Study Center

Q: What is the role of chemistry in aerospace engineering?

A: Conventional aeronautical vehicles are driven by jet fuel, which is a form of high-grade kerosene. Fuel is burned in the combustion chamber and releases its chemical energy as heat. All large airplanes are driven by jet engines, and all medium- and large-size helicopters are driven by turbo-shaft engines, which are a different form of jet engine. Hence, jet fuel combustion is the driving power for most aeronautical transportation. Space propulsion systems are driven by multistage engines that, in the initial stages, are powered by heat released from combustion of solid propellant (fuel). The solid propellant is composed of a hydrocarbon compound and an oxidant. The fuel, a polymer, acts as a binder where the oxidant (in the form of particles) is embedded. The propellant can be a hard solid (for example polyester, epoxy, or polystyrene), and it forms the solid propellant when combined with the oxidant. There is also the option of a more elastic, soft, rubberlike material, based on polyethylene, polyurethane, or polybutadiene, which is cast within the rocket engine cavity. Solid oxidants are mainly based on perchloric acid ($HCLO_4$) and nitric acid (HNO_3). In order to increase the energy density of the fuel, small metal particles, mainly aluminum, can be added to the fuel. Large rockets such as those driving the space shuttles are also powered by heat released through the combustion of liquid hydrogen and liquid oxygen. Hence, all forms of aerospace propulsion are powered by heat generated mainly from the chemical reaction between hydrocarbon fuel and oxygen.

The widespread use of air transportation requires very large quantities of jet fuel. As all combustion products remain in the atmosphere, aerospace propulsion affects the globe by altering its gaseous composition. Knowledge of the detailed combustion process inside the engine is very important in order to design efficient engines and to minimize the amount of pollutants discharged into the atmosphere. Hence, while analyzing the chemical processes associated with aerospace propulsion, one should consider both the chemical reaction within the combustion chamber of the jet engine (or rocket/missile) and the chemical interaction between the combustion products and the atmosphere.

Considering that airplane propulsion is the dominant type of aerospace propulsion, we shall focus our attention on its chemical process. Jet fuel is classified as a fossil fuel and contains a mixture of hydrocarbon molecules (C_xH_y). In fact, it is a homogenized mixture of hundreds of different molecules of predetermined chemical and physical characteristics. The critical parameters of jet fuel are the calorific value which determines the amount of heat released during combustion, density, viscosity, naphthalene content, flash point, boiling and freezing points, smoke point, sulfur content, thermal stability, as well as corrosivity, lubricity, electrical conductivity, and more. Most of the hydrocarbons in jet fuel are members of the paraffin, naphthene, or aromatic classes, which are types of hydrocarbon molecules with different structures and properties. The properties of jet fuels from different sources may vary slightly, because they contain slightly different proportions of compounds from these three classes. The total aromatic content of Jet A and Jet A-1 is limited to 25%, and total naphthalene content is limited to 3%.

In order for the chemical reaction to occur in the combustion chamber of the jet engine, several conditions have to be met. First, there should be a mixture of hydrocarbon molecules and air (oxygen) in the right proportions. Thus, fuel has to be atomized to small droplets that will rapidly vaporize and mix with the surrounding air. Two additional conditions should also be met: a hot environment and sufficient time for the reactance (fuel and oxygen) to remain within the hot environment. The latter conditions are met through the incorporation of a stabilization flow region within the combustor (region with very low flow velocities), typically formed by internal swirling of the flow. Given these three conditions, the hydrocarbon molecules and oxygen molecules will react and convert, through a series of intermediate reactions to carbon dioxide (CO2) and water vapor (H_2O). The nitrogen in the air can, at first approximation, be considered as a passive component. When the amount of oxygen is exactly that needed to burn all the fuel, the mixture is considered as stoichiometric and a stable flame can be maintained. In such a case the heat released will raise the temperature of the combustion products to the highest possible value. In the jet engine combustor configuration, where air is compressed before it is introduced to the combustor and

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its temperature is increased by the compression, the temperature can be as high as 2300°C. Such high gas temperature is beyond the permissible operational condition of the turbine (following the combustor), and therefore combustion gases are cooled downstream by mixing with additional air from the compressor. Hence, the temperature at the inlet of the combustor is about 300-600°C (depending on the engine s compressor), it rises quickly to above 2000°C, and it is cooled to about 1100-1300°C.

The combustion regimes and the associated temperature profile within the combustor have a direct effect on the pollutant emitted from the engine into the atmosphere. Jet engine manufacturers are trying hard to minimize pollutants, however, all engines emit pollutants harmful to the environment, mainly NOx and unburned hydrocarbon (UHC). At ground level, the engine produces nitrogen oxides (NO and NO_2, commonly termed NOx). The absolute amounts formed are small and measured in parts per millions (ppm) - the portion of NOx within the exhaust gases. However, even at such quantities, these oxides are harmful, and attempts are made to limit NOx to below a few tens of ppm. The NOx results mainly from reaction between the air nitrogen and the oxygen. Its generation depends mainly on the temperature, and it starts forming at above about 1500°C. At ground level, the NOx combines with volatile organic compounds (VOCs), especially on warm and sunny days, to create ozone smog. Ozone smog is a highly reactive form of oxygen. It is corrosive and harmful to humans and plants. At high flight levels, NOx has the potential to attack the atmospheric ozone (O_3) layer and, hence, contributes to the depletion of the ozone layer which protects the Earth from harmful solar UV radiation. This chemical reaction process is expressed, in a simplified way, as a two-step process,

$NO + O_3 \dashrightarrow NO_2 + O_2$
$NO_2 + O \dashrightarrow NO + O_2$.

where ozone can be destroyed by nitric oxide and forms nitric dioxide and oxygen. The resulting nitrogen dioxide breaks down into nitric oxide and thereby continues destroying the ozone layer.

The extent of this reaction and the amount of ozone actually destroyed by this process is not yet exactly known. However, this mechanism is a main obstacle to the development of supersonic transport airplanes which will fly much higher and closer to the stratosphere, thus presenting a higher risk for the depletion of the ozone layer. In addition, due to the extreme cold temperatures at typical flying levels (10,000 meters), about -60°C, the water vapor within the exhaust gases turns into fine icy particles. These particles form white clouds, seen from the ground as white stripes in the sky which, to some extent, also affect the solar radiation to the Earth.

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