TOOLS AND METHODOLOGIES FOR NATURAL GAS DOMESTIC BURNER AND BOILER DESIGN

To satisfy the growing need for natural gas household appliances designed for both the European and world markets, technical constraints that interact, and sometimes conflict with each other, must be taken into account. Until now, few studies have been conducted which address multidimensional laminar partially premixed flames with real natural gas and realistic boundary conditions.

A consortium of gas companies (Gaz de France, BG Technology, and Gasunie), a burner manufacturer (Worgas Bruciatori), and academic institutions (Centre National de la Recherche Scientifique, University of Heidelberg-PCI, and Imperial College of Science Technology and Medicine) have formulated a project called TOPDEC. This project is supported by the European Commission in the framework of its Brite EuRam III program. Its aim is to develop new design tools and methodologies in the form of design guidelines and computer codes for the simulation of burner and boiler performances.

Household appliances form one of the main application areas of natural gas combustion. The specificity of this application is the use of partially or totally premixed laminar flames. These types of flames are particularly sensitive to gas composition which affects flame stability and pollutant emissions. Such effects should be understood in order to satisfy the growing need for appliances designed for the European and world markets, using a wide range of natural gas blends. Constraints must be taken into account. For example, most of the markets require low-NO_x (below 60 mg/kWH), low-noise, compact, and low-cost boilers. If the technology exists to design low-NO_x boilers using fully premixed advanced burners, it induces additional costs that are often not acceptable. Boiler manufacturers need design tools able to analyze and predict flame stability, pollutant emissions, and burner-boiler interactions to reach these objectives.

Design Guidelines

Flame measurements of idealized and commercial boilers were made to capture the main basic mechanism of flame stability and pollutant emissions in conditions representative of real appliances. In addition, the design methodology of domestic boilers was analyzed to identify and quantify the critical parameters influencing global performance. Furthermore, the characteristics of boiler components, which influence boiler behavior, were investigated. From these detailed measurements and analysis, complemented by insights from the modeling, actual design guidelines could be derived.

Recent progress in numerical simulation techniques and combustion kinetic modeling have opened the way to simulation of practical laminar flames encountered in commercial appliances. Nevertheless, problems remain to be solved. Firstly, Imperial College had to derive from a detailed kinetic mechanism of natural gas combustion (not only methane) a simple, although realistic (flame speed, pollutant emission), reduced mechanism able to be incorporated in a computer code using Computational Fluid Dynamics (CFD) techniques. Secondly, Imperial College, BG plc, and Gaz de France had to couple this reduced mechanism into a CFD code in an efficient manner to make the resulting design tool usable in an engineering environment.

Idealized Boiler

The idealized boiler was developed by Gaz de France and Worgas Bruciatori to mimic the key features of practical appliances while simplifying the problem from a 3D to a 2D flow. The configuration is similar to real boilers equipped with blade burners. Attention was paid to the knowledge and control of the inlet conditions, the air/gas mixture composition, the secondary air flows, and the heat fluxes at the boundaries. It was first characterized by global measurements (stability, total emission levels) for different loads, primary and secondary aerations. It was concluded that the idealized appliance has a similar behavior to practical boilers with respect to correlations between the input and output parameters.

Subsequently, detailed measurements were made in the idealized boiler, for different regimes and flame shapes relevant to practical equipment by GDF, BG, PCI, and CNRS. Five test cases were defined which span from totally premixed to partially premixed flames.

Bunsen and V-shape flames burning pure methane or natural gas blends were considered changing primary and secondary aeration and flame shape while keeping constant the thermal load to 10 kW and the total aeration to 1.4. Local temperatures, molecular (CH_4, O_2, CO, CO_2, NO, NO_2), and radical (CH, OH, CN, C_2) species concentrations were measured using advanced diagnostic techniques in the idealized boiler. Velocity was measured by Particle Image Velocimetry, temperature was measured by Fine Wire Compensated Thermocouples, and C_2 and OH radicals concentrations were imaged by Spontaneous Emission Spectroscopy.

For the aerodynamic field, the homogeneity of the secondary air distribution was verified and gradients were identified, along with the laminar nature of the flow. The temperature field measurements showed that the maximum was reached in the region between the premixed reaction zone (inner cone) and the diffusion reaction zone (outer cone). The excited-state OH distribution showed that the flame was attached to the burner and the maximum located at the burner vicinity, while the C_2 formation was delayed leading to a concentration maximum at the top of the inner core. From all the detailed measurements collected in a database, a clear understanding of the basic mechanism could be achieved.

Commercial Boilers

Commercial boilers utilize multiblade burners that resemble the idealized 2D burner, but which are essentially 3D in nature. In this fashion, the similarities and differences between the idealized and practical cases could be evaluated, and the information obtained had served to establish the guidelines. A commercially available, partially premixed, instantaneous hot-water heater was modified for optical access by Gasunie. As a first step, a series of input/output measurements (emissions versus thermal load) intended to ascertain that the modified appliance behaves similarly to the original one were carried out. In addition, it was checked that when properly scaled at the same surface thermal throughput, the NO_x emissions were nearly identical and CO emissions were similar. The difference in scaling behavior results from the fact that NO formation is governed mainly by a bulk phenomenon while CO emissions are more influenced by local conditions. The distributions of the concentrations of NO and CO and of the temperature were measured by Laser Induced Fluorescence (LIF) and Coherent Anti-Stokes Raman Scattering (CARS). In particular, the effects of mixing between the hot flame gases and the cold secondary air on pollutant formation were studied under realistic conditions of thermal load and limited access of secondary air. The analysis of the results yielded a number of minor differences with the idealized boiler.

First, the flames in the practical water heater were substantially less stable than those in the idealized boiler—the practical flames tended to show high-frequency fluctuations ("jitter"). In addition, the CO measurements showed substantial CO concentration between the burner blades (as a result of fuel-leakage), which the measurements on the idealized boiler only suggested under fuel-lean conditions. However, none of these observations indicated any real difference in the behaviors of these appliances.

The general design and assembly processes of a boiler were considered in terms of different parameters thought to determine the boiler performance. Therefore, a detailed analysis of the manufacturing and development processes was carried out by Worgas to quantify their contribution on the operating conditions and global performance. In parallel, to produce design tools of practical use for manufacturers, it is essential to link the design guidelines to the manufacturing process and the boiler's individual components. These results were incorporated into the guidelines.

Floor standing and wall mounted boilers equipped with a burner designed for 8.8 kW of nominal input have been instrumented with flue gases sample probes, thermocouples, and optical accesses for Laser Sheet Visualization by Worgas. All of the tests were made with the same nominal power input of about 8.8 kW, varying the secondary air entrainment, the slots pattern, and the flue gases obstruction. As an example, the influence of secondary air distribution of the NO_x emissions for different total aerations were assessed.

Development of Burner Design Guidelines

These guidelines feature correlations and trends which are based on scientific knowledge acquired during the project. The results obtained in the idealized and commercial boilers were analyzed by all the TOPDEC Consortium partners and gathered to obtain a comprehensive description of the phenomena governing flame stability, flow behavior, and pollutant formation in domestic boilers. In particular, the combinations of primary and secondary aeration, the relative velocities and distributions of primary mixture and secondary air, the influence of these parameters on NO_x and CO emissions, and the effects on flame structure revealed by the diagnostic and modeling studies were analyzed to assess the effects of the variations of these parameters on boiler performance. The design guidelines and the experimental methodologies are now available, validated during a real exercise of burner development.

Development of CFD Based Design Tools

For basic research purposes, 1D laminar flame codes are widely used (i.e. PREMIX code). They are very helpful to analyze the combustion behavior of a fuel and are widely used among the scientific community to validate combustion kinetic schemes against experimental data obtained in low-pressure (flat) laminar flames. However, they are not incorporating features needed to design a practical burner of a domestic boiler. For computer simulation of multidimensional combusting flows, several commercially available 3D codes, running on workstations, are able to predict the flow in the bar burner system of domestic boilers (PHOENICS, FLUENT, CFX, ESTET, etc). Nevertheless, none of these codes have the capability to use a complex chemistry for combustion and have been validated against experimental data in such a configuration. They have been designed for general purpose in the industry and most of the current improvements are targeted towards fluid mechanics and heat transfer.

Predicting multidimensional laminar premixed reactive flows implies the coupling of 3D flow calculation with a detailed chemistry. In the flames concerned, chemistry is very important: the flame position and shape must be calculated with great accuracy because they are strongly related to the heat transfer with the burner, which influences the temperature field and, consequently, the combustion kinetics, flame stability, and final composition of the exhaust gas. Moreover, relatively complex phenomena such as hydrogen atom recombination near the burner surface must be considered. Such a chemistry-flow coupling for multi-dimensional gaseous fuel combustion has not yet been made in a commercially available code, only in 2D research code.

Modeling work, using recent scientific knowledge related to laminar combustion and the reduced kinetic mechanism described above, were used and implemented into commercially available CFD codes. Two CFD codes were used, one developed by BG and Mantics Numerics (COBRA) and one developed by Electricité de France and used by GDF (ESTET). COBRA, that had already the capability of handling reduced chemical kinetics, was enhanced to provide global results to the user like CO, CO_2 and NO concentrations at the fire box exit. ESTET was coupled with the GDF chemical kinetics library BISCUIT, resulting in a specialized version of the ESTET code, called ESTET-CC for Complex Chemistry. These efforts have together with experimental data obtained in the idealized boiler, resulted in two numerically validated tools. Particular attention has been paid to the methodology of use of such numerical design tools to ensure the efficiency of computations related to manufacturers' needs and to ease of use.

Evaluation of Design Tools

In order to assess the benefits of the new tools and methodology, a real case exercise featuring the development/improvement of a commercial burner was performed by Worgas, GDF, and BG. A V-shape flame burner was improved employing the design guidelines and CFD tools. By testing in the idealized combustion chamber, a new version of the prototype was developed. It was then tested in the full size appliance (prototype combustion chamber) and appeared to produce more NO_x in that configuration. After identifying the causes, the prototype combustion chamber was further modified, finally leading to results meeting the targeted NO_x emissions. The tools could be further optimized as a result of this exercise. At the end of the latter, the benefits obtained by using the tools in improving the design of practical appliances were compared to their costs.

Conclusion

An idealized household boiler was designed, built, and characterized. The results show that it reproduces commercial domestic boiler behavior with a simplified geometry and a better control of the boundary conditions. Detailed measurements were made in both idealized and commercial household boiler flames which highlighted the key mechanisms of combustion control in such appliances.

Two CFD computer codes are being enhanced to extend their capability to allow simulations of household boiler flames in an engineering environment and to offer a user-friendly interface for the burner designer. Good results were obtained in terms of trend predictions of flame shape, stability, and NO emissions.

From the detailed measurements, burner/boiler development analysis, and some simulation results, guidelines were derived. These design guidelines, in the form of a book, help support the designer in analyzing the results of prototype tests and provide key parameters to meet design specifications such as CO and NO emissions. In addition, a methodology of use of in-flame measurement techniques is given.

The evaluation of the tools (design guidelines and CFD codes) was made during a real exercise. A new burner and boiler could be developed, meeting the design targets, particularly in terms of NO_x emission and cost. These new validated design tools are now available to the gas industry. AE

Dr. Marc Perrin *is project manager and TOPDEC project coordinator, Gaz de France, R&D Division (France).* **Dr. Philippe Miquel** *is research engineer, Gaz de France, R&D Division.* **Dr. Martin Hilka** *is research engineer, Gaz de France, R&D Division.* **Anne Garnaud** *is research engineer, Gaz de France, R&D Division.* **Feliciano (Felix) Lasagni** *is director of R&D and product marketing, Worgas Bruciatori S.r.l., (Italy).* **Howard Levinsky** *is program manager of combustion research, N.V. Nederlaundse Gasunie (The Netherlands).* **Maurizio Beghi** *is project manager, R&D Department, Worgas Bruciatori S.r.l..* **Dr. Steve Hasko** *is TOPDEC project manager, Gas Utilization Division, BG Technology, (UK).* **Dr. Mike Fairweather** *is resource manager, Gas Utilization Division, BG Technology.* **J.C. Rolon** *is professor, CNRS-Ecole Centrale Paris-Laboratoire EM2C (France).* **J.P. Martin** *is director of research, CNRS-Ecole Centrale Paris-Laboratoire EM2C.* **A. Soufiani** *is researcher, CNRS-Ecole Centrale Paris-Laboratoire EM2C.* **Dr. Hans-Robert Volpp** *and* **Dr. Thomas Dreier** *are Dres. of Natural Science, Physikalisch Chemisches Institut (PCI)-Ruprecht-Karls Universitaet Heidelberg, (Germany).* **Dr. R.P. Lindstedt** *is reader in thermofluids, Mechanical Engineering Department, Imperial College of Science Technology and Medicine, (UK).*