be close to the natural frequency of the heat exchanger assembly. When this occurs, tube vibration at high amplitudes is induced and, unless corrected, ultimately leads to heat exchanger failure. Research in fluid elastic instability of shell-and-tube heat exchangers was supported by DOE to provide a better understanding of the flow regimes within which an actual heat exchanger must operate to avoid structural failure. Using an instrumented laboratory setup capable of accommodating industrial size heat exchangers, pressure drop and tube vibration data from waterflow tests were developed. In cooperation with Heat Transfer Research, Incorporated, actual cases of industrial heat exchanger failures were documented and made part of the extensive data base. A multidimensional flow velocity model for numerical simulation of shellside flow distribution was also developed for predicting tube bundle fluid-elastic instability thresholds and pressure drop. The model was validated using the extensive data base of experimental results and actual documented cases of heat exchanger failure. Improved understanding of fluid-elastic instability in shell-and-tube heat exchangers should lead to more reliable designs, better heat exchanger effectiveness, and subsequent reductions in process energy requirements. Heat exchangers are used extensively in industry, so this work should lead to substantial energy savings nationwide.

Improved Pulse Combustion Technology

Although pulse combustion technology has been known for many years, devices utilizing pulse combustion have not been widely implemented in spite of attractive characteristics such as high heat transfer and combustion intensity, low emissions of nitrogen oxides, high thermal efficiencies, and self-aspiration. The lack of information on fundamental fluid dynamics and combustion processes has caused the design and development of pulse combustors to proceed largely by trial and error, a method that does not guarantee an optimum design. In a DOE-funded research, a wide variety of in-situ optical diagnostics have been applied to an experimental pulse combustor to elucidate the re-ignition, unsteady valve dynamics, mixing, and combustion processes. A simple model for combining the effects of fluid mixing time and ignition delay time (a property of the fuel used) has been developed and will be incorporated into a one-dimensional, nonlinear pulse combustor model. Valving dynamics, improved heat transfer estimates, inlet and exhaust decouplers, and a method of determining combustor resonant frequency were also incorporated in this model. In a complementary effort, the feasibility of using alternative fuels in pulse combustors has been established. A modified version of a Rijke pulse combustor has been successfully tested using a variety of liquid fuels including kerosene and No. 2 to No. 6 fuel oils. Combustion efficiencies of over 99 percent were obtained when burning fuel oil No. 6. This new understanding of pulse combustion processes will provide useful knowledge and design guidelines for the development of pulse combustion systems that may capture the inherent advantages of this technology.

Ceramic Surface Modifications

Ceramic materials fail catastrophically through the growth and propagation of defects, particularly of cracks initiated at free surfaces. Surface modification techniques can reduce the size and number of defects and provide in the ceramic matrix a secondary phase that can absorb the crack propagation energy. DOE-funded research has established that ion and laser surface modifications are capable of arresting surface initiated crack propagation thereby significantly increasing the strength and reliability of ceramics. An increase of about 40 percent in the fracture toughness of silicon carbide has been achieved by laser treatment of nickel deposited on the ceramic surface. In partially stabilized zirconia (PSZ), implanting with aluminum ion (Al^+) and annealing results in a 70 percent increase in fracture toughness and a 30 percent increase in microhardness. The development of tougher ceramic materials using these surface modification