Pulsed compression reactor

Many industrial chemical reactions require high temperatures, often in combination with high pressures. Heating and compressing of the feed and subsequent recovering of heat of the products entail high capital and operating costs and large sizes of the plants. These costs increase considerably with the process temperature and pressure.

A fundamentally new chemical reactor concept based on the principle of compressive heating and cooling promises substantial improving many chemical processes at high temperatures and pressures in terms of energy efficiency, capital costs and portability. The new reactor permits exploration of temperature-pressure range that is not covered with the available manufacturing technologies.

Reactor concept

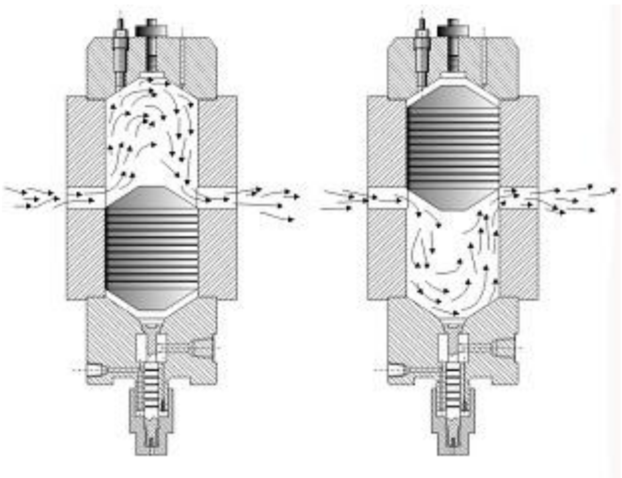

Figure 1. Pulsed compression reactor. Two limiting positions of the reciprocating piston are shown

The basic operating principle of the reactor is shown in Figure 1. The reactor consists of a double-ended cylinder with inlet and outlet ports in its wall for feeding reactants and removing reaction products. A free piston, dividing the cylinder into two compression-reaction chambers, reciprocates with a very high frequency (up to 400 Hz) compressing in turn the feed gas in the lower and upper chambers. Rapid, almost reversible compression of the gaseous feed in each chamber results in its heating to sufficiently high temperatures to drive chemical reactions. The reciprocation is maintained by heat generated in exothermic reactions. For endothermic reactions the reactor design is different, although the operating principle remains the same. An essential feature of the reactor is that gas lubrication (gas bearing) is used to prevent any contact of the piston and cylinder.

Development of the reactor(s)

Eight reactors of different design and dimensions and many pistons of various materials, dimensions and shapes were studied without chemical reactions in order to develop effective methods to start up the reactors and to determine conditions that provide smooth, wearless reciprocation of the pistons. The apparatuses demonstrated remarkable performance e.g.: compression ratio - 45, piston frequency - 200 Hz; piston speed - 30 m/s; piston acceleration - 104g; maximum pressure - 200 bar; maximum temperature - 1360 K.

Based on the results obtained two different reactors for carrying out chemical reactions were designed to demonstrate the technical feasibility of the new reactor concept. Figure 2 shows a photograph of one of the reactors with inner diameter of 60 mm.

The experiments were performed with different hydrocarbon (gaseous and liquid) - air mixtures. Figure 3 shows an example of the pressure change in a reactor during synthesis gas production by partial oxidation of propane. It explains some of the remarkable capabilities of the reactor. The maximum pressure in this particular experiment was about 400 bar at temperature of about 3000 K. Any other reactor would instantly melt or break down at such conditions whereas both the reaction temperature and pressure can significantly be increased in the pulsed compression reactor. This is possible because the average pressure and temperature in the chamber are much smaller than the maximum values. The feasibility of the novel reactor was demonstrated for synthesis gas production and combustion of volatile organic compounds. The experiments showed also that the reactor permits reacting of very reach and very lean hydrocarbon - oxygen mixtures. In particular, stable operation of the reactors was observed during combustion of propane with air at concentration of propane less than 0.5 vol %.

Figure 2. Double-chamber reactor placed inside massive frame

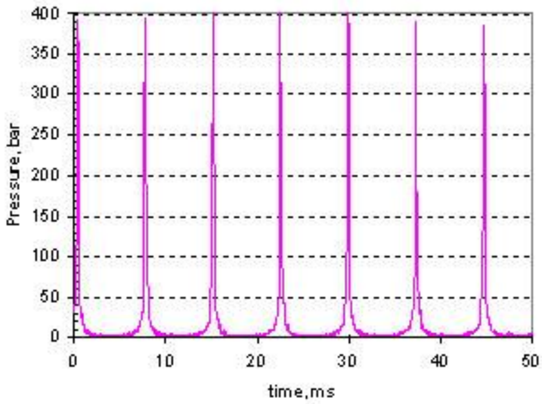

Figure 3. Pressure change in a reactor during continuous production of synthesis gas by partial oxidation of propane with air: fuel/air equivalence ratio f =3.6

Advantages of the novel reactor concept

Energy efficiency. The energy spent for compressive heating of a feed in the reactor chamber is recovered reversibly during compression of the next feed portion in the adjacent chamber. Thus the reactor eliminates the large energy expenses on heating and compression of feed and accordingly prevents energy losses during heat recovery from the products. In case of exothermic reactions the reaction heat can be utilized in the reactor for heating and/or compression of the reaction products.

Process intensification. Extreme pressures and temperatures from several hundreds to several thousands of bars and up to several thousands of K are ideal for almost instantaneous completion of many chemical reactions. The measured reaction times in the performed experiments were less than 10-4 s. The considerable increase in the reaction rates occurs not only due to the high temperature but also owing to the significant increase of the concentrations of the reagents during compression.

Space velocity. Very high reaction rates and high frequencies of the piston oscillation (100 – 400 Hz) allow space velocities (ratio of volume throughput at normal conditions to reactor volume, GHSV ~ 107) three-four orders of magnitude as high as that in the conventional chemical reactors.

Selectivity and yield. Very large rates of temperature and pressure change (up to 107 K/s, 107 bar/s) afford an excellent way of “freezing” the high temperature products and producing a better selectivity and yield.

Distribution of product properties. Very uniform conditions in the reactor permit uniform distributions of the product properties.

Compactness. Reactor volume is expected to be 103 – 104 times smaller than that of the conventional reactors.

Scaling up and down. The laboratory reactor, shown in Figure 2, with the chamber volume of 150 cm3 is already of small industrial scale. Several reactors with inner diameter of 0.3 m could, for example, generate syngas for the largest methanol, ammonia, GTL plants. Micro pulsed compression reactors, which could be used as e.g. reformers for fuel cells for vehicles, are a subject of the planned research.

Investment. Several factors determine significant reduction in the capital cost:

- The reactor comprises the entire processing train: gas compression and heating, reaction itself, cooling of products and utilization of released reaction energy all together occur in the single unit; expansive heat exchangers, furnaces, compressors, heat recovery boilers and turbines can be eliminated or replaced by relatively inexpensive low temperature units.
- Very small dimensions.
- Very simple reactor designs, piston is the only moving part.
- No catalyst is needed.

Safety. In spite of extreme reaction temperatures and pressures the reactor is inherently safe due to the very small inventory.

Environmental issues. Since heating of feed is eliminated no combustion of fuel is needed. Therefore emissions of CO_2 and NO_x due to combustion are eliminated.

Application. Figure 4 shows approximately the pressure-temperature scopes of different process technologies. Very large pressure - temperature area is becoming accessible now for industrial exploration.

The reactor is anticipated to be superior for conducting of many industrially important gas phase, gas-liquid and gas-solid chemical reactions as has been proven experimentally with single-shot compression apparatuses. Example are:

- production of synthesis gas from various gaseous, liquid and solid hydrocarbons
- manufacturing of acetylene, ethylene, propylene, carbon black etc. by (hydro/oxy-) pyrolysis of methane and other hydrocarbons

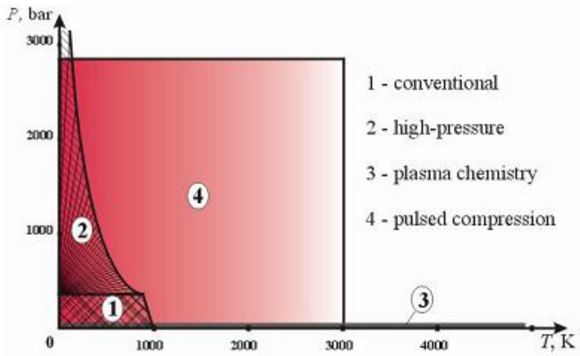

Figure 4. Pressure-temperature scopes covered by different process technologies

- controlled generation of monodisperse ceramic and metallic nanoparticles by thermal decomposition of appropriate precursors (carbonyl- and organometallic compounds, salts, etc.)
- direct oxidation of natural gas to methanol, formaldehyde, formic acid and higher alcohols
- direct synthesis of nitric oxide, nitric acid, hydrogen cyanide
- air cleaning by thermal destruction of impurities
- production of carbon-based nanoparticles – fullerenes, carbon nanotubes, etc.

The new technology can also be adapted for many technical applications outside the chemical industry and due to the unique performance is expected to create new and yet undiscovered processes.