Combustion - overview

It is now widely accepted that emissions of greenhouse gases (GHG) lead to global warming, which could severely influence the global climate over the next century. The vast majority of of GHG emissions, approximately 85 %, is in the form of CO_2. The emitted CO_2 originates almost entirely from the combustion of fossil fuels, which provides approximately 85 % of the world energy demand with oil being the dominant source. CO_2 is with water the main product of the combustion of hydrocarbon fuels, and can therefore only be reduced by burning a smaller amount of such fuels. It is clear that alternative energy resources need to be utilized for a substantial reduction of GHG. However, the Department of Energy's International Energy Outlook of 2006 projects that the energy demand in 2030 will be more than 70 % higher than that of 2003, and that oil, coal, and natural gas remain as the dominant resources at 85 %. Approximately 50 % of the total energy demand will be in the industrial sector, and 25 % will be from transportation. This demonstrates the need and urgency for a substantial improvement of the efficiency of present combustion processes in these areas. Computational modeling and optimization holds the promise of leading to a substantial change in the design process of such combustion devices. However, predictive computational methods are required.

The understanding and improvement of combustion theory and its application in computational models was the emphasis of the project of the combustion group during the 2006 CTR summer program. The projects were concerned with the understanding of combustion instabilities and improvements in premixed turbulent combustion modeling, which are both crucial in the improvement of industrial burners and gas turbine engines for power generation, with the understanding of soot formation in non-premixed combustion systems, and with introducing detailed chemical kinetics in combustion models for turbulent combustion.

The stability of combustion in premixed confined combustors has been traditionally assessed using the so called Rayleigh criterion, which provides a simple condition that can easily be evaluated without the need for computationally reproducing the instability. This criterion is empirical and has often been found to have severe limitations. The project of Giaque et al. was concerned with providing a more rigorous expression for a stability criterion. Towards this end, an equation for the disturbance energy was derived. The analysis for 2D laminar flames demonstrates the importance of individual contributions to a more general stability criterion, which could be used for a simple but accurate analysis of the dynamic behavior of the combustion process in realistic geometries. Detailed simulations of turbulent combustion process requires modeling of the nonlinear interactions of turbulence and chemistry. The development of an advanced model for the turbulent burning velocity for use in detailed LES or RANS simulations of premixed turbulent combustion was the focus of the project of Oberlack et al. Previous models have used a scaling for the turbulent flame brush thickness that is proportional to the integral length scale of the turbulence. Based on the symmetries of the governing equations, Oberlack et al. propose a different scaling that leads to a new improved model for the turbulent burning velocity and the turbulent flame brush thickness. In comparisons with DNS data, the new model shows significantly improved results compared to standard models.

Two projects were related to the formation of soot. The understanding of the formation and oxidation of soot is a highly complex process that is influenced by chemical kinetics of the gas phase, heterogeneous reactions on the surface of the soot particles, the soot particle dynamics, and the intricate interaction of the soot formation processes with the turbulence. Soot strongly influences the heat transfer rates in accidental fires, and is a major pollutant emitted from many technical combustion devices. The project of Hewson et al. focused on the investigation of soot transport effects in a turbulent flow. The conditional moment closure equations for the soot number density have been derived, and an assessment of the importance of individual terms was conducted. A different aspect of the soot formation process was studied by Watanabe et al., who investigated soot formation in a laminar counterflow diffusion flame using liquid dispersed fuel injection. In this system, the interactions of the formation of soot, soot radiation, and evaporation of liquid fuel can lead to a non-linear feedback. The results from the study are compared with experimental data and will ultimately be utilized in the design of industrial burners for power plants.

The final two projects are concerned with the incorporation of detailed chemical kinetics in large-eddy simulations of turbulent combustion. The method applied in these studies is to express the scalar space of species and energy as a state relationship in terms of a small number of principal reaction progress variables. Then, chemical tables need to be created and stored providing these state relationships. The generation of these tables is done by solving simple generic systems, that resemble the considered turbulent system. In the project of Domingo et al., the optimal strategy for generating such tables was investigated for the case of highly preheated turbulent premixed flames, which is a configuration that is relevant for afterburners or flame stabilization in systems with exhaust gas recirculation. The stabilization in these systems might occur by premixed flame propagation or auto-ignition. Hence, the generation of the tables with both premixed laminar flames and homogeneous auto-ignition is investigated and the possible combination of both methods is discussed. In the project of Naudin et al., chemistry tabulation is discussed in the in the context of multi-fuel systems, which are of relevance for low calorific gases produced as by-products in industrial processes and subsequently burned in furnaces or boilers. The tables for such mixtures have a high complexity and the tabulation needs to be done in multiple dimensions. Using appropriate normalizations, Naudin et al. could show that all profiles in the table almost collapse. This reduces the multi-dimensional table lookup to the evaluation of analytic functions describing the normalized profile.

As always, the discussions and interactions in the combustion group and with other participants in the summer program were very enjoyable, inspiring, and led to very high quality, sometimes unexpected, and very interesting results.

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