is only approx. 44% of the open tube area. In the end, this resulted in the final settings for the reburning experiments as indicated in Table 5.1.

5.4 Experimental programme

In the limited period of time available during the workshop, it was decided to perform a maximum number of experiments. It was planned to do two types of experiments, viz.:
- Reburning experiments with SPC;
- Devolatilisation/combustion experiments under the same conditions with normal-size coal (approx. 50 µm average diameter).

In addition, the axial temperature profile was to be determined.

Reburning experiments with SPC
For the reburning experiments, first the particle residence times were estimated. This was conducted with a rather simple, straightforward (but fairly accurate) approach. The approach is based on the following assumptions:
- The gas flows from the inner and outer burner and the tertiary ring are fully mixed throughout the reactor and the laminar flow pattern is fully developed already at the burner.
- The temperature in the reactor is uniform at a level of 1200 °C.
- The particles stay in the centre of the tube and the difference between particle velocity and gas velocity is negligible (which indeed is the case for the very small particles considered, see below).

With these assumptions, the total normal flow rate of 21.79 l_n/min, given the inner tube diameter of 73 mm, corresponds to an average actual gas velocity of 46.8 cm/s. The assumptions of a fully developed laminar flow profile and the particles staying in the centre imply that the particles will encounter a gas velocity equal to twice the average velocity, i.e. 93.6 cm/s. With the particle velocity being equal to the centre-line gas velocity, this value then can be used for the residence time calculations.

It was decided to do four experiments, two at short residence times to characterise the devolatilisation behaviour and two at long residence times to characterise the burnout behaviour. The probe positions and calculated particle residence times are given in Table 5.2. It was furthermore decided to use a maximum particle feed rate (estimated at approx. 5 g/h; no calibration of the feeder had taken place yet) in an attempt to get reliable data on the changes in

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[2] Much care has to be taken when operating the inner burner without a honeycomb or another type of flame stabiliser. There is the danger of the flame going into the tube, i.e. ignition/combustion inside the tube. In particular, this is risky at higher temperature levels (> 1200 °C)! Therefore, one should preferably avoid inner burner operation without a flame stabiliser.

the gas phase from gas measurements (notwithstanding warnings from ECN that too high feed rates will have a negative impact on the particle heating rate).

Table 5.2 *Probe positions and calculated particle residence times for the reburning experiments with SPC.*

Experiment nr.	Distance between gas burner and probe tip (cm)	Calculated particle residence time (ms)
1	61 (= 1 cm in the furnace from the bottom of the furnace)	651.7
2	42 (= middle of furnace)	448.7
3	10	106.8
4	5	53.4

The experiments were conducted with Hegang coal, a Chinese bituminous coal. The coal sample was obtained from a power plant, where it was sampled after the mill. This sample was processed at Harbin Institute of Technology (HIT). A normal-size fraction was obtained by sieving the power plant coal (100% < 75 µm). The SPC was prepared by grinding the normal-size coal. The proximate and ultimate analysis data are given in Table 5.3, while the particle size distribution of the SPC is presented in Figure 5.5. From Figure 5.5, it can be observed that the SPC-fraction with an average particle size of approx. 5 µm indeed is superfine, even finer than envisaged for the actual reburning process.

Table 5.3 *Proximate and ultimate analysis data of Hegang coal (air dried sample).*

	Value
Proximate analysis (wt%)	
Moisture	1.28
Volatile matter	21.06
Ash	36.87
Fixed carbon	40.79
Ultimate analysis (wt%)	
C	52.39
H	3.62
O	4.96
N	0.58
S	0.30
Heating value (kcal/kg)	
Gross	5196
Net	5010

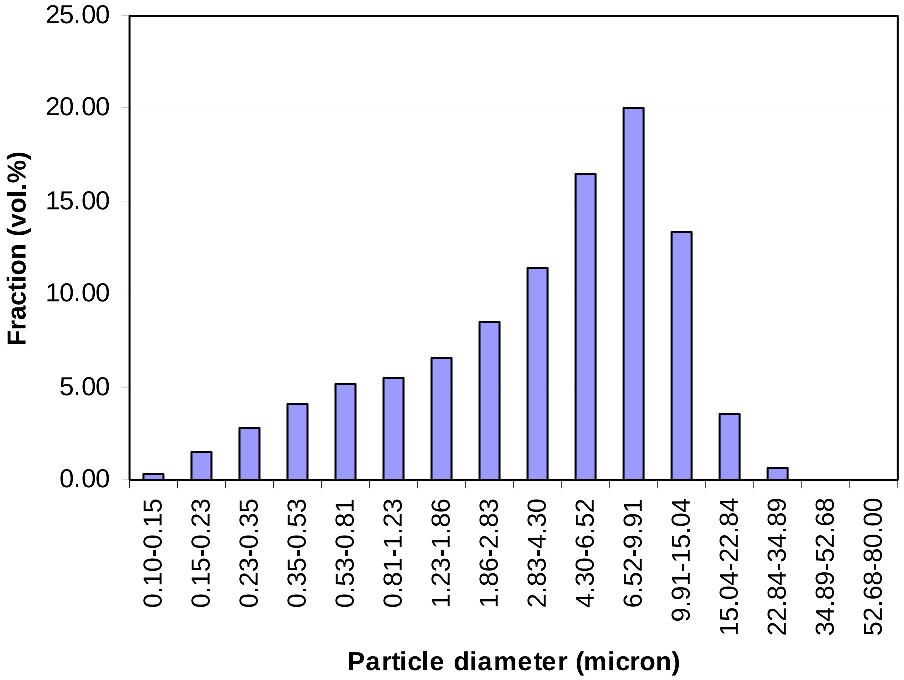

Figure 5.5 *Particle size distribution of the SPC-fraction, determined with a Malvern Mastersizer at HIT.*

D(0.1) = 0.60 μm, D(0.5) = 4.86 μm and D(0.9) = 12.06 μm.

(Reburning) experiments with normal-size pulverised coal.
Following the experiments with SPC, the same simulator conditions were applied in a series of experiments with normal-size particles. The experiments were aimed at obtaining an idea of the effect of particle size on devolatilisation, N-release and burnout. Due to time limitations, in this case only three sampling positions (5, 42 and 61 cm from the burner) were chosen. In the interpretation of the results from these larger particles, it must be kept in mind that the resulting particle residence times will be somewhat smaller than for the SPC due to a higher free falling velocity of the particles.

Measurement of the axial temperature profile.
It appeared to be impossible to measure the axial temperature profile due to malfunctioning of the thermocouple. This could not be solved on-site. ECN will prepare and send a new thermocouple to allow proper temperature profile measurements.

Nevertheless, from the colour of the alumina reactor tube between the furnace and the burner it can be judged, that the temperature drop in this part should be limited. Therefore, it is most likely that the axial temperature profile does not deviate strongly from the one measured at ECN and shown in Figure 5.4.

5.5 Experimental results and discussion

The results of the four conversion experiments with the SPC-fraction and the three experiments with the normal-size fraction are presented in Table 5.4 and Figure 5.6. The conversions were calculated from the proximate analysis data, as obtained for the air-dried parent coal and cyclone and filter samples by thermogravimetric analysis, using the standard ash tracer method.

According to this method, the conversion (ξ) is related to the actual (x_a) and the original (x_{a0}) ash mass fraction as follows:

$$\xi = 1 - \frac{x_{a0}}{x_a} \cdot \frac{1 - x_a}{1 - x_{a0}} \qquad [1]$$

where:

ξ [-] : conversion
x_{a0} [-] : fuel ash mass fraction determined by proximate analysis (815 °C)
x_a [-] : ash mass fraction of partly converted sample

It can be seen in Figure 5.6, that the conversion rapidly increases to a level considerably above the value corresponding to the devolatilisation of the volatile matter fraction, as determined by proximate analysis. Apparently, as it is observed for many coals, the volatile matter yield in the actual process, with a much higher particle heating rate, is considerably higher than the proximate analysis volatile matter yield.

After the rapid initial increase, the conversion levels off indicating a rather slow char combustion. Furthermore, there appears to be a limited influence of particle size. These results tend to indicate that the Hegang coal is a less suitable reburn fuel, since it requires long residence times to achieve high burnout. The limited reactivity is expected to be due to the relatively low volatile matter yield of the coal, and its high ash content. In general, coal-over-coal reburning is preferably conducted with high-volatile, low-ash coals.

Table 5.4 *Experimental results.*

Experiment	1	2	3	4	5	6	7
Coal	SPC	SPC	SPC	SPC	normal	normal	normal
Total coal fed (g)	3.74	3.79	3.58	3.91	4.22	4.61	4.80
Coal feed rate (g/h)	4.68	4.64	4.57	4.12	5.28	5.76	5.87
Probe position (cm)	61	42	10	5	61	42	5
Particle residence time (ms)	652	449	107	53	652(1)	449(1)	53(1)
Weight cyclone sample (g)	1.31	1.50	1.73	2.08	2.03	2.17	3.05
Weight filter sample (g)	0.24	0.25	0.25	0.36	0.09	0.05	0.09
Weight total sample (g)	1.55	1.75	1.98	2.44	2.12	2.22	3.14
Conversion cyclone fraction	0.782	0.747	0.616	0.586	0.760	0.671	0.591
Conversion filter fraction	0.887	0.876	0.673	0.617	0.853	0.838	0.427
Conversion total sample	0.800	0.768	0.624	0.591	0.764	0.675	0.587

(1) For normal-size coal, the actual particle residence times will be somewhat smaller than for the SPC due to a higher free falling velocity of the particles.

However, care should be taken when drawing firm conclusions because of uncertainties concerning the applied operating conditions. In particular, as mentioned in the previous section, the axial temperature profile could not be measured. It is likely that this profile does not deviate largely from the one shown in Figure 5.4, because the higher outer burner temperature may compensate the larger initial heat loss due to a larger distance between the burner and the furnace. But, this is a qualitative estimate only. If, in reality, the temperature in the centre of the reactor tube shows a much larger drop in the section above the furnace, then this will have a quenching effect on the char combustion. Furthermore, the relatively high coal throughput may have led to a somewhat lower particle heating rate and possibly a shielding effect, lowering the effective oxygen level at the particle surface. To verify the impact of this latter effect, it is recommended to duplicate a few experiments with a lower coal throughput (typically 1 g/h).

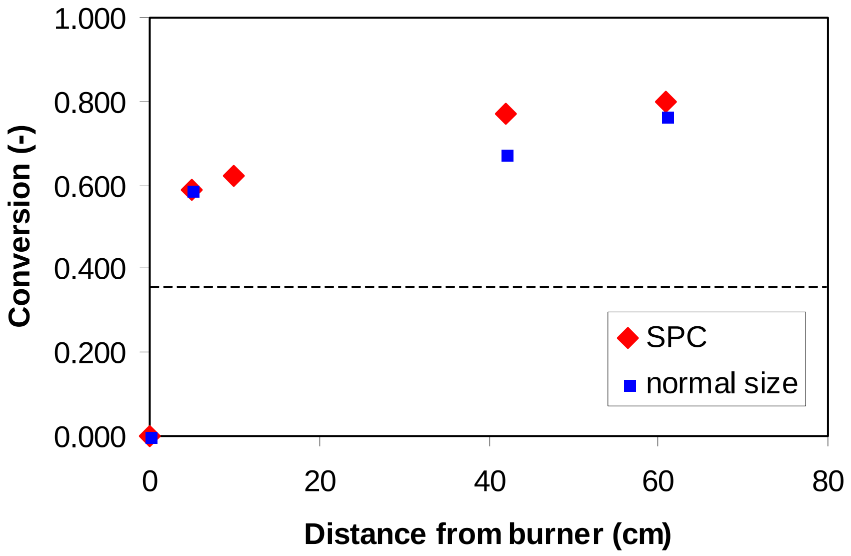

Figure 5.6 *Conversion of the total sample (cyclone + filter) vs. probe position for both SPC and normal-size coal.*

The dashed line indicates the conversion if only the volatile matter fraction as determined by proximate analysis would devolatilise.

6. CONCLUSIONS

The workshop and the initial reburning experiments, as described in the previous chapter, formed a successful conclusion of the project. In this way, a solid basis has been established for a durable co-operation between ECN and NPCC as envisaged.

In general, from the project the following conclusions can be drawn:

- Overall, the project was successful, despite the longer time it took to completion. NPCC personnel received an extensive training to maintain and operate a state-of-the-art lab-scale combustion simulator, as developed by ECN, and the simulator was built at NPCC. Subsequently, initial experiments were conducted successfully in the framework of a Chinese research project on reburning, and information on the possibilities of the simulator and the combined skills of NPCC and ECN in the field of pulverised-fuel combustion was disseminated to representatives of the Chinese power sector, boiler manufacturers, other research institutes and universities.

- Long distance, cultural differences and differences in regular business practice between the Netherlands (or Western industrialised countries in general) and China make that the preparatory phase of a co-operative project like the current one requires large efforts. However, a solid preparation does pay out.

- Money transfer from China to the Netherlands and shipment of equipment from the Netherlands to China turned out to be much more complex and time consuming then initially anticipated. In this respect, it may help to involve an external organisation with experience in this field.

- For the future, there remains the challenge to build on these first steps and maintain a durable co-operation between ECN and NPCC through a continuous chain of joint R&D activities.

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APPENDIX A. ECN LAB-SCALE COMBUSTION (AND GASIFICATION) SIMULATOR

The ECN lab-scale combustion (and gasification) simulator, as it was available at ECN in 1998-1999 at the start of the project[3], is shown schematically in Figure 13 and design parameters are presented in Table A.1. At that time it was officially named as the “Atmospheric Entrained-Flow Gasification and Combustion simulator (AEFGC-simulator)”.

The facility can be characterised as an entrained-flow reactor with an integrated, premixed and multi-stage flat flame gas burner. By feeding different gas mixtures to the different stages, the staged gas burner is used to simulate the high initial heating rates, temperatures and the gaseous environment history that coal/biomass/char particles experience in pulverised-coal combustors or entrained-flow gasifiers. From Figure A.1 it can be observed that the burner consists of two sub-burners viz. an inner burner (10.9 mm) and an outer burner (60.7 mm). A tertiary gas stream (consisting of nitrogen) is applied to create suitable mixing profiles and to protect the tube from the hot secondary gas stream.

Table A.1 *Design parameters of the ECN lab-scale combustion (and gasification) simulator.*

Particle feed rate (g/h)	1 - 5 (1)
Particle residence time (ms)	10 - 300
Particle heating rate (°C/s)	$> 10^5$
Gas composition inner burner	methane, carbon monoxide, carbon dioxide, hydrogen, nitrogen, oxygen, hydrogen sulfide
Gas composition outer burner	methane, carbon monoxide, hydrogen, oxygen
Reactor tube inner diam. (m)	0.076
Reactor tube length (m)	0.55
Max. electrical heating temperature (°C)	1600(2)
Number of heating zones	1
Probes	fast quenching collection probe, deposition probe (axially adjustable under operating conditions)

(1) Higher rates may be used for specific experiments.

(2) The particle temperature history is determined not only by the electrical heating temperatures but also by the flame temperatures of the staged gas burner.

Coal/char particles are fed through the inner burner and undergo rapid heating ($> 10^5$ °C/s) up to the high temperature level of the near-burner zone. The particles are fed at a feed rate of approx. 1 g/h by means of a commercial rotating brush feeder (Palas RGB-1000 Feststoffpartikel Dosierer). The coal is brought into a cylinder and a piston presses the powder against a rapidly turning brush. The particles are dispersed by the brush and transported into the reactor pneumatically. The gas/particle flow is confined in a 76 mm ID reactor tube with a length 550 mm. The tube is surrounded by a controllable heating section equipped with Kanthal Super 33 elements to create the required temperature history for the particles.

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[3] Since then, the facility at ECN went through a major modification, in particular in order to enable longer particle residence times and therefore higher burnout, emphasising pulverised-fuel combustion simulation. The new name of the facility at ECN is Lab-scale Combustion Simulator (LCS). Details of the modified set-up can be found elsewhere [14].

Particle sampling between residence times of 10-300 ms is possible with a fast quenching probe, as shown in Figure A.2, in combination with a multicyclone, a filter and/or a cascade impactor (see Figure A.3). The particle collection probe is hot-oil cooled and nitrogen or helium can be used for sample quenching. Alternatively, a deposition probe as shown in Figure A.4 may be used for slagging and fouling tests. On this probe different materials can be attached to simulate deposition surfaces. An axial probe transport mechanisms ensures the possibility of sampling at different axial positions, i.e. at different particle residence times.

Finally, the particle collection probe can be equipped with a ceramic residence time extension chamber, as shown in Figure A.5, by which particle residence times can be extended to 2-3 seconds.

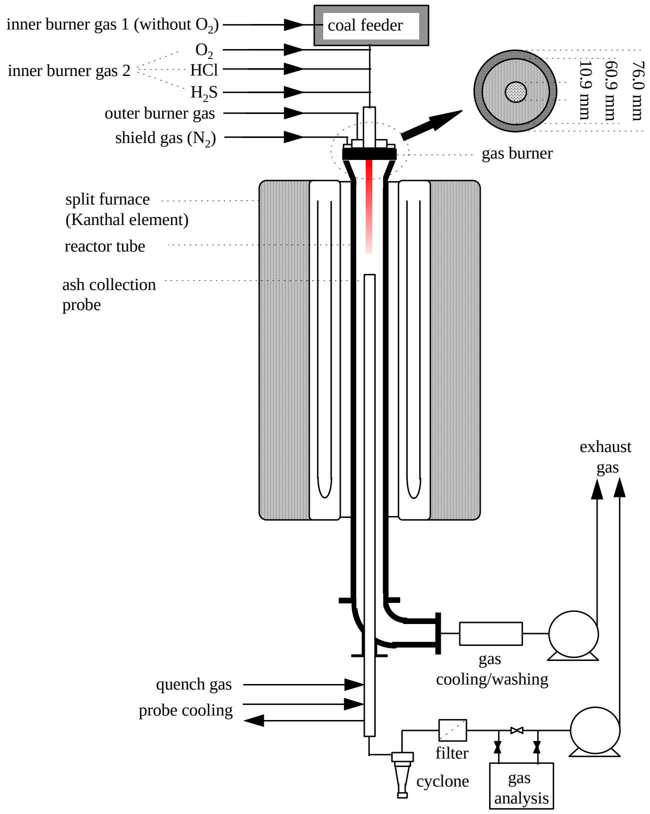

Figure A.1 *Schematic representation of the lab-scale combustion (and gasification) simulator.*

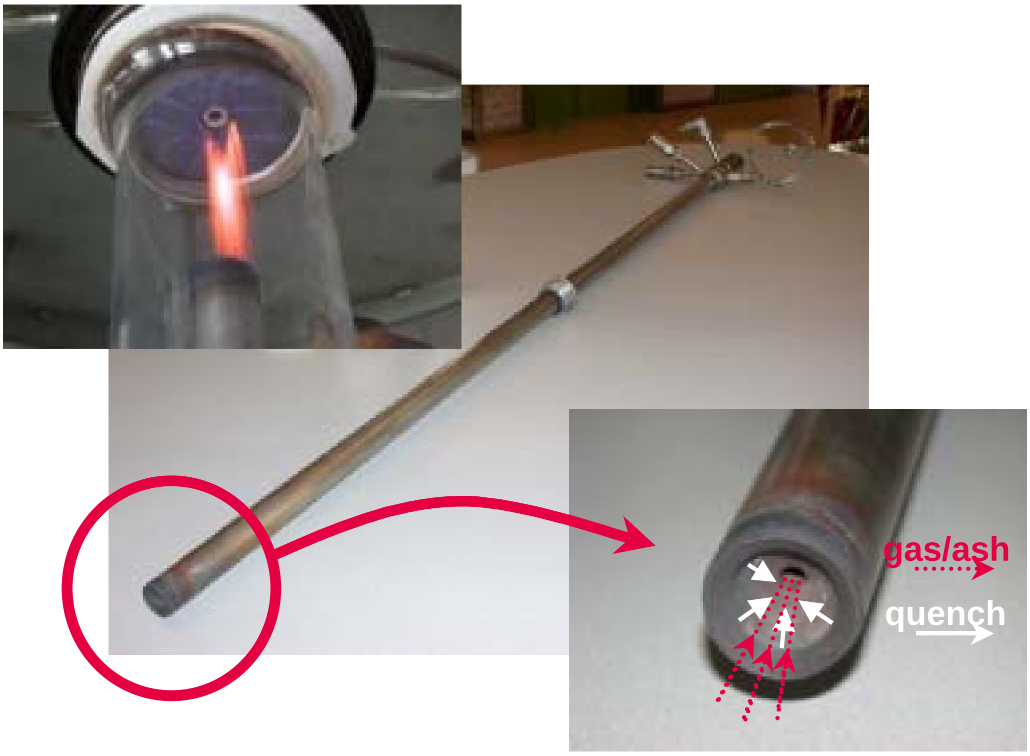

Figure A.2 *Particle collection probe.*

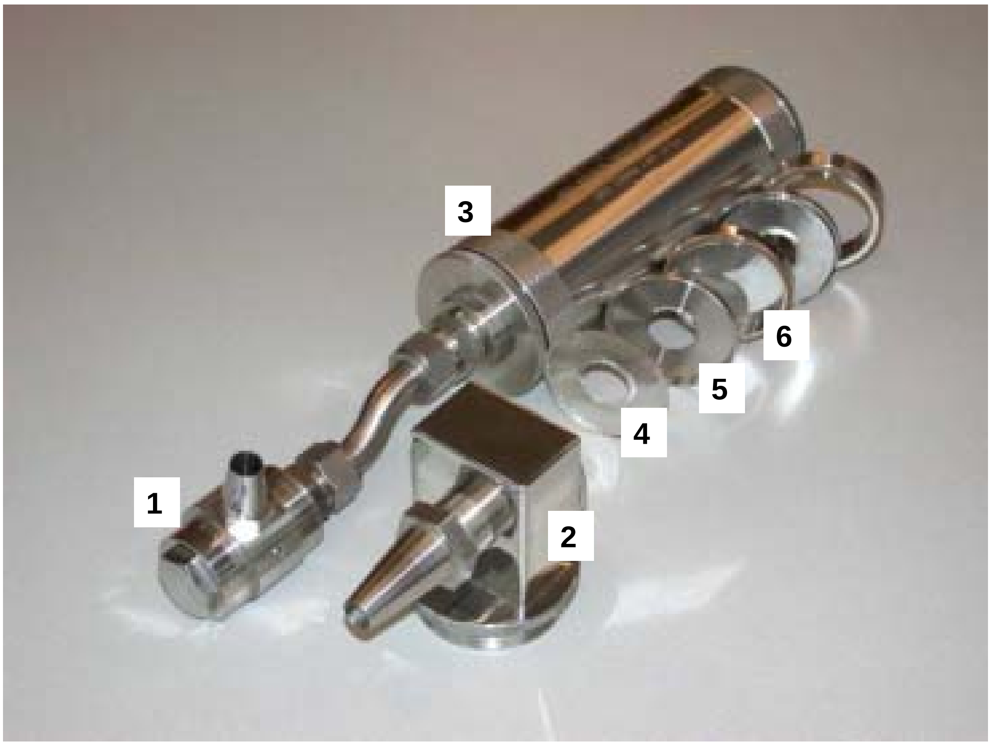

Figure A.3 *PCS Corp. Mark V cascade impactor for size-fractionated particle separation.*

1 = precutter (high loads), 2 = right-angle attachment, 3 = body, 4 = collection substrate, 5 = collection plate, 6 = multi-jet stage.

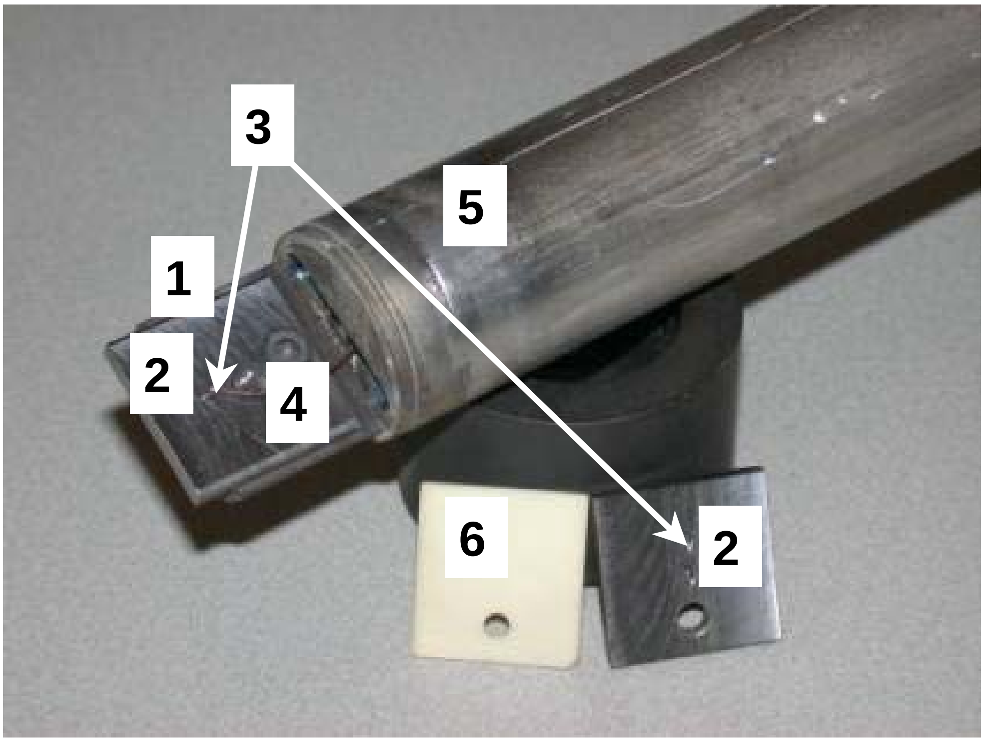

Figure A.4 *Deposition probe.*

1 = cooling body, 2 = metal deposit plate, 3 = thermocouple tunnels, 4 = thermocouple, 5 = probe body, 6 = ceramic deposit plate.

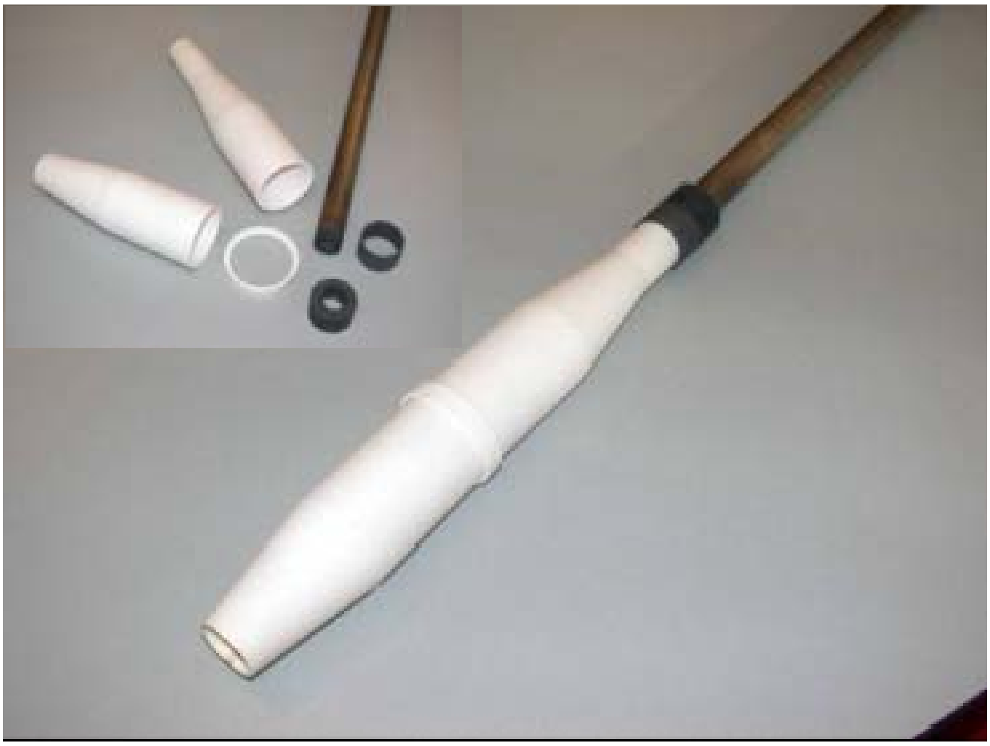

Figure A.5 *Residence Time Extension chamber, allowing for 2-3 seconds residence time extension at 1500 ^{o}C and 1.5 l/min gas flow rate.*

APPENDIX B. PROJECT AGREEMENT ON THE REALISATION OF AN AEFGC-SIMULATOR AND SUPPORTING ANALYTICAL EQUIPMENT AT NPCC

THIS PROJECT AGREEMENT is made the 1st day of April 1999
between:

(1) **The Netherlands Energy Research Foundation**, with principal offices at Westerduinweg 3, P.O. Box 1, 1755 ZG Petten, The Netherlands (hereinafter 'ECN'); and

(2) **The State Engineering Technology Research Centre of Combustion of Power Plant**, with principal offices at No. 185 Huanghe North Da Street, Shenyang, People's Republic of China (hereinafter 'NPCC');

(hereinafter together referred to as 'the Parties')

WHEREAS the Parties, having considerable experience in the field concerned, have decided to co-operate in the research in the field of Pulverised Fuel Combustion, and have concluded a Co-operation Agreement dated April 1, 1999 in this respect (hereinafter called “the Co-operation Agreement”);

THE FOLLOWING IS HEREBY AGREED:

1. TITLE OF THE PROJECT

Realisation of an AEFGC-simulator and supporting analytical equipment at the NPCC

2. OBJECTIVES

In the framework of the establishment of a durable co-operation between ECN and NPCC in the area of Pulverised Fuel (PF) Combustion, the objectives of this project are to make ECN research facilities and expertise available to the NPCC. More specific, this project will be aimed at:

- The realisation of a bench-scale simulator for coal combustion research according to an ECN design at the NPCC in China. Coal and ash characterisation experiments in this simulator are a valuable addition to burner tests in a 150 kW Combustion Research Facility, which NPCC has acquired recently from Ontario Hydro Technology in Canada.
- Transfer of know-how required for the construction and operation of this facility and for the installation of supporting analytical equipment from ECN to NPCC.

3. TERMS AND CONDITIONS

Unless otherwise agreed, the Parties shall be bound by the terms and conditions of the Co-operation Agreement.

4. AVAILABLE INFORMATION

For a detailed description of the available information, it is referred to the Programme Description, attached as an Annex to the Co-operation Agreement.

5. WORK PROGRAMME

5.1 Brief description

In the project, the following tasks are identified:
task 1 - Detailed design (incl. detailed construction work plan and cost estimate)
task 2 - Construction
task 3 - Engineer/operator training at ECN
task 4 - Commissioning
task 5 - After-care
task 6 - Guidance supporting analytical equipment

5.2 Detailed description

To meet the general objective and the specific aims described above, it is foreseen that all activities will be conducted in close co-operation between employees of ECN and NPCC.

task 1 - Detailed design (incl. detailed construction work plan and cost estimate)
Starting from detailed documentation on the AEFGC-simulator available at ECN (Design specs, Layout, P&ID, component specs, etc.), the detailed design documents for the AEFGC-simulator at NPCC will be made. In principle, the detailed design of the simulator at NPCC will be equal to the existing one at ECN. However, it is anticipated that minor adaptations may be required depending on the specific situation and possibilities at NPCC.

To ensure that the detailed design is adapted in a proper way to the situation and possibilities at NPCC, two specific actions are envisaged, viz.:

- A one-week visit of two ECN-employees to NPCC at the start of the project to make a detailed inventory of the local situation (fact finding mission).
- A two-month stay of an NPCC-engineer at ECN to allow for detailed discussions (after an intensive training period (see task 3).

In addition to the adapted detailed design, a detailed work plan and cost estimate for the construction phase (task 2) will be made. This will also require close involvement of the NPCC-engineer at ECN.

task 2 - Construction
It is foreseen that all key equipment of the AEFGC-simulator will be ordered by ECN, collected at ECN and then shipped to NPCC. However, in consultation with the NPCC-engineer stationed at ECN, it may be decided to manufacture certain parts at NPCC or order them in China.

When all equipment has arrived at the NPCC, an ECN-engineer will initiate the construction during a one-week visit. Subsequently, the actual construction will be directed and supervised by the NPCC-engineer, who has been trained thoroughly during his two-month stay at ECN (see task 3). ECN will offer distant support and guidance (by e-mail, fax). NPCC will be responsible for providing the necessary infrastructure facilities, although ECN will also provide guidance in this respect.

task 3 - Engineer/operator training at ECN
It is envisaged that two NPCC-employees will receive a thorough training during a two-month stay at ECN. The training of one employee will be focused mainly on the construction phase such that he will be able to direct and supervise the construction at NPCC. The other employee will be trained in operating and conducting experiments with the AEFGC-simulator.

task 4 - Commissioning
The commissioning of the AEFGC-simulator at NPCC will be conducted by NPCC personnel with the aid of ECN specialists. Clearly, the NPCC trainee who visited ECN will play an important role in this task. The ECN-involvement will consist of two one-week visits of one ECN specialist to NPCC as well as distant support (by e-mail, fax).

task 5 - After-care
Some costs are accounted for to cover the expected after-care, required to ensure an effective utilisation of the AEFGC-simulator by NPCC-personnel during the entire project.

task 6 - Guidance supporting analytical equipment
To make optimal use of the test facilities, viz. the OHT Combustion Research Facility and the AEFGC-simulator, NPCC will acquire and install supporting analytical equipment with guidance provided by ECN.

6. RESULTS

6.1 Envisaged project results

- Commissioned AEFGC-simulator at NPCC adapted to the specific local situation and possibilities.
- Two NPCC-employees, who are well experienced in the construction and operation of the simulator. This should ensure, that the AEFGC-simulator will be used at NPCC as a valuable experimental facility for addressing coal conversion and ash related problems in pf boilers.
- A non-confidential joint NPCC-ECN report on the construction and commissioning of the AEFGC-simulator at NPCC.

6.2 Requirements with respect to the results

The set-up of the design, construction and commissioning phase, the training of NPCC employees at ECN and the joint research and exchange programme should ensure that the AEFGC-simulator will be used at NPCC as a valuable experimental facility for addressing coal conversion and ash related problems in pf boilers.

7. COST BREAKDOWN

In Table 1, the estimated cost breakdown of the project is given in Dutch Guilders (1 kfl.. = 1000 Dutch Guilders; all cost including Value Added Tax (VAT)).

Table 1. *Estimated cost breakdown*

Item	Specification	NPCC cost (in kfl.)	ECN cost (in kfl.)	Total cost (in kfl.)
1	Key equipment AEFGC-simulator	225	125	350
2	Design/construction/commissioning simulator (NPCC-part)	135		135
	Modification of accessory installations 50			
	Fuels and air supplying system 6			
	Stabilised power supply 5			
	Platform for simulator (3 levels height) 20			
	Man-hours (5 persons, 1 year) 25			
	Administrative expense 4			
	Unforeseen 25			
3	Design/construction/commissioning simulator (ECN-part)		165	165
	Detailed design, construction work plan and cost estimate 50			
	Construction 50			
	Operator/investor training 20			
	Commissioning 20			
	Guidance and after-care 25			
4	International travel	30	25	55
5	Accommodation and travel inside China resp. Netherlands	10	10	20
	Total cost	kfl. 400	kfl. 325	kfl. 725

NB. The cost of acquiring and installing the supporting analytical equipment (estimated total cost 500 kfl.) will be covered by NPCC and are not included in this project. Only the (cost of) guidance provided in this respect by ECN is accounted for.

8. TIME SCHEDULE

In Table 2, the project time schedule is given.

Table 2. *Time schedule*

TASK	DESCRIPTION	YEAR 1				YEAR 2				YEAR 3			
1	Detailed design	▨	▨										
2	Construction			▨	▨								
3	Engineer/operator training at ECN		▨										
4	Commissioning				▨	▨							
5	After-care						▨	▨	▨	▨	▨	▨	▨
6	Guidance supp. anal. equipment	▨	▨										

IN WITNESS WHEREOF, the Parties have caused this Project Agreement to be executed by their duly authorized representatives;

ECN
Name : Prof. dr. F.W. Saris
Title : Managing Director
Date : 14/IV/99

ECN
energy innovation

Li Zhenzhong

NPCC
Name : Prof. Li Zhenzhong
Title : Deputy Director
Date : 99.4.21