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12.1.2 Example: Forced Oscillation Combustion

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MO2.7

Combustion processes such as in a variety of engines, power generators, furnaces, etc. often operate in a continuous mode in which the fuel and oxidizer are added to the combustion zone at a constant rate. However, multiple investigations have been conducted into oscillating the amount of fuel and/or oxidizer with results showing it is possible to both reduce harmful emissions as well as improve overall efficiency. We will look at a very simple model of such a forced oscillation combustion process to illustrate the concept of stiffness. It is important to note that the simplicity of this model will not allow investigation of the potential benefits of forced oscillation combustion. However, it will allow us to illustrate stiffness in a simple setting.

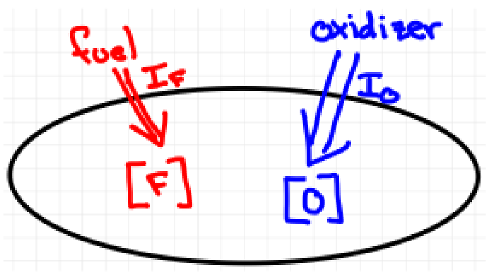


Figure 12.1: Combustion zone to which fuel and oxidzier are injected at rates I_F and I_O, respectively.

Consider the combustion zone shown in Figure 12.1. We will model the rate at which the fuel is combusted by assuming that there is always sufficient oxidizer to combust any fuel that is present. The molecular concentration of fuel in the combustor will then evolve due to the combustion with the oxidizer and the injection of fuel. We use the following simple differential equation to model this behavior,

$$\frac{\mathrm{d}\,[F]}{\mathrm{d}t} = -\frac{1}{\tau}[F] + I_F \tag{12.1}$$

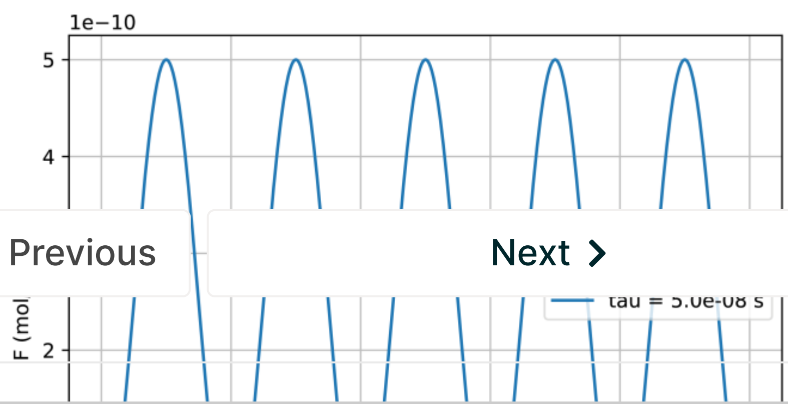
where τ is the timescale at which the combustion occurs and $I_F\,(t)$ is the rate at which the fuel concentration increases due to injection into the combustor. A typical value of $\tau = 5\text{E-}8\,\mathrm{s}$.

We will express $[F]$ in $\mathrm{mol/cm^3}$. And hence, I_F will have units of $\mathrm{mol/cm^3}/\mathrm{s}$. For the fuel injection, we will utilize a simple periodic behavior given by,

$$I_F = \frac{1}{2} A_F \left(1 - \cos\left(2\pi \frac{t}{T_F}\right)\right) \tag{12.2}$$

where A_F is the peak amplitude of the injection rate and T_F is the period of the injection rate. For the results shown, we consider $T_F = 0.1\,\mathrm{s}$ (i.e. 10 Hz oscillation frequency) and $A_F = 0.01\,\mathrm{mol/cm^3/s}$. Thus, for these typical values, $T_F/\tau = 2\mathrm{E}6$. This large ratio of timescales is the essential ingredient in what is called a stiff system, and as we will see must be accounted for in the choice of numerical algorithm used to approximate the solution of the IVP.

Figure 12.2 shows the evolution of the fuel concentration for the typical combustion timescale of $\tau = 5\mathrm{E}\text{-}8\,\mathrm{s}$. Because $\tau \ll T_F$, then any fuel injected is rapidly combusted and hence the amount of fuel present at any time is small. Further, the oscillation is essentially immediately periodic without any initial non-periodic transient.



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