# Compact Fired Heating Units (CFHU)

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# Compact Fired Heating Units


## Abstract

A two-year (1996-'97) investigation into the use of three different combustion technologies for the production of heat in a variety of applications in the power and process industries has been excuted under a research program consequently named "Compact Fired Heating Units". These three state-of-the-art technologies are respectively fully premixed swirling combustion, air staged combustion and flameless oxidation combustion. Key features of this research are: the use of medium to high preheated combustion air to increase the thermal efficiency of those appliances where the flue gas exhaust temperature is higher than 300 oC; the enhanced use of NOx abatement strategies such as in-furnace flue gas recirculation and/or air-fuel staging; and the use of the potential for increasing the firing intensity of furnaces and process fluid heaters in order to reduce the volume and floor space when needed. To successfully complete this research, a strategy was followed in which carefully planned experiments were conducted in combination with selected numerical simulation studies with commercial CFD computer codes. The five experimental facilities that were used for studying the effect of furnace conditions and burner operations on NOx and CO emissions from natural gas combustion include respectively, *for the premixed swirling combustion research:* a 30 kW and a 300 kW oil heating furnace with wall temperatures up to 300 °C and combustion air preheat up to 300 °C, and a 200 kW water heating furnace; *for the air staged combustion research:* a 200 kW load heating furnace with an air staged, integral bed natural gas burner with up to 1350 °C furnace wall temperatures and 600 °C preheat of combustion air, and a 600 kW furnace with similar facilities; *and for the jlameless oxidation combustion research:* a 300 kW load heating furnace with a FLOXTM (flameless oxidation), natural gas burner and with combustion air preheat up to 1100 °C. In addition, post-flame compact heat exchangers and indirect fired heating with radiant tubes were extensively researched as well. These experimental facilities enable a comparative study in alternative combustion techniques for natural gas and this for a wide range in operating conditions such as combustion air preheat, furnace temperature and furnace volume. They were deployed by the research institutes that were the contractors in this research. The burners were supplied by the industrial partners that acted as associated contractors in this project.

# 1. Strategic Aspects and Objectives

Based upon expertise gained from ongoing research projects in the partner's institutions, and based upon discussion with design engineers from a variety of industries, the following strategic aspects with regard Compact Fired Heating Units (CFHU's) were identified.

**Strategic Aspects**

*Combustion air preheating* is an established technique to save energy in these processes where combustion flue gases cannot be cooled to a sufficient degree. Heat recovery from the flue gas for combustion air preheating lowers energy consumption substantially. For example if, in a process operated at a temperature of 1,200°C, the combustion air is preheated to 1,000°C, fuel consumption is reduced by about 50% compared to the cold combustion air case. Energy consumption decreases and CO2 emissions are also lowered.

Combustion air preheating in general leads to a higher flame temperature and, as a consequence, to an *increase of thermal* NOx production and emissions.

NOx *abatement techniques* for combustion air preheating up to 300°C in utility type large boilers and refinery furnaces have been well established. In these units, wall type burners are used that employ successful techniques such as staging and internal flue gas recirculation to prevent an excessive increase of flame temperature. These techniques invariably lead to flames which are spread out over the large internal volume that is available in these units.

In CHFU's the ratio of heat exchange surface to furnace volume is much larger than in utility boilers. As a consequence, NOx abatement to counteract the effects of combustion air preheating in general leads to in an *increase in .furnace volume* (typically 30%) to accommodate the larger flame size. These leads to a design that is more costly in terms of materials and that requires larger floor areas in the plant.

There are several reasons why established NOx abatement techniques *cannot be extrapolated* to CFHU's with medium to high air preheat :

I. In CHFU's, flames are enclosed between walls that to a large extent affect the thermo- aerodynamics of the flow pattern, and the overall flame behaviour in general. Although the principles of NOx reduction may be the same as for wall type burners, the practical implementation is quite different. The performance of the burner is strongly dependent upon *the geometric and thermal boundaries* of the combustion chamber. These conditions vary widely among the different applications that are the subject of this research.
2. There is also the *scaling problem.* It is well established that the aero-thermochemistry of small to medium sized burners is much different from that of large utility burners.
3. In addition, *the higher air preheating* in these applications needs special low NOx techniques.

As a consequence, design strategies for the integration of the burners inside the furnace have not been fully established. Although sophisticated-CAD codes may exist for selected applications, these codes are not general and are definitely not accessible for the large body of engineers that design these systems. *Moreover, engineering design handbooks for integrating new types of burners in CFHU's are simply not available!*

**Objectives of the CFHU Project**

The general objective was *"to establish and disseminate generic knowledge on how to save energy and .furnace costs and on how to constraint pollutant emissions in those applications where compact .furnaces are used in combination with preheated combustion air.* "

The following qualitative as well as measurable objectives were set forward:

1. To simultaneously research three combustion technologies -swirling, staging and flameless oxidation -for applications in .C.ompact Eired Heating Qnits (CFHU) with the aim of simultaneously lowering NOx emissions and reducing furnace volume and floor area for the specific case of increased combustion air preheating.

*Targets of* 10 *to* 30 % *reduction in .furnace volume for constrained NOx are set forward in this study.*

2. To promote the rational use of energy by constraining NOx emissions for higher temperatures of combustion air preheating than currently used in CFHU applications where the performance is restricted by emission standards.

*Targets of* 10 *to* 30 % *increase in energy efficiency of NOx constrained process units with combustion air preheating are set forward in this study.*

3. To build a comprehensive set of experimental data which will serve as a database from which simplified design methodologies for optimally integrating burners in CFHU's can be derived. This study is committed to provide information to a large body of design engineers of companies, whether they participate in this research project or not.

*At least one international seminar will be organised that will be exclusively targeted to European industries and in which the results of this study will be presented and discussed.*

## 2. Technical Description

The work programme was organised in three main parallel work packages which correspond with the different techniques that were explored. These work packages are subdivided into a set of tasks of which the interdependency is shown in Figure 1.

WORK P ACKAGE: SWIRLING COMBUSTION TECHNIQUES
Task SWRL.l : Testing of swirl burners in compact heating units.
Task SWRL.2: Testing of enhanced heat exchange techniques with combustion
Task SWRL.3: Simulation of enclosed swirling flame combustion and with heat transfer.

WORK PACKAGE: STAGING COMBUSTION TECHNIQUES
Task STAG.l: Testing of regenerative staged burners in a laboratory size furnace.
Task STAG.2: Testing of regenerative staged burners in semi-industrial scale furnace. Task ST AG.3 : Simulation of enclosed staged combustion and with heat transfer

WORK PACKAGE: FLAMELESS OXIDATION TECHNIQUES
Task FLOX.l : Testing of flameless oxidation firing in compact furnaces.
Task FLOX.2: Simulation of flameless oxidation firing in compact furnaces Task FLOX.3 : Testing of flameless oxidation firing in radiant tubes.

Task FINAL: Bringing the results together.

The Partners that were involved in this project are:

| | | |
|---|---|---|
| 1. K.U.Leuven (BE) | KUL | Contractor |
| 2. University of Leeds (UK) | ULeeds | Contractor |
| 3. Gaswarme Institiit-Essen (D) | GWI | Contractor |
| 4. Tech. Univ. Eindhoven (NL) | TUE | Contractor |
| 5. SINTEF (NO) | SINTEF | Contractor |
| 6. Gaz de France (F) | GdF | Contractor |
| 7. Wanson (BE) | WANSON | Associated Contractor |
| 8. Stordy (UK) | STORDY | Associated Contractor |
| 9. BOC Group Techn. Center (UK) | BOC | Associated Contractor |
| 10. WS (D) | WS | Associated Contractor |
| 11. Peder halvorsen (NO) | P. HAL VORSEN | Associated Contractor |

PROJECT OVERVIEW

CFHU Project Co-ordination K.U. Leuven

1 1 Work Package 1 Work Package 2 Work Package 3 (Potential of) (Potential of) (Potential of)
Swirling Staging Flameless Oxidation - K. U .Leuven U niv .Leeds Gaswiirme Inst.

~ask SWRL 1 Task FLOX 1 TESTING TESTING
-+1 SWIRL BURNER I~ ~ FLOX TECHNIQUES 1--
K.U. Leuven Task STAG 1 G.W.I
TESTING -i -+ STAGED BURNERS
Task SWRL 2 Univ. Leeds Task FLOX 2 TESTING SIMULATION -..ENHANCED HEAT --4-- FLOX &
FURNACES 1-
EXCHANGE
SINTEF Task STAG2 G.W.I TESTING
-+ SCALING ~
Task SWRL 3 Gaz de France Task FLOX 3 SIMULATION TESTING
-..SWIRL (& FLOX) --INDIRECT FIRING .-
T.U. Eindhoven Task STAG3 G.W.I SIMULATION
-..STAGING -- Univ. Leeds

Final Task Seminar Project Summary K. U .Leuven

Figure 1

Table 1 shows the range of the main variables that were studied in this program. For process fluid heaters, flfing intensity and medium combustion air preheat are the key variables, whereas for furnaces high combustion air preheat and (the uniformity ot) the wall temperature should be considered. All of the burners were state-of-the-art burners that did not need high excess air ratio's to reduce the NOx emissions. Excess air in these studies varied between 5 and 10 %.

This very elaborate experimental and computer simulation research program has unequivocally shown that this program has met all of the targets that were set forward in the objectives with regard to NOx reduction in combination with combustion air preheat and increase in flfing intensity. All of the three techniques that have been studied have shown their potential for the use in fluid heaters or furnaces with a wide degree of freedom in selecting furnace firing intensity and combustion air preheat while still meeting current as well as future regulations on NOx emissions. Not one of the combustion technologies can be favoured over the others with regard to any of the objectives set forward. Many other factors such as burner stability and ease of start-up need to be considered. Proper tuning and maintenance of the burners for a particular application are very important as well.

Table I. Representative values for the key variables of the CFHU project.

Appliance Burner Firing Firing Wall Tem- Combustion NOx Rates Intensity perature air preheat emissions
kW kW /m" oC °C mg!Nm3 (dry-3%O2)

thennal oil premixed 30 and 300 300 -3000 300 300 20 -80
heater swirl
hot water premixed 50-200 1000 -4000 80 none 80 -100 boiler swirl
furnace nozzle mixing 75-150 45-90 1100 600 30-400 air staged
furnace nozzle mixing
air staged 200-400 80 -160 1200 600 140 -180 oppositeflring 1100-1300 650-740 100-450

furnace FLOXCM 250 60-1100 1200 920 100- 900

# 3. Results and Conclusions

## 3.1 Work Package: Swirling Combustion Techniques

3.1.1 Task SWRL.1: Testing of swirl burners in compact heating units. *Contractor: Katholieke Universiteit Leuven*

The experimental facilities include a set of three 30 kW thermal oil heaters and one 300 kW thermal oil heater. Their combustion chambers are cylindrical shells that are formed by a continuously coiled tube. The back of the combustion chambers are made of a concrete disc that can be moved such as to vary the length of the combustion chamber. The diameters of these heaters are respectively 0.26, 0.33, 0.40 and 0.500 m. The range of the lengths of the combustion chambers are respectively 0.2 -0.5 m. and 0.5-1.5 m. These units are representative of process fluid heaters that are widely used in the chemical process industries. The burners that are used in this study are manufactured by the International Flame Research Foundation (IJmuiden, The Netherlands). They provide an annular rotating flow of almost fully premixed natural gas and air that exits at a speed of 28 m/s in a conical quarl with a 20 degree opening angle. The gas is mixed with the air near the annular exit. The swirl is generated by a movable block swirl generator that generate a swirl number which can be varied in a range from 0 to 1.345.

The experimental program includes: (1) experiments in open air: flame temperature measurements; (2) experiments with the 30 kW burner in a quartz octagonal chamber: flame temperature and flow field measurements; and (3) experiments with the burners installed in the thermal oil heaters: temperature measurements in the combustion chamber and flue gas emission measurements. The variables that were investigated for a given combustion chamber and burner were: burner thermal output, air/fuel ratio, combustion air preheat, swirl number, and gas gun design. The main conclusions of this elaborate experimental study are:

- The low NOx potential of swirl stabilised burners in steam boilers and process fluid furnaces is conf1rIned (values down to 20 mg/Nm3 were measured).
- The burners are highly resistant with respect to an increase in NOx emissions due to combustion air preheat. 300 °C Air preheat is tolerable.
- The burners are also highly resistant with respect to an increase in NOx emissions due to an increase in firing intensity. Whereas nozzle-mixing burners are restricted to the range of 1 to 1.5 MW/m3, swirl burners may be used up to 3 MW/m3.
- There exists an optimal degree of non-premixedness of the air/gas mixture. Reducing the degree of non-premixedness in this otherwise almost fully premixed burner, reduces the NOx emissions and reduces the stability of the burner also.
- The NOx emissions of the burner depends in a complex manner on the length and the diameter of the combustion chamber. More research in this field is needed.

A new research program will start in which the gas gun will be optimised with respect to burner stability and NOx output. In addition, research will start on the design of centrifugal fans with high pressure head at the expense of low fan noise.

### 3.1.2 Task SWRL.2: Testing of enhanced heat exchange techniques with combustion

***Contractor: SINTEF***

This study contains two parts: Combustion chamber heat exchange and post-flame compact flue gas heat exchangers.

A. Combustion chamber investigations

A rather extensive experimental program has been carried out to investigate the effect of decreased furnace volume (furnace length and diameter) on the emissions of NOx and CO and heat transfer to the furnace walls. A swirl burner developed by SINTEF is used this study. The swirl burner has an operating range from 75 kW to 250 kW for propane and from 75 kW to 220 kW for methane.

The burner is mounted in a 200 kW CEN (Central European Norm) furnace. The furnace inner diameter is 0.4 m. The inner length is variable, up to 1.3 m, by means of an adjustable water-cooled end wall. A shutter device is used to enable a variable pressure drop to be created at the combustion chamber outlet. All walls, with the exception of the front wall, are cooled. The furnace is fitted with sealed windows enabling visual inspection of the flame to be made. In the present experiments the furnace is operated as a straight through furnace, meaning that the outer flue gas passes are blocked. In this CEN furnace measurement of NOx and CO at different air/fuel ratios (3 and 5% O2) and different lengths of the combustion chamber have been carried out for lOO, 150 and 200 kW. The volumetric heat load was varied by reducing the length of the combustion chamber from the length determined in the CEN standard down to 0.4 m in steps. The results in the CEN furnace with increased volumetric heat release rate show flfSt at 3% O2 and 100 kW that CO emissions start to increase at 1500 kW/m3. Increasing the energy input to 150 kW the CO emissions start to increase at about 2600 kW /m3 and at 200 kW the CO emissions are kept low up to 4000 kW/m3. All these values of volumetric heat release rates are significantly above the standard values recommended by CEN. The NOx emissions at 3% O2 decrease with increasing energy input due to better mixing conditions. Increasing the O2 content up to 5%, cause lower NOx emissions by an average of approximately 20%. At 5% O2 the CO emissions are kept low in the whole range of volumetric heat loads tested. At 50% O2 there is also a clear effect that increased energy input decrease the NOx emissions due to improved mixing. Using methane as fuel decreased the emission of NOx by a factor of two. Adding water-cooled spiral inserts into the CEN furnace in order to investigate how close to the flame heat can be extracted, cause a somewhat increase CO emissions at 3% O2 (increase from 12 to 20 ppm) at 100 kW, but give no difference to the results at 5% O2. The same conclusions can be drawn from the 150 kW energy input, i.e., some increase in CO at 3% O2 and no difference in CO at 5% O2.

An experimental combustion chamber with reduced furnace diameter (300 mm compared to 400 mm in the CEN-furnace) has been used also. The furnace is 740 mm in length. The cooled wall consists of four sections, three sections of 10 cm and one 30 cm section, which can be combined in any desired order. A 50 mm uncooled section with a hole can be placed between any of the other sections in order to insert different measurement equipment. Experiments in this combustion chamber have been carried out with the purpose of measuring heat transfer to the cooled walls as a function of distance form the burner head with reduced furnace diameter. The heat transfer measurements show that the maximum heat transfer is obtained close to the burner. Reducing the furnace diameter gives less total heat transferred and worse mixing conditions.

The overall conclusions are that furnaces can be made significant more compact giving higher volumetric heat loads by a factor of two to three above the recommended values. However, the furnace dimensions are burner dependent and for this particular swirl burner the volume have to be reduced by reducing the length of the furnace and not the diameter.

B. Flue gas heat exchanger investigations

The objective of this study was to investigate tube layout and tube diameter effects on the thermal-hydraulic performance of serrated fin tube heat exchangers, and identify the effects that may increase the compactness of such heat exchangers. An experimental investigation of heat transfer and pressure drop in a total of eight tube bundles with serrated fin tubes was conducted. The test geometries all had identical fin parameters and minimum fin-tip clearance, but tube layout angle and base tube diameter were varied.

The experimental results showed that the tube layout effect on heat transfer was to increase the heat transfer coefficient with increasing tube layout angle up to the point where the net free flow areas in the transversal and diagonal planes are equal. For larger tube layout angles there was a pronounced decrease in heat transfer. The pressure drop coefficient, or Euler number, was not influenced by the tube bundle layout angle for tube layouts where the transversal net free flow area was smaller than the diagonal free flow area. For tube layout angles above this limit, a sharp decrease in the Euler number with increasing layout angle was observed. These experimental data did not agree with existing correlation available in the literature.

The experimental heat transfer and Euler numbers were converted to volumetric heat transfer coefficients and friction factors per unit heat exchanger length. High volumetric heat transfer coefficients coincided with high friction factors. For a constant tube layout angle both heat transfer and friction increased with increasing tube diameter. The relative change in friction was however much higher than the change in heat transfer. For a constant tube diameter both friction factors and volumetric heat transfer coefficients decreased with increasing layout angle. Also in this instance the relative change in friction factor was higher than the change in volumetric heat transfer coefficient.

The consequence of these findings on tube bundle volume for a given heat duty and pressure drop showed that the required tube bundle volumes could be up to 30% larger than that for the optimum configuration. The general trend was that tube diameters should be kept small, and that the tube layout angles should be kept small The heat exchanger core volume was more influenced by tube layout variations than base tube diameter variations.

### 3.1.3 Task SWRL.3: Simulation of enclosed swirling flame combustion and heat transfer .

*Contractor: Technische Universiteit Eindhoven*

This theoretical study was intended to give a better understanding of the swirl stabilised bummer characteristics as they were observed in the experimental program of the Tasks SWRLl and SWRL2 in the CHFU project. In addition, the ability of accurate combustion modelling with a state-of-the-art commercial CFD code, the CFX code, was examined.

Two combustion models and two turbulence models have been used for this investigation. A mixed-is-burot combustion model together with the RNG k-a approach for the turbulence field was used at the beginning of this investigation. In order to obtain a more complete understanding of the physical processes involved, a multi-step Eddy Break Up model for combustion was adopted later. Convergence difficulties when using the simple turbulence model with software was found. By adopting the Algebraic Stress Model for the turbulence field, these difficulties were overcome and a more reliable prediction of the flow field (by including anistropic turbulence effects) whilst retaining computation efficiency was provided. Both turbulence models are part of the standard CFX flow solver package, as is the one step combustion model.

The multi-step combustion model was obtained from the manufacturers together with a state- of -the-art six step reduced chemical scheme for methane and propane. This model is an extension of the eddy-break-up concept to allow for multi-step chemistry .For each chemical reaction comparisons are made between the turbulent mixing rate and the Arrhenius rate. Carbon monoxide is included as an intermediate species. A one step NOx reaction mechanism has been included as a post processor .

The research shows that there exist two steady solutions for strongly swirling input flows. The first solution shows very rapid combustion within a compact recirculating region close to the burner. The second solution has no significant chemical reaction occurring close to the bummer, and the recirculating region extends to the opposite wall of the furnace. The CO distribution shows a "V" shaped feature at a large distance from the bummer which is characteristic of swirling combustion. This dual behaviour has been observed experimentally in the K.U. Leuven experiments. The second mode of combustion, a flameless combustion mode, is to be avoided for safety reasons.

A further study of the bummer stabilised flame is presented. The effects of swirl, excess air, combustion chamber dimensions and gas gun design on NOx and CO emissions, and thermal efficiency are investigated. The advantages of swirl in reducing the flame volume and thereby the CO and NOx output levels are demonstrated. Although the predicted levels of NOx are lower than those found experimentally, the overall tendencies with regard to the key variables show reasonable agreement with experiments.

## 3.2 Work Package: Staging Combustion Techniques

### 3.2.1 Task STAG.1: Testing of regenerative staged bummers in a laboratory size furnace.

*Contractor: University of Leeds*

The main objective of the staging (STAG) work package was to explore, both experimentally (STAG 1) and computationally (STAG 3), the optimal use of air and oxygen based staging for commercial regenerative-type bummers. Particular emphasis was given to increasing the combustion air preheat and hence the thermal efficiency while simultaneously reducing the furnace NOx emissions and the combustion volume.

The bummer was an industrial nozzle-mix burner with an integrated packed bed regenerative combustion air preheater. The nominal capacity of this burner for natural gas rated at 200 kW. The bummer incorporated an interchangeable bummer head. Both an unstaged and air- staged bummer head configuration were experimentally investigated for air preheat temperatures of up to 600°C and at firing rates up to 150 kW. In addition, the effect of replacing the preheated combustion air through both the primary and secondary air staged ports with oxygen enriched air (35 % $O_2$) was experimentally observed. Excess air in these studies measured 10 %.

The bummer was fired into a laboratory-size rectangular rapid-heating furnace with inner dimensions being a width of 0.6 m wide, a height of 0.9 m, and a length of 3 m. The inner furnace walls were made of high temperature resistant ceramic fibre. Typical wall temperatures in this study measured 1100 °C. The furnace incorporated a water-cooled furnace base, enabling the heat transfer from the flame to the base to be calculated. In addition, a water-cooled exhaust gas sampling probe and numerous furnace inlet ports, for insertion of a water-cooled sampling probe, enabled in-fuillace combustion gas samples to be obtained. Measurements of O2, CO, CO2, NOx (on a dry basis) and temperature were obtained via standard gas analysis units and thermocouples respectively. All readings were recorded on a computerised data acquisition system. The NOx readings varied from lOO to 400 mg/Nm3.

The present study highlights the different combustion characteristics of unstaged and air- staged industrial burners. The main conclusions from this extensive experimental program are:

.By staging the preheated combustion air, a dramatic reduction in exhaust NOx could be obtained when compared with the unstaged configuration for similar burner operating conditions (,..., 70% reduction at 125 kW, 600°C air preheat, 10% excess air, furnace wall temperature of 800-1180°C).
.Staging the combustion air produced a 25% increase in heat transfer to the furnace base, when compared to the unstaged configuration for identical operating conditions.
.Preliminary investigations into oxygen enriched air-staged burners indicated their potential to maintain acceptable NOx levels in the exhaust and combustion efficiency whilst increasing the heat transfer properties of the flame and reducing the volume of combustion.

3.2.2 Task STAG.2: Testing of regenerative staged bummers in semi- industrial scale furnaces.

*Contractor: Gaz de France*

This experimental study complements the experimental STAG 1 study. The burner used in this study was identical to the STAG 1 burner except that the burner was nominally rated at 600 kW. Two experimental programs have been executed in this task. The first program concerned a single burner that was mounted in a furnace with boundary conditions similar to those in STAG1. This study therefore acted as a *scaling study.* In the second program, two identical burners were mounted in a furnace opposite to each other with the burners each firing alternatively. This study therefore acted as a *dynamic approach* of staged burners.

In the *scaling study*, the burner was mounted in a high temperature test furnace that measured 0.9 m in diameter and 3 m in length. The test furnace is equipped with a variable heat load which consists of water cooled tubes that can be introduced in the test cell to varying depths in order to control the combustion chamber temperature. A measuring section was added tot the furnace (length 1 m) to provide direct access of various measuring probes in the flame region. Combined techniques were used for measuring velocity (LDV), temperature (fine- wire thermocouple ), and mean species concentrations in the combustion zone of a staged burner with preheated air. Three flames with firing rates of 200, 300 and 400 kW were investigated for a combustion air temperature of 600 °C, a furnace wall temperature of 1200 °C and excess air levels of 10 %. The experimental data consists of detailed maps of the full flame structure (up to 539 measuring points per flame!), of emission levels in the chimney

and furnace heat extraction. The results show only weak effects of the firing rate on flame aerodynamics and heat transfer. However, a significant increase in NOx emission level was measured with increasing input power. The NOx emission varied between 140 and 180
3 mg!Nm.

These detailed measurements, made under extreme operating conditions, e.g., confined atmosphere with preheated air and fine investigation mesh, offer considerable potential in achieving a better understanding of the phenomena influencing the flame properties in a process burner with combustion staging. For instance, the results presented here will first be used to input a quality data base for the validation of numerical simulations. Moreover, they will also be used to investigate scaling factors for larger size furnaces.
The *dynamic approach* experimental study has been fully presented in deliverable 10 of the CFHU project. Two burners were mounted opposite to each other in the same furnace that was used for the scaling study. The effect of firing rates (200, 300 and 400 kW), of furnace wall temperatures (1100-1300 °C), and of reversing cycle time (40, 80 and 120 s) on NOx emissions and thermal efficiencies were investigated at an excess air level of 10 %. The combustion air preheat was realised through regenerative flue gas cooling and varied between 650 to 740 °C. It was observed that the NOx emissions increase with burner throughput and this increase is more pronounced at higher furnace temperatures. NOx emissions ranged between 250 to 450 mg!Nm3. The NOx emissions decrease with larger cycle times and this trend is amplified at higher furnace temperatures. Thermal efficiency of the furnace was however not affected by the periodic burner switching. The main conclusions of this work is that combustion air staging lowers the NOx emissions to levels below future legal limits despite high preheat and furnace temperature. Dynamic operation of the burners provide for an additional degree of freedom in operation that can be used to enhance their performance.

3.2.3 Task STAG.3: Simulation of enclosed staged combustion and with heat transfer .

*Contractor: University of Leeds*

A commercial computational fluid dynamics (CFD) code was employed to simulate the combustion processes taking place when firing the burner into the furnace with both the unstaged and air-staged heads. In addition, a NOx post-processor was used to predict the NO (thermal-NO and prompt-NO) concentrations and rates of formation throughout the furnace.

Combustion was modelled using a mixture fraction/probability density function (pdf) approach. The commercial CFD code (Fluent V4.3) utilises a finite volume numerical procedure to solve conservation equations for the time averaged values of mixture fraction, the mixture fraction variance, enthalpy and additional equations for the k-e turbulence model, by means of the SIMPLE algorithm. The formation of NO was calculated using the thermal (Zeldovich) mechanism and a global reaction mechanism to represent the prompt contribution. The interaction of turbulence and NO chemistry was accounted for through a pdf approach.

Through the experimental measurements, a comprehensive set of experimental data was built which served as a database from which simplified design methodologies could be derived computationally. Experimental data from a geometrically similar, physically larger, nominally rated 600 kW air-staged burner was also supplied by Gaz de France for purposes of comparing experimental data with that obtained computationally.

The CFD/NOx models proved to be valuable as a practical design tool in the optimisation of air-staged burners. Modelling results revealed the sensitivity of the staged burner performance to the angle of injection of the secondary preheated combustion air. The computational data showed that by optimising the orientation of the secondary air inlet angle (5°-8° divergent), low emission levels of NO and high combustion efficiency could be achieved throughout the entire flame volume.

Preliminary computational investigations into replacing the preheated combustion air with oxygen enriched (35 % 02, 65 % N2) air indicated that changing the secondary air injection port to a convergent angle improved the combustion efficiency and provided good flame stability. In addition, the study highlighted the potential of oxygen enriched air-staged burners to maintain acceptable NOx levels and combustion efficiency whilst simultaneously increasing the heat transfer properties of the flame and reducing the volume of combustion. Hence, satisfying all the criteria of the compact fired heating unit project. The main conclusions are:

- The modelling results revealed the sensitivity of the burner performance to the angle of injection of the secondary combustion air. In the present case, the process of mixing significantly and dramatically affects the formation of NO as well as flame volume.
- The computational data showed that by staging the combustion air and optimising the orientation of the secondary air inlet angle (5° -8° divergent angle), low emission levels of NO and high combustion efficiency could be achieved through the entire flame volume.

## 3.3 Work Package: Flameless Oxidation Techniques

### 3.3.1 Task FLOX 1: Testing of flameless oxidation firing in compact furnaces.

*Contractor: Gas Wiirme Institut*

The main objective was to investigate the potential of the FLOXTM low NOx burner technique for the use in compact fired heating units. Detailed investigations were done by experimental tests as well as by means of mathematical modelling. In conventional burners, the reaction zone covers only a small part of the volume of the furnace chamber, thereby increasing the reaction zone temperature and consequently NOx formation. The principle of staging a burner is based on enlarging the combustion zone volume and thus lowering the flame temperature through the increase of the radiation losses that increase linearly with the gas volume. In the FLOXTM burner, the reaction zone is distributed almost uniformly across the complete furnace chamber volume. To achieve this objective, the preheated combustion air and fuel gas are injected at high velocity where they mix intensively downstream of the burner with the resident flue gas atmosphere.

Three different FLOXTM burners with a nominal firing rate of 250 kW have been mounted in two different rectangular test furnaces which offered four different geometries. The combustion air preheat of 920 °C added 90 kW to the furnaces to achieve firing intensities that ranged from 60 to 1100 kW/m3. Excess air levels varied between 5 and 10 % and the furnace wall temperature measured 1200 °C. The NOx emissions varied substantially throughout the experimental program from a value as low as 100 mg/Nm3 up to 900 mg/Nm3. It was observed that the NOx emissions increased with furnace firing intensity (from lOO to 400 mg/Nm3 for 60 to 1100 kW/m3 for a particular burner). Changing the design of the burner resulted in a dramatic increase in NOx formation when the combustion zone volume is decreased due to enhanced mixing near the burner outlet (from 400 to 900 mg/Nm3 for two different FLOX burners and for identical thermal boundaries of the furnace).

Detailed experimental investigations of the reaction zone structure have been performed as well. A suction pyrometer for temperature, a suction probe for stable chemical species, a laser sheet system for quantifying mixing rates and a OH-radical sensitive CCD-camera for mapping the combustion reaction intensity were used for the full field measurements. These field data were used as the reference base for comparison with computer simulations. This extensive experimental database was used to appreciate the change of reaction zone volume and the associated change of combustion intensity with mixing rate due to a change in burner design.

To demonstrate the application in an industrial facility two test furnaces were designed and built which simulate the industrial furnace geometries of a shuttle kiln for the ceramic industries and a belt furnace for the steel industry .Chimney measurements of CO and NOx emissions indicated that there exists an optimal burner design for staged air injection that minimises the emissions of both species. The best design creates a mixing zone that is optimal with respect to the volume size such as to maximise the burn-out, and consequently to minimise the CO exhaust, and to maximise the zone cooling by radiation, thereby minimising the NO exhaust.

### 3.3.2 Task FLOX.2: Simulation of flameless oxidation firing in compact furnaces.

*Contractor: Gas Wiirme Institut*

Mathematical modelling was used to supplement the experimental work. In this work package the CFD code FLUENT was used to model the flow with a standard k-e turbulence model and with standard presumed beta pdf-functions for the mixture fraction as well as for other variables. On the order of 100.000 grid points were used for the simulations. The results of these simulations consisted of the distribution of temperature, CO and NOx across the volume of the furnace as well as averaged chimney values.

Throughout the investigations the mathematical modelling guided the design modifications for the burner. In particular, the different burner designs could be modelled with enough accuracy as to explain why the swirling inlet to the burner with intense near-burner mixing gave higher reaction zone temperatures and consequently higher NOx formation rates than the burner with delayed mixing. Comparisons of computed and measured CO and NOx emissions and of computed and measured CO concentration and temperature field data were presented. Although the experimental values could not be predicted with high accuracy, the tendencies with varying burner designs and with different furnace geometries could be correctly predicted.

3.3.3 Task FLOX.3: Testing offlameless oxidation firing in radiant tubes. *Contractor: Gas Wiirme Institut*

Besides the investigation of the FLOXTM burner in combination with furnaces also investigations of radiant tubes fired with FLOXTM burners were done. The experimental tests were done at a test facility in the laboratory of the associated partner of GWI, WS, Warmeprozesstechnik placed in Renningen, Germany.

The experimental investigations were done with different burner loads and different air ratios. The specific radiant tube firing intensity was raised up to 2.2 MW /m3 for a burner load of 40 kW and a combustion air temperature of 462 °C. The flue gas exit temperature measured almost 900 °C. For all burner set-ups no CO was detected in the flue gas exhaust. The highest measured NOx concentration was 50 mg!Nm3.

Simultaneous to the experimental investigation a calculation was carried out the CFD- program FLUENT. The burner load was set to 40 kW with an air/fuel ratio of 1.05. The combustion air temperature was set to the measured value of 462 °C. The reaction zone is developing only inside of the flame tube. Due to the backflow between the flame tube and the outer tube the resident time in the chamber was considerable extended. Also the calculations yielded no CO emission at the outlet.

As a results of the experimental investigations the use of the flameless oxidation technique in radiant tubes is possible for a wide range of operating conditions. The emissions of the burner are very low even for very high heating densities.

## 3.4 Main Conclusions

This extensive two year research program, which was originally planned for three years, has provided the partnership with a huge amount of new experimental data as well as a variety of state-of-the-art mathematical modelling approaches. New techniques have been researched, and the applications of these new techniques have been extended. The main conclusions are:

1. For "cold-wall appliances" such as small to large steam boilers, hot water boilers, thermal oil heaters and process fluid heaters in general like those used in the chemical process industries, swirl burners are superior to the conventional and widely-used nozzle-mixing burners with regard to NOx emissions. In particular:

- Swirl burners are more robust with respect to the increase of NOx in combination with combustion air preheat up to 300 °C and possible up to 400 °C.
- The use of swirl burners does allow for an increase in the fIring intensity of the heating units by at least a factor of 2.
- With a proper design of the gas gun, i.e. with an optimal degree of non-premixedness of the gas mixture that is jetted out of the burner, a turn-down ratio of I :5 of the burner is possible.

2. For "hot-wall appliances" such as the vast number of heating and reheating furnaces and melting furnaces, staging to variable degrees is recognised as the better technique to combat NOx formation. In particular:

- Staging burners are very robust with respect to the increase of NOx in combination with combustion air preheat up to 600 °C and even up to 900 °C.
- The degree of staging should be optimised with respect to the application, i.e. the combustion air preheat and the furnace temperature. In general, the higher temperatures allow for an extended delay of mixing up to the point of flameless oxidation.
- In this project, modified designs for the staged and FLOXTM burners have been proposed for the first time that have reduced the NOx emission noticeably.

The overall main conclusion is that an optimisation of the system: burner -furnace -furnace load has to be done to reach satisfying results with regard to combustion air preheat and compactness of the furnace volume.

These findings have been presented to the scientific and engineering community at the EUROTHERM Seminar No.54, *"Compact Fired Heating Units,* " which was held at Leuven (BE) on December 11-12, 1997. The seminar was attended by almost 50 persons from academics and industry .

## 4. Exploitation Plans and Anticipated Benefits

The exploitation plans and anticipated benefits are listed separately for each of the work packages.

### Swirling Combustion

This research concerns applications in the energy industries such as hot water and steam generation up to 10 MW , thermal oil heating up to 320 C, and small to medium sized process fluid heaters such as commonly used in the chemical process industries. The anticipated benefits of the use of highly swirling partially-premixed combustion in comparison with conventional nozzle-mixing burners are outlined in the previous section. However, the outcome of this investigation is not directly exploitable. Several practical burner-related issues have to be resolved: the shape and dimensions of the burner quarl; the integration of the burner head with low-noise high-pressure burner fans,; and the electronic guarding of non-attached blue flames. As these items are application related as well, burner manufacturers should consult with equipment manufacturers for further designs.

### Staged Combustion and FLOXTM combustion

This research concerns applications in the thermal industries such as metal, ceramics and clay heating and reheating. The anticipated benefits of the use of staged combustion are outlined in the previous sections. Both techniques have been researched in close collaboration with the burner manufacturers: STORDY for staged combustion and W.S. Waermeprocesstechnik for FLOX combustion. The outcome of these investigations show that air staging is the best strategy for both recuperative and regenerative burners, and that there exists optimal degrees of primary to secondary air ratio, and the degree of delayed mixing of the primary fuel/air mixture with the secondary air. The intensity of mixing as well as the flame volume determine the thermal NOx production. Both companies are currently employing the results of this project with success.

## 5. Potential Applications of the Project

The following figure lists the potential applications of the investigations that were carried out
in this project. Please note that this figure is merely illustrative and for each application, the proper partner should be consulted for more details.

**RECOMMENDED COMBUSTION TECHNIQUES**

**Low** NOx **combustion -High Combustion Air Preheat -High Volumetric Firing Intensity** Space heating and

domestic hot water services

Hot water and steam boilers, fire tube boilers, high swirling combustion with
steam generators, ...proper ratio of premix to nozzle-mix;

Thermal Oil Heaters

Water-tube type fired fluid heaters in the Chemical Process Industries

Metal heating and reheating furnaces

Ceramics and clay heating furnaces Building brick, refractory and
pottery industries air staged combustion with proper degree of staging and mixing intensity
continuous furnaces, batch furnaces,
intermittent furnaces; regenerative bummers, rapid heating systems,