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## FlexHeat

### Flexible Premixed Burners for Low-Cost Domestic Heating Systems

Specific Targeted Research Project

Thematic Priority: INCO C1: Environment

## Publishable final activity report

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Project coordinator:

Prof. Dr. Dimosthenis Trimis

Friedrich-Alexander-Universität Erlangen-Nürnberg

Revision 1

## Flexible Premixed Burners for Low-Cost Domestic Heating Systems

The FlexHEAT project was aimed at developing low-cost, fuel-flexible, efficient and low-polluting premix burners for domestic heating appliances (floor-standing boilers, wall-hung boilers, stoves,...) by means of advanced modelling and design tool ad hoc developed and validated. Low cost and fuel flexibility are essential features to achieve wide penetration of this advanced technologies in an economically depressed region as the Western Balkan one, where local natural gas composition is significantly changing in terms of both space and time coordinates. The major targets of the project are summarised here:

- Development of 1:3 power modulating atmospheric metal premix burners without water cooling, optimised burner material composition and pollutants emissions lower than 50 mg/kWh (state-of-art atmospheric burners operate in a partially premixed mode with high NO<sub>x</sub>-emissions, while in fully premixed mode they do not allow a power modulation).
- Development of 1:5 power modulating fully premixed metal burners, optimised burner material composition and pollutants emissions below 40 mg/kWh over the entire power modulation range (state-of-art burners with these characteristics are mainly manufactured with very high cost materials).
- Achievement of enhanced fuel flexibility, i.e. capability of handling different gases as feedstock (e.g. natural gas, LPG), with special focus on direct use of low heating value resources (biogas, low methane-containing natural gas coming from Western Balkan regions, blast furnace gases, ...). Furthermore, the developed burners should guarantee the usual durability targets for such appliances of at least 30,000 hrs and 200,000 thermal cycles.
- A fully-validated modelling and design platform, including simultaneous CFD modelling of flames and finite-elements modelling of burner stress and strain, primarily aimed at tailoring the burner geometry, the slits and holes shape and distribution pattern. Pollutants emission, flame stability and especially thermoacoustic effects (noise analysis) are also included.
- Model validation to be performed in *ad hoc*-designed experimental test rigs as well as in real-life experimental set-ups (validators), assembled and tested by the end-users, where the achievement of the above objectives would be proven.

In order to meet the challenges of the FlexHEAT project, lying at the borderline of the technological feasibility, it was necessary to involve in a common research effort the consolidated experience, manpower and knowledge of leading companies and research organisations. The consortium overview is given in the following table.

No.	Participant Name	Short Name	Country
1	Friedrich-Alexander-Universität Erlangen-Nürnberg	UERLN	Germany
2	Metalna industrija "Alfa-Plam" A.D. Vranje	ALFA PLAM	Serbia & Montenegro
3	EUROTEH-GAS DOO	EUROTEH-GAS	Serbia & Montenegro
4	Faculty of Mechanical Engineering Belgrade – University of Belgrade	MFB	Serbia & Montenegro
5	Faculty of Mechanical Engineering Banja Luka	MEF-BL	Bosnia & Herzegovina

6	Bekaert Combustion Technology B.V.	BCT	Netherlands
7	Politecnico di Torino	POLITO	Italy
8	Instituto Superior Técnico	IST	Portugal

### **FlexHEAT Consortium Overview**

The consortium included one Dutch burner manufacturer (BCT), two industrial domestic heat appliances manufacturers from Serbia&Montenegro (ALFA PLAM and the SME EUROTEH-GAS, both considered as end-users), 5 academic partners from Bosnia & Herzegovina, Serbia & Montenegro, Portugal, Italy and Germany (MEF-BL, MFB, IST, POLITO and UERLN). The work of the academic partners was mainly devoted to material development, modelling studies and to the development of an advanced design tool for metallic-slits-and-holes premix burners.

Besides the technological aims of the project and the obvious corresponding impact on environment, competitiveness and employment, the project also aimed at stabilizing and reinforcing the research potential of the participants from the Western Balkan both in the research community (universities) and in industry. It activated the human research potentials, form the basis for incorporating young, high quality researchers and MSc and PhD students, it enabled to get in touch with the European research community, gaining from their knowledge. It brought modern experimental techniques and enabled the exchange of people and ideas and giving hope for the return of those, mainly the most promising young researchers who left the region due to the war and the general crisis.

The involved industrial partners plan to further exploit the results. All of them are already active in the market of domestic heating and would be able to later explore the commercialization of the developments of the project.

The German academic partner UERLN was the project co-ordinator due to its long existing relations with all partners, especially with those in the Western Balkan countries. The contact details of the co-ordinator are:

Friedrich-Alexander-Universität Erlangen-Nürnberg  
 Institute of Fluid Mechanics  
 Dr.-Ing. Dimosthenis Trimis  
 Cauerstraße 4  
 D-91058 Erlangen  
 Germany  
 E-mail: dimos@lstm.uni-erlangen.de

A web site was launched in February 2005 ([www.flexheat.uni-erlangen.de](http://www.flexheat.uni-erlangen.de)) having a public part describing the project objectives and the partnership and a password protected restricted area for data exchange and access to important documents like templates, guidelines, minutes, presentations, deliverables etc. The public area also hosts publishable results and presentations. The restricted area is only accessible by the project partners and the commission officers.

The workplan was structured in the following 6 work-packages and the additional work-package 7 on project co-ordination:

- WP1: Burner Material Development
- WP2: Modelling
- WP3: Burner Mantle Design & Manufacturing
- WP4: Burner Prototyping and Testing
- WP5: Validator 1 assembly and testing
- WP6: Validator 2 assembly and testing

The work in the work-packages 1-4 was conducted continuously through the project duration, i.e. during the first reporting period (01.11.2004 to 31.10.2005), the second reporting period (01.11.2005 to 31.10.2006), and the third reporting period (01.11.2006 to 31.10.2007). Concerning the work-packages 5 and 6, preliminary activities dealing with the selection of the validator appliances from the product portfolio of ALFA PLAM and EUROTEH-GAS and the corresponding specifications were accomplished during the first reporting period. In the second reporting period, the preliminary activities dealing with the preparation of the Validator 1 (ALFA PLAM) and Validator 2 (EUROTEH-GAS) for being ready to host the final evolution stage atmospheric and fan-assisted burners started according to the plan. In the third reporting period, the preparation of the validators was finished, and the long term tests of the developed burners were conducted according to the project plan.

Concerning the activities on the burner material development (work package 1), an investigation of the properties requirements, imposed to the constituent burner material by the specific application of atmospheric and premix burners, was performed by POLITO. With the help of BCT, it led to a final selection of three promising commercially available materials: 1) a reference stainless steel EN 1.4016, 2) an advanced stainless steel AK SR 18, and 3) an advanced Ni-based alloy Supermet. Detailed oxidation resistance characterization was performed, with the major result that the relatively low cost AK SR 18 material was the most promising material from the oxidation resistance point of view. The high cost material Supermet has the superior thermomechanical stress characteristics, which is of great practical importance in perforated burner mantle production. Thus, it was clear that compositional design of innovative metal sheets must be a trade-off between oxidation and mechanical stress resistance at high temperatures, trying to maintain a potentially low cost composition.

Definition/preparation and study/characterization of different alloys that were proposed as burner materials were done. New/advanced materials were prepared in POLITO laboratories (Figure 1), through addition of alloying elements to the basic SR 18 composition, which would form second phase hardening. The aim of such additions was to improve the materials mechanical properties at high temperatures. Two solutions were applied: 1) moderate additions of Ni and Al, which were expected to improve the thermal stability of the conventional stainless steel, and 2) Ti and Al additions were employed as a cheaper solution. Oxidation tests, modulation of mechanical properties in temperature and thermo-mechanical fatigue resistance tests on the commercial and advanced alloys were carried out. Further, morphological and metallurgical characterizations were performed, together with the compositional and thermal analysis.



Figure 1. Machine for producing plates of new materials (POLITO).

Based on the characterization of the newly prepared materials, the material that was finally chosen for the burner mantel production is based on the commercially available AK Steel 18SR, with addition of alloying elements Ti and Al to the basic 18SR composition, in order to improve the materials mechanical properties at high temperature. The new material, named 18SR\_TiAl (Figure 2), was defined and prepared in the POLITO laboratories. Further, POLITO carried out oxidation tests, tests of mechanical properties behaviour with

temperature and thermo-mechanical fatigue resistance tests on the developed alloy. Laboratory test verified the advantages of the developed material under combustion conditions.



Figure 2. Fabricated ingots of the new material, which were aimed to be used for the final application (POLITO).

Thin sheets of the 18SR\_TiAl material were sent to BCT for further production of the burner mantels. The produced pieces were not big enough to produce a complete burner mantel, thus the new material must be integrated into the standard material. This was not accomplished by the end of the third reporting period. BCT and POLITO are interested in continuing the cooperation on further refinement and testing of the developed new burner material.

The modelling activities, planned in the scope of the work package 2, were carried by the academic partners MFB, MEF-BL, UERLN and IST. These activities included investigation of the available chemical kinetic mechanisms for different fuels (including biogas) and their reduction, simulation and the parametric optimization of the overall burner performance (e.g. primary air entrainment of the atmospheric burner, thermoacoustic emissions), coupling of the CFD and the finite element modelling (FEM) for the thermo-mechanical stresses of the perforated burner mantles, and modelling of thermoacoustic instabilities.

The overall target of these activities was to establish the methodology and to validate the performance of the numerical tools against experimental results, so that the numerical tools could be used for understanding and identifying potential problems of the burner behaviour. The expected end results of these activities were:

- an optimized design for the atmospheric burner concerning the air entrainment allowing fuel flexibility and power modulation,
- an optimized burner mantle pattern design minimizing thermo-mechanical stresses and allowing the use of lower cost materials for both burner types.

The investigation of the chemical kinetic mechanism and the possibilities for their reduction were carried by MFB and MEF-BL. They performed 1D investigations, testing the performance of different chemical kinetic models with the final target to select proper reduced mechanisms to be implemented in the 2D or 3D burner simulations with combustion. In the scope of this analysis detailed and simplified combustion modeling, flame structure, flame behavior, emissions of pollutants, and different reduced chemical kinetics were investigated. The investigation was carried out using a commercial software package Chemkin. The finally suggested 15-step reduced mechanism is based on GRI-mechanism and it includes  $\text{NO}_x$  chemistry.

Concerning the numerical simulations of the complete burner geometries with combustion, it was concluded that a 2-equation combustion mechanism with a post-processing  $\text{NO}_x$

prediction is sufficient for the optimization purposes, while more detailed mechanisms can be used only in typical small geometrical segments (i.e. burner ports).

In terms of the simulation of the burners performance, the work was divided between MFB, MEF-BL and UERLN. MFB focused on the atmospheric burner, performing detailed numerical and experimental investigations at the component level (nozzle, Venturi, burner mantle and ports including combustion, housing). Figure 3 presents the analysis of the influence of the burner mantel construction (mantel shape) on the emission of NO. Based on the obtained results, MFB developed 1D semi-empirical code for designing and optimizing the atmospheric burner.

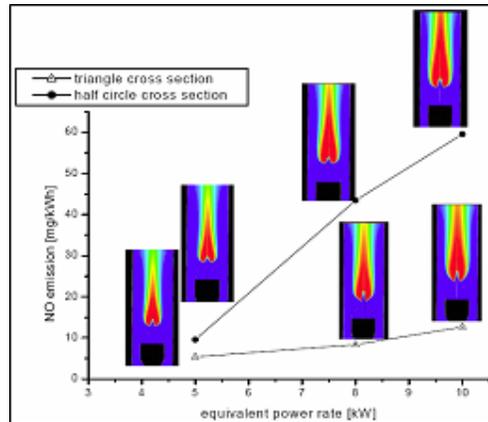


Figure 3. Variation of the NO emissions depending on the burner power rate for two cross sections of the burner (MFB).

MFB was involved in the work devoted to the coupling of CFD and finite element modeling. Flows with chemical reactions and thermo-mechanical behavior for different burners and mantle geometries were studied using the commercial package. Experimental work was carried out in order to validate the numerical results. The obtained CFD results were in good agreement with the experimental research and provided valuable guidelines for the development of the target burners. Figure 4 shows the comparison between the values of the surface temperatures of the burner mantel, obtained by the numerical simulations and by the experimental investigation.

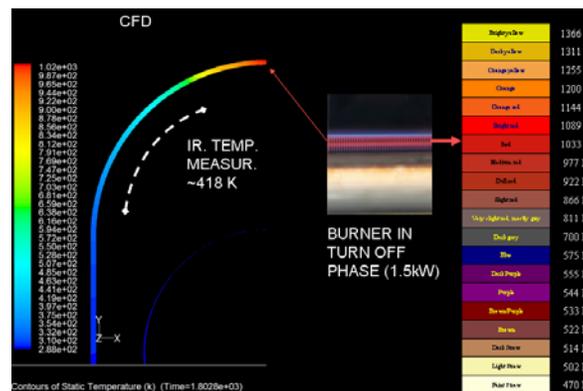


Figure 4. Calculated and measured surface temperatures of the atmospheric burner mantel (MFB).

MEF-BL focused on the simulation of the fan assisted burner and performed detailed numerical investigations including combustion on a typical 3D segment of the perforated burner mantle pattern. Methane-air combustion, gas flow (Figure 5) and the heat transfer

through the complex burner geometry with resolving the details of the burner mantle were simulated.

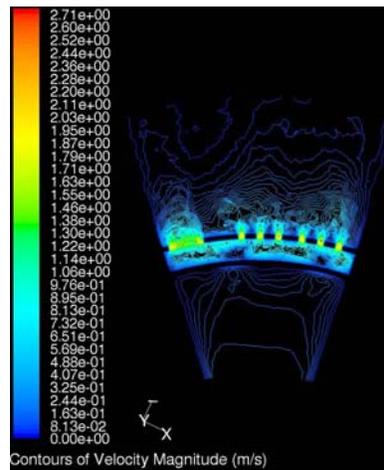


Figure 5. Velocity profile for P = 45 kW (MEF-BL).

Regarding the thermo-mechanical stress modelling, MEF-BL did modelling with the data for standard reference materials: Haynes\_230, AVESTA 253 MA, AISI 441, using the SolidWorks software package (Figure 6). A more detailed analysis of thermo-mechanical stresses of the burner mantle was performed with the more suitable ProMechanica software tool.

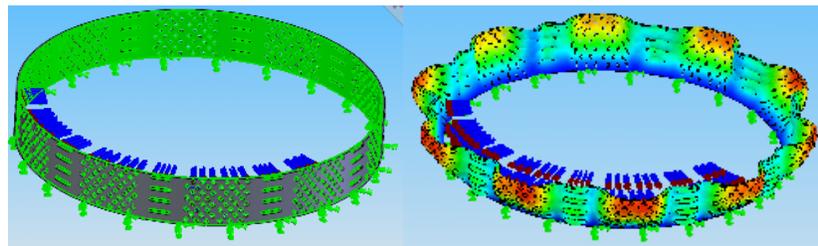


Figure 6. Simulation of the thermal stresses for the fan assisted burner. Maximum deformation is  $5.33 \mu\text{m}$  (MEF-BL).

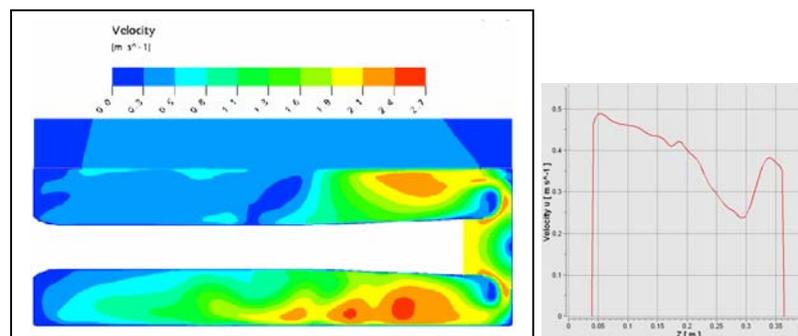


Figure 7. Numerical simulation of the flow field inside the atmospheric burner, and the velocity distribution over the surface pattern (UERLN).

UERLN performed detailed 3D numerical analysis of the complete atmospheric burner geometry without combustion (in cold flow), using the commercial package ANSYS – CFX. The focus of attention was on the prediction of the primary air entrainment behaviour and the gas flow through the atmospheric burner. A parametric optimization of the burner geometry and the burner mantle pattern was performed, utilizing the numerical simulation tools. The main problematic zones in the fluid flow field through the atmospheric burner were identified,

e.g. uneven flow velocity over the burner surface pattern, as is shown in Figure 7. Based on the obtained results, some suggestions for improvement of the atmospheric burner were given. Representative numerical results were experimentally verified.

UERLN also performed detailed experimental and numerical investigations of the cold flow through the different mantle patterns (detailed 3D simulations, detailed LDA measurements, flow visualization) for the fan assisted burner and investigated the effect of the pressure distribution plate. It was found that the geometry of the pressure distribution plate has a significant influence on the overall performance especially concerning instable transient flow behaviour and the flow distribution over the burner mantle. Numerical simulation was used for the optimization of the gas flow and the pressure distribution plate of the fan-assisted burner, in order to obtain a more homogeneous flow distribution within the combustion chamber, as is shown in Figure 8. UERLN also identified possible improvements in the perforation pattern, dealing with the formation of recirculation regions, which would further improve the emission behaviour.

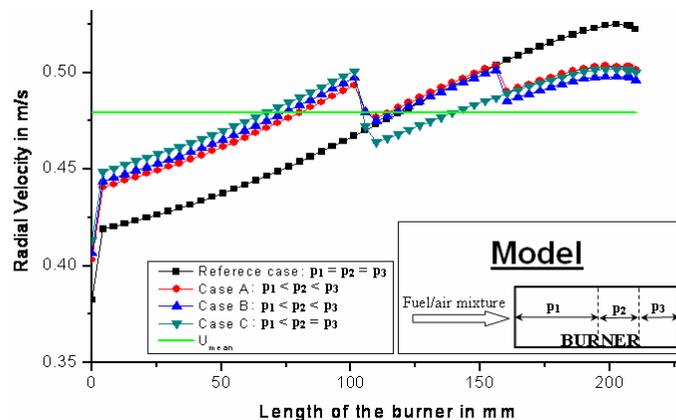


Figure 8. Optimization of the gas flow through the fan-assisted burner (UERLN).

The problem of thermoacoustic oscillations was studied by IST, MFB and UERLN. Such oscillations produce a very high noise level and occur whenever burners (e.g. made of perforated metal sheets with circular and slit holes), are installed in a combustion chamber (e.g. heater configuration), being coupled with upstream and downstream length/volumes. This problem is enhanced if the system has to work under lean conditions, due to increased sensitivity of weak flames to any perturbation. The expected end result of these activities was improved burner design passively prohibiting thermoacoustic oscillations.

In this context, IST investigated simplified systems (slit/holes acoustic analysis of BCT plates), but also a complete BCT burner. The work started with analysing the ability of premixed flames, stabilised either in circular and slit holes w/o a backplate flow distributor (current commercial burner geometry), to drive/sustain thermoacoustic instabilities. Their stability/flammability limits, structure, velocity and light emission were characterized, as well as the acoustic transfer function, as a function of forced oscillations in the exiting premixed flow velocity. It was found that the influence of the pressure distribution plate upstream the burner mantle introduced a major change on the sound emission phase response between circular and slit holes, suggesting the potential for a passive method for preventing thermoacoustics to occur. The acoustic characterization of the fully premixed commercial burner with different acoustic end termination was performed. It was found that a dominant longitudinal acoustic wave was independent of backplate and number of holes/slit on burner mantle.

IST developed a mathematical model for the study of the mantle characteristics (Figure 9), accompanied by experimental acoustic characterization with and without flame. The model

provides the information about the onset of thermoacoustic oscillations and the influence of different parameters. Mathematical modelling (example of results shown in Figure 10) and experimental investigation of the thermoacoustic instabilities resulted in the series of recommendations, which lead to the reduction of noise, emitted by the burner.

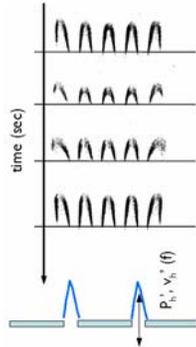


Figure 9. Acoustic analysis: Simplified Model (IST).

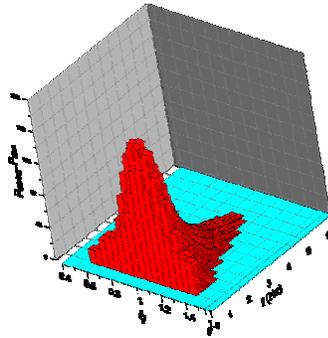


Figure 10. Modelling result: Stability Diagram for 900 Hz (IST).

The work of MFB and UERLN was concentrated on mapping of the acoustic instability region of the atmospheric burner and the suppression of the thermoacoustic emissions.

Concerning the burner mantle and burner construction design, which was the contents of the work package 3, the first evolution stage burners were designed by an ad-hoc analysis performed by BCT. Two different perforation patterns for the fan assisted burner and a third perforation pattern for the fully premixed atmospheric burner were designed. BCT manufactured corresponding burners and provided the mantle patterns and the complete burners to all project partners involved in the experimental characterization and modelling studies.

Concerning the atmospheric burner, the first step toward the target was to produce a burner, which would fit to Validator 1 in length (the first evolution stage burner was ca. 100 mm shorter compared to the Validator unit). Based on results of the experimental and numerical analysis, BCT manufactured six burner prototypes, representing the second evolution stage atmospheric burner. The experimental characterization of these burners, which differ in the burner mantle design (semi-circular and triangular, as shown in Figure 11) and surface perforation, provided data for designing the third and the final evolution stage burner. Concerning the fan-assisted burner, BCT manufactured the second evolution stage fan-assisted burner, with the nominal power of 50 kW. The final perforation pattern was chosen based on the experimental characterization of the first evolution stage burners, done by UERLN.



Figure 11. Prototypes of the second evolution stage atmospheric burner, with triangular and semi-circular mantel shape (BCT).

Based on the extensive experimental analysis performed by the university partners UERLN and MFB the final evolution stages of the atmospheric and the fan-assisted burners were chosen and manufactured by BCT. The burners were made from the standard material. The burners were delivered for the long term testing to Validator 1 and Validator 2.

The performances of the atmospheric and the fan assisted burners at different stages of their development in the scope of the project were evaluated by UERLN, MFB, IST and MEF-BL in the scope of the work package 4. Different aspects of the burner performance like emissions, power turndown ratio, performance with limit gases and varying gas composition and thermoacoustic behaviour were covered.

The results of the evaluation of the first evolution stage burners can be summarized:

- The performance of the first evolution stage atmospheric burner was not sufficient. According to the investigations of MFB and UERLN the burner mantle design of the atmospheric burner was sufficiently good, fulfilling the corresponding project targets on emissions and power turndown ratio. The target of achieving the fully premixed operation was fulfilled, due to which the first evolution stage burner reached the NO<sub>x</sub>-emission targets, as is shown in Figure 12. However, the power modulation targets were not met and the performance with limit gases and varying gas composition was not sufficient. The overall performance was however not sufficient due to the burner housing (Venturi and gas nozzle, flow distribution) design, affecting the air entrainment behaviour. The development efforts on the atmospheric burner were planned to further focus on the optimization of the flow distribution and the Venturi and gas nozzle design, in order to meet the power modulation and fuel flexibility targets.

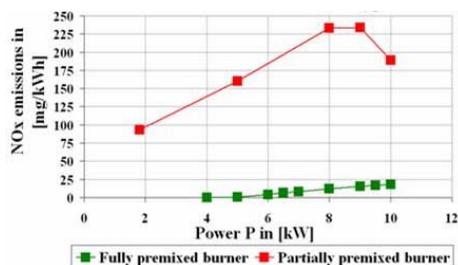


Figure 12. Comparison of the NO<sub>x</sub>-emissions of the fully premixed FlexHEAT burner and the partially premixed burner (the excess air ratios are 1,3 and 0,8, respectively).

As one of the primary concerns of the atmospheric burner design was the primary air entrainment and the quality of mixing inside the Venturi tube, UERLN performed the visualization of the fuel-primary air mixture, using the method Laser Induced Fluorescence (LIF). The investigation showed that the mixture at the exit of the Venturi tube is completely homogeneous, which is a prerequisite for the optimal burner operation.

- The burner mantle and construction of the fan assisted burner fulfilled the project targets in terms of power modulation and emissions. Since the tested burner samples were of a lower nominal power (20 kW) compared to the required for Validator 2 (50

kW), an appropriate scale-up was needed to be done in the second evolution stage. It was concluded that the development efforts on the fan assisted burner should focus on the material development (POLITO), due to material cost aspects, and on the thermo-acoustic behaviour (IST), which is a typical problem for fan assisted gas boiler appliances.

The results of the evaluation of the second evolution stage burners can be summarized:

- The experimental characterization of the prolonged atmospheric burner showed that it was possible to operate it with all test gases. Experimental investigation of the three semi-circular and the three triangular atmospheric burner prototypes, representing the second evolution stage atmospheric burners, showed that they operate as fully premixed atmospheric burners and that they reached the NO<sub>x</sub>-emission targets. However, the power modulation targets were not met. Further development efforts were planned to be focused on the additional optimization and improved control of the air entrainment through the Venturi and gas nozzle design, and velocity distribution/flame height over the surface perforation. An additional open issue for the second evolution stage burner prototypes was the a high frequency noise, emitted during their operation with the upper limit gas G21.
- The fan assisted burner of 50 kW fulfilled the project targets regarding the power modulation and emissions. Further improvements in the flow distribution inside the burner chamber and above the burner surface perforation could be obtained, in order to further decrease pollutant emissions at low excess air ratios and thermal stresses over the burner mantel. UERLN experimentally investigated the temperature field over the burner surface mantel, which was uneven due to the burner length, as is shown in Figure 13. Numerical simulation of the flow field in the fan assisted burner gave suggestions for possible improvements in the upstream flow distribution plate pattern (Figure 8).

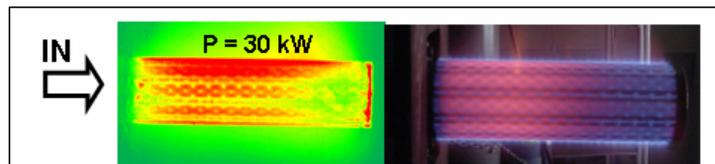


Figure 13. Hot and cold regions on the surface of the fan assisted burner, documented by thermo- and normal camera. (UERLN)

The results of the evaluation of the third evolution stage burners can be summarized:

- Experimental investigation of the final evolution stage atmospheric burner showed that the burner fulfilled the power modulation target (1:2,5) with the nominal gas. The targeted NO<sub>x</sub>-emission was fulfilled already with the first evolution stage burner, while the detailed investigation showed that the CO emissions, which were above the targeted value below 6 kW, can be successfully regulated by adjusting the secondary air flow. This can be achieved by adjusting the gas appliance in which the burner is to be placed.
- The target power turndown ratio and emissions of the 50 kW fan assisted burner fulfilled the project targets.

The sensitivity of the operation of the nominal, the first, the second and the third evolution stage burners was tested toward different gases, i.e. the nominal gas (G20, corresponding to pure methane), the lower limit gas (G231, represented by mixture 85% CH<sub>4</sub> and 15% N<sub>2</sub>), the upper limit gas (G21, represented by mixture 87% CH<sub>4</sub> and 13% C<sub>3</sub>H<sub>8</sub>), and different lean

mixtures representing biogas. Figure 14 presents the third evolution stage atmospheric burner operating at  $P = 3,4 \text{ kW}$  with G20 and with one biogas mixture.

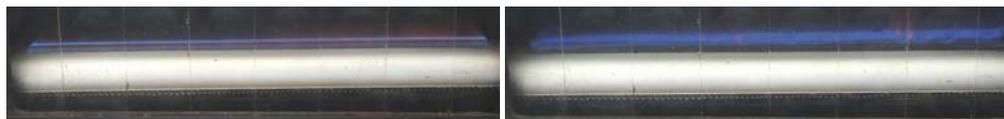


Figure 14. Operation of the final evolution stage burner: a) with the nominal gas (99,5%  $\text{CH}_4$ ; 0,5%  $\text{N}_2$ ), and b) with biogas (59,7%  $\text{CH}_4$ ; 0,3%  $\text{N}_2$  ; 40%  $\text{CO}_2$ ) (MFB).

In the scope of the work package 5, the long term tests of the newly developed atmospheric burner were conducted, where the Validator 1 hosted the burner under development. The burner was targeted to operate as fully premixed, in order to reach the emission targets. As platform, the gas room heater ALFA-9 from ALFA PLAM with a power output of 9 kW was selected. In the existing product a partially premixed atmospheric burner with high  $\text{NO}_x$ -emissions was used. The existing product is produced with 15.000 - 30.000 pieces per year, pending on the market demand, and is basically distributed in the local market and in the market of the neighbouring Western Balkan countries. During different stages of the project ALFA PLAM delivered samples of the ALFA-9 appliance to MFB, UERLN and BCT, to be used in the experimental investigations.

ALFA PLAM, with the help of MFB and EUROTEH GAS, completed the experimental set-up for testing the Validator 1. The necessary adjustments of the gas appliance (Figure 15), which hosted the final evolution stage atmospheric burner, were done. In the period August-October 2007 the long term cycling tests of the Validator 1 were performed, using the local Serbian natural gas. The tests were done according to the agreed schedule.

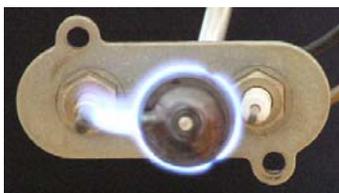


Figure 15. Reconstruction of the pilot flame: operation with 41,3 %  $\text{CO}_2$  (MFB).

Based on the results, obtained from the long term tests the following can be concluded:

- Long term tests of Validator 1 showed that the main project goals were achieved:
  - Minimum agreed power modulating level of 1:2 was reached.
  - Pollutants emissions of  $\text{CO}$  and  $\text{NO}_x$  lower than 50 mg/kWh were achieved.
- The  $\text{NO}_x$  emissions at lowest power regime (3,4 kW) were about 30% over the ELV. This was due to inadequate flow field around the burner for low power regime, as a consequence of performance of Validator1 combustion chamber characteristics. Following the testing results of the burner performance, done at UERLN and MFB, this situation can be solved with reshaping of the combustion chamber.
- Some of the results with higher emission levels for  $\text{CO}$  and  $\text{NO}_x$ , obtained during the long term tests of Validator 1, were explained by serious changes in Serbian natural gas quality, which resulted in variations of primary/secondary air coefficients.

In the scope of the work package 6, the long term tests of the newly developed fan assisted burner were conducted, where the Validator 2 hosted the burner under development. As a platform, a wall hung condensing boiler was selected. The nominal thermal power was selected to be 50 kW, which was suitable for larger houses and/or public buildings. EUROTEH GAS is a small SME company, and it can compete with big manufacturers

profiting from the economy of scale only in the sector of larger nominal powers ( $> 50$  kW) with significantly smaller production numbers.

EUROTEH GAS, with the help of the MEF BL, completed the experimental set-up for testing the Validator 2, presented in Figure 16. In the period July-November 2007 the long term cycling tests of the Validator 2 were performed, using the local Serbian natural gas. The tests were done according to the agreed schedule. As the natural gas, distributed in the region of north Serbia experiences strong fluctuations in quality, the measured discrepancy between the powers obtained using the nominal gas G20 and the Serbian gas are presented in Figure 17.

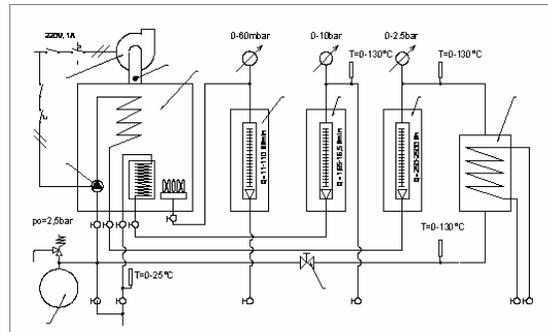


Figure 16. Scheme of the test rig (EUROTEH GAS)

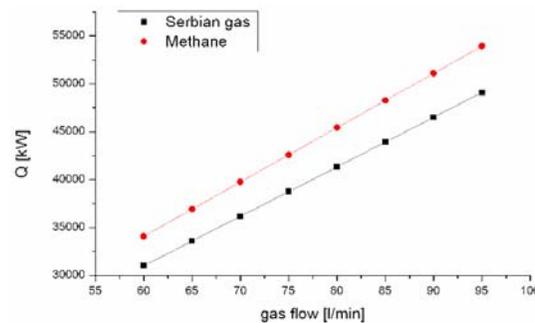


Figure 17. Comparison between the power obtained by the corresponding gas flows for the nominal gas (methane) and Serbian gas (EUROTEH GAS).

Based on the results, obtained from the long term tests the following can be concluded:

- Performance testing of Validator 2 showed that the main project goals were achieved:
  - Power modulating level of 1:5 was reached.
  - Pollutants emissions of CO and NO<sub>x</sub> lower than 40 mg/kWh were achieved.
- Due to the low quality of local natural gas, which contains a lot of ballasts, and with a composition which varies in relatively short time period (hourly and daily) it was difficult to keep stable operation regime over the whole proposed modulation range (1:5), particularly at maximum and minimum thermal outputs.
- Irrespective that low grade natural gas from drills in the surrounding of Zrenjanin was used in the experiments, one of the most important goals, i.e. NO<sub>x</sub> < 40 mg/kWh, was accomplished over the whole regime of fan-assisted burner operation.