Convective Vaporization and Burning of Fuel Droplet Arrays

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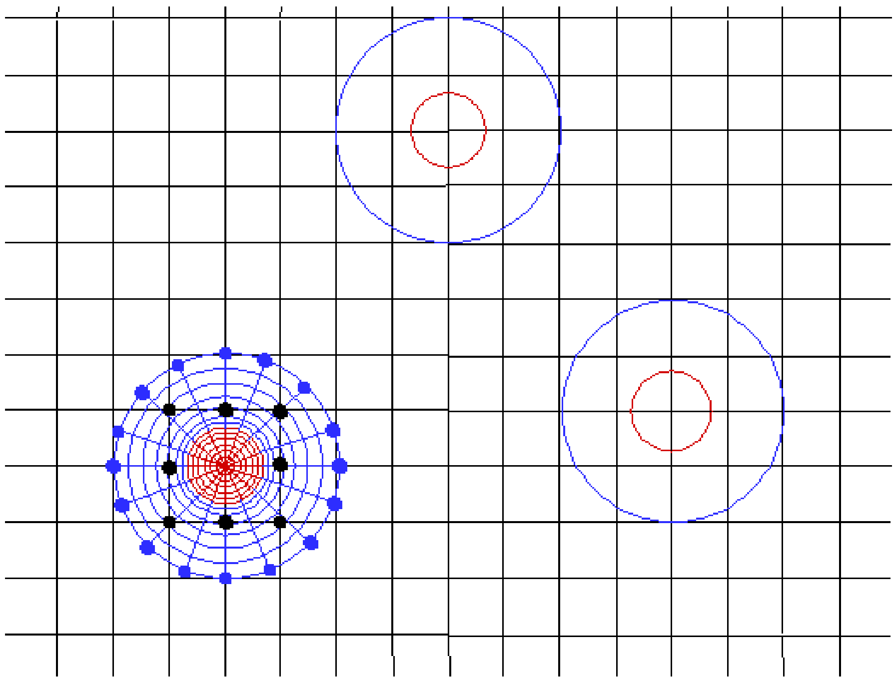
Background and Task

- In many practical combustors, liquid fuel is first atomized into a large number of droplets, and then vaporized and burned in a convective gas stream.
- Correlations between vaporization rates of interactive droplets and isolated droplets have been built for stagnant cases.
- Convecting and vaporizing droplets in axi-symmetric cases have been studied and simulated.
- The complexities for modeling spay combustion include droplet interactions, gas stream convection, non-axi-symmetry, liquid internal circulation, and relative motion amongst droplets.
- The task of this study is to numerically simulate convecting, vaporizing and interactive droplets for 3D non-axi-symmetric array configurations, and study the transient vaporization or burning rates and important dimensionless numbers (C_d, Nu, Sh, etc.) under various conditions.

The Gridding Scheme for Multi-droplet Calculation



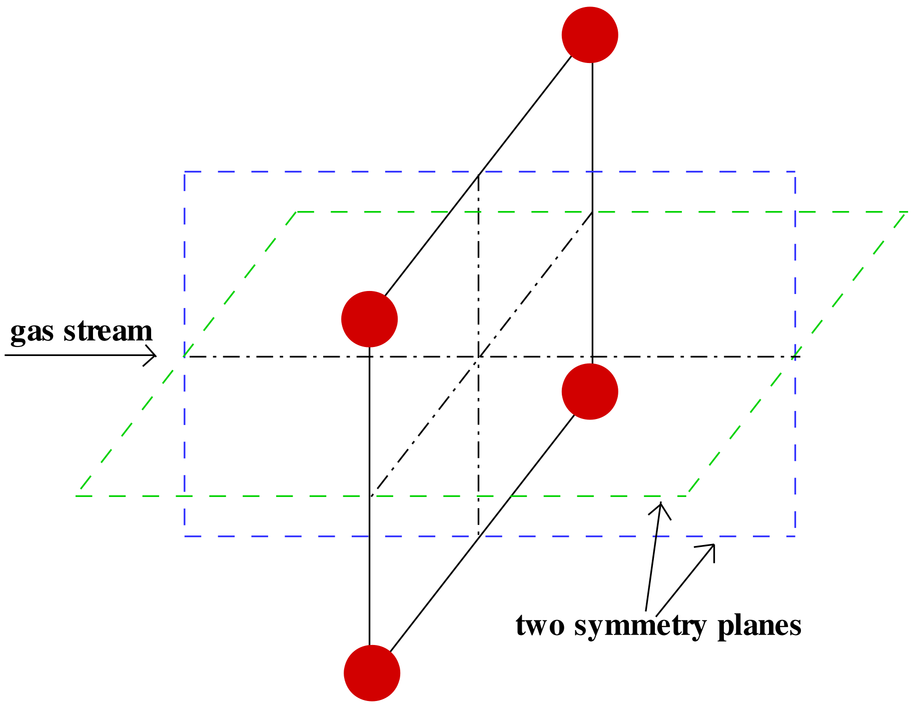
The computational domain is divided into N (number of droplets) liquid-phase spherical domains, N gas-phase spherical domains around the droplets, and one Cartesian domain outside of the gas-phase spherical domains.

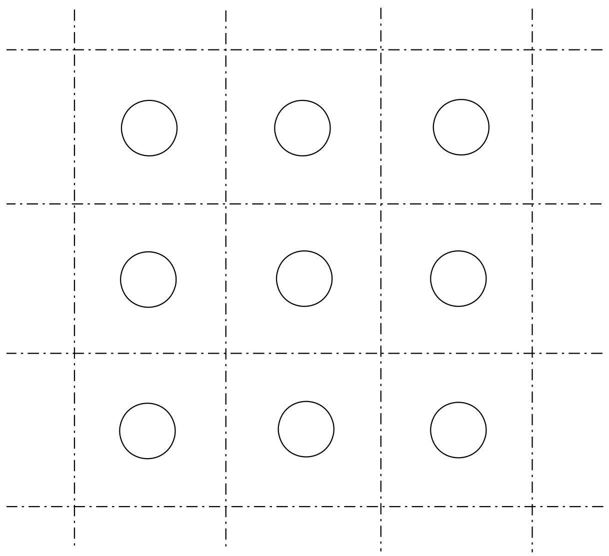
- The radial position for each droplet is normalized by R(t), to consider the droplet regression.
- The mesh is fixed for the gas phase, once the decrease of droplet radius reaches the mesh size Δr at the interface, include more nodes in the gas-phase computational domain.

Numerical Scheme

- A complete set of Navier-Stokes, energy and species equations with BCs and ICs needs to be solved over the spherical domains and the Cartesian domain.
- A global single-step chemical reaction mechanism is used to model oxidation kinetics.
- Use Semi-Implicit Method for Pressure linked Equations (SIMPLE), and staggered mesh with four different control volumes U, V, W and h (P,Y_i and properties).
- Use Forward Time scheme and boundary conditions with 2nd order precision, and apply ADI to sweep in all the three directions for each time step.
- Interpolation are needed at the interfaces of spherical domains and Cartesian domain in the gas phase.
- Stream velocity and mesh in r direction are modified with time, it may take several time steps for the mesh to require update.

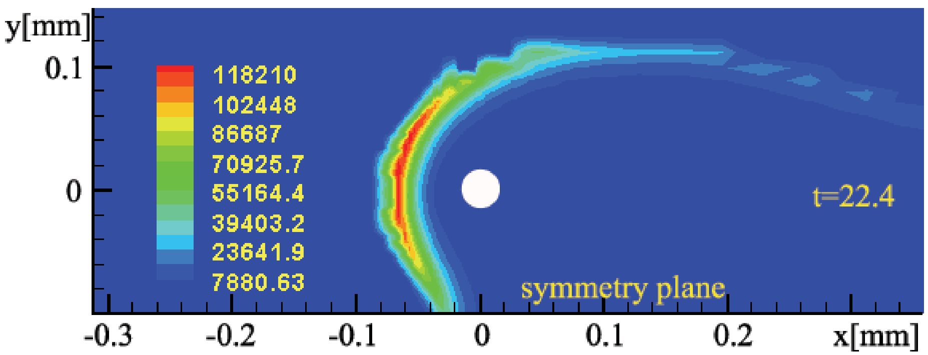
Configurations and Conditions for the Sample Calculations



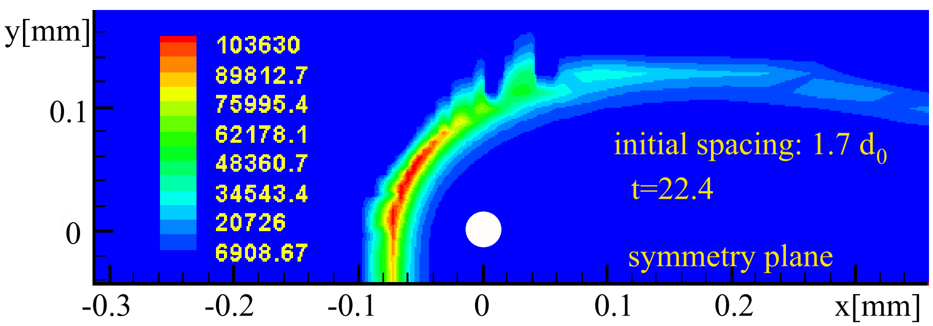


- The array configurations in the calculations include two droplets placed side-by-side, four droplets placed in square array, and infinite periodic configuration.
- Droplets are composed of pure octane; the free stream is air flow with pressure 20atm and high temperature (1500K).

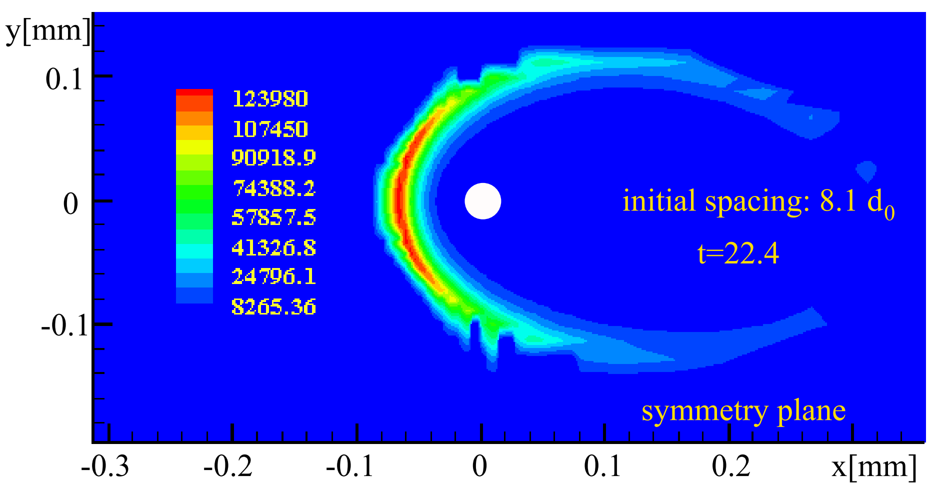
Shape of the flames (two droplets)



The flame (group) for the case with initial diameter 50 microns, spacing 4.2d_0 , and Re=3.4

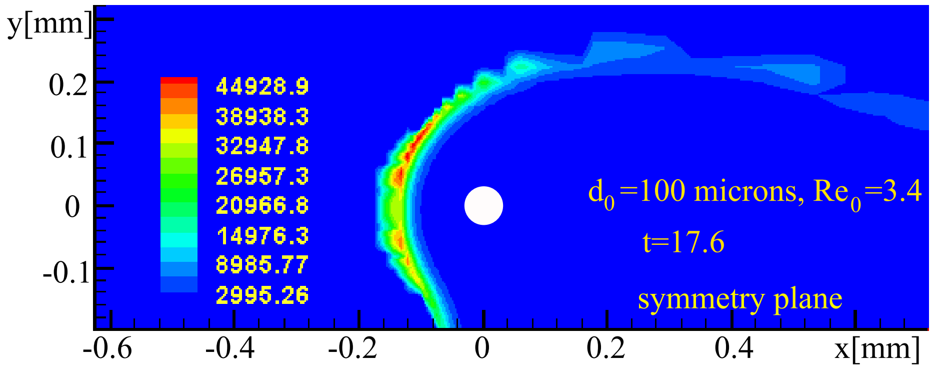


The flame (group) for the case with initial diameter 50 microns, spacing 1.7d_0 , and Re=3.4

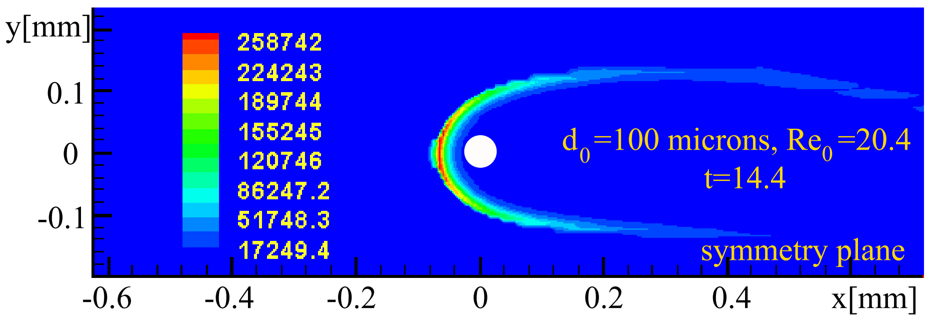


The flame (separated) for the case with initial diameter 50 microns, spacing 8.1d_0 , and Re=3.4

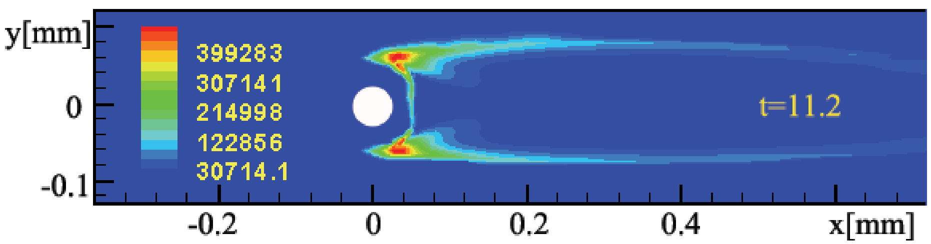
Shape of the flames (two droplets) - continued



The flame (group) for the case with initial diameter 100 microns, spacing 4.2 d_0, and Re=3.4

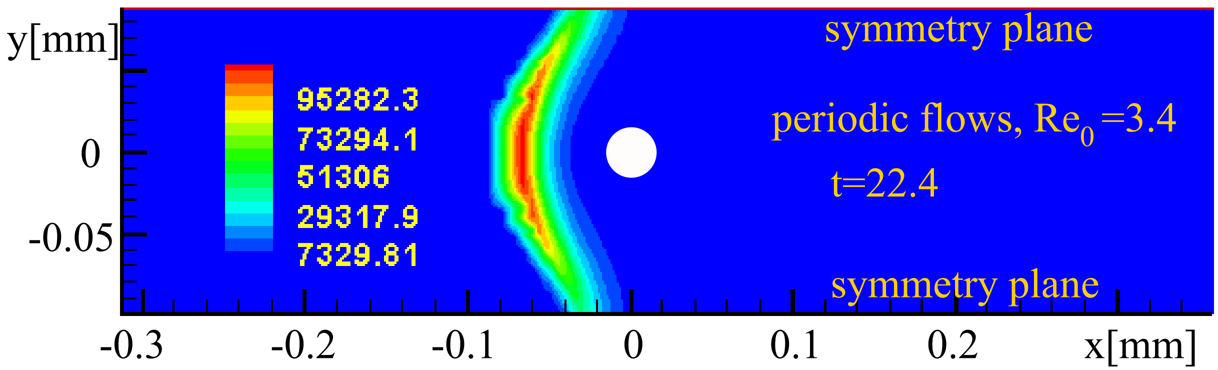


The flames (separated) for the case with initial diameter 100 microns, spacing 4.2 d_0, and Re=20.4

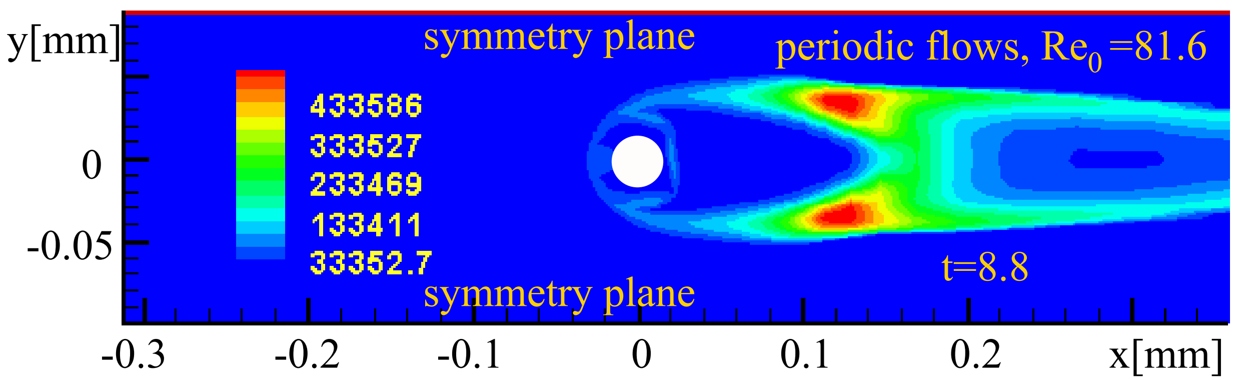


The flames (separated and wake) for the case with initial diameter 100 microns, spacing 4.2 d_0, and Re=81.6

Shape of the flames (infinite periodic configuration)

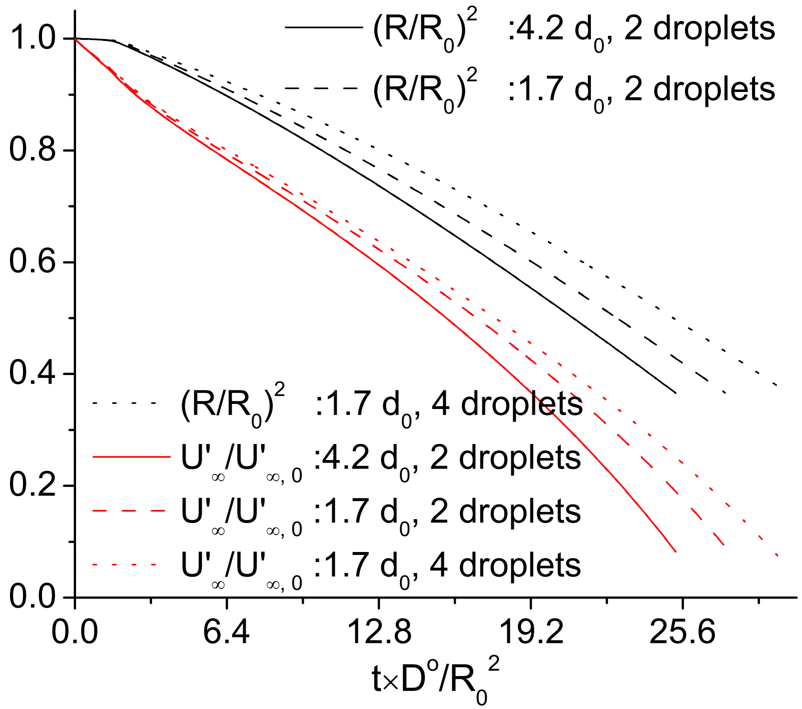


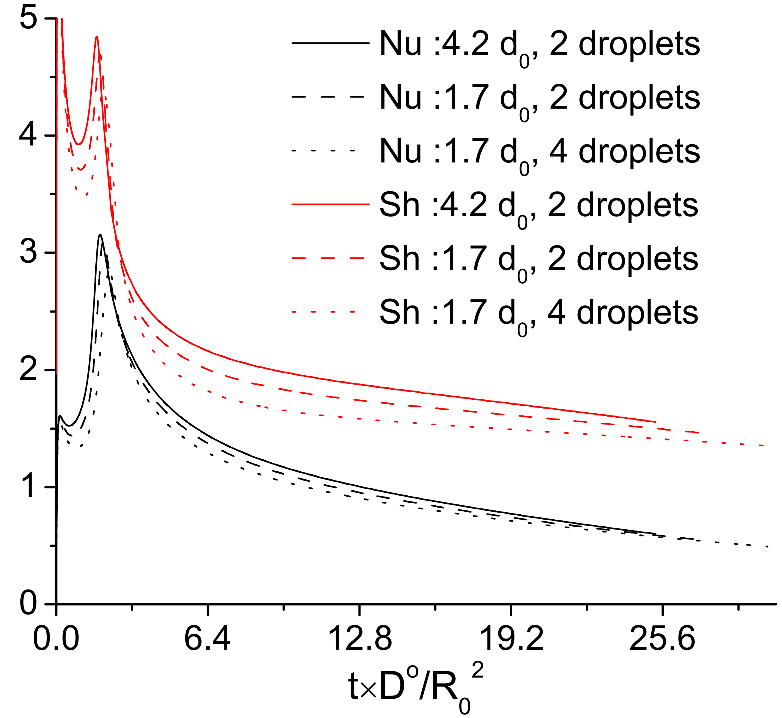
The flame (group) for the case with initial diameter 50 microns, spacing 4.2 d_0, and Re=3.4



The flames (separated and wake) for the case with initial diameter 50 microns, spacing 4.2 d_0, and Re=81.6

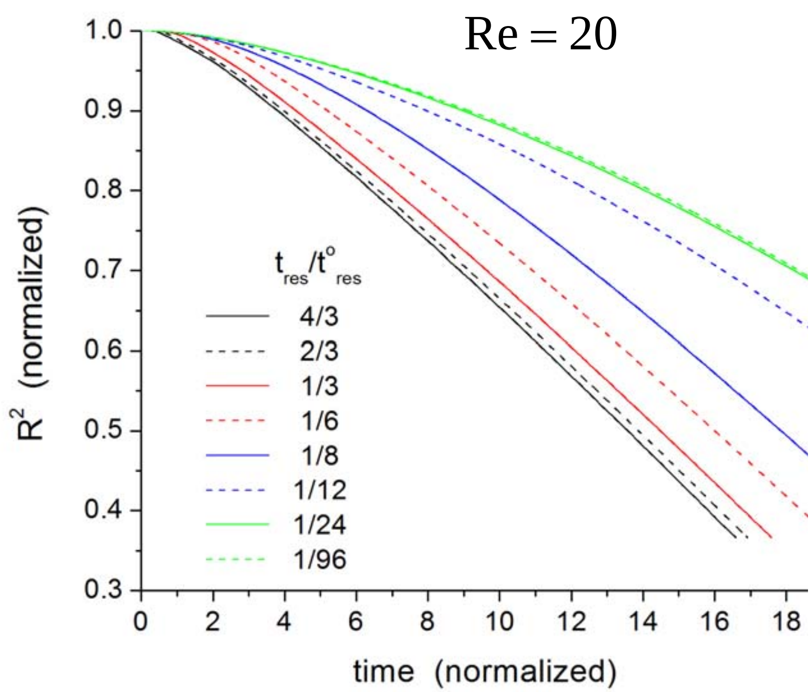
Different droplet configurations and spacing

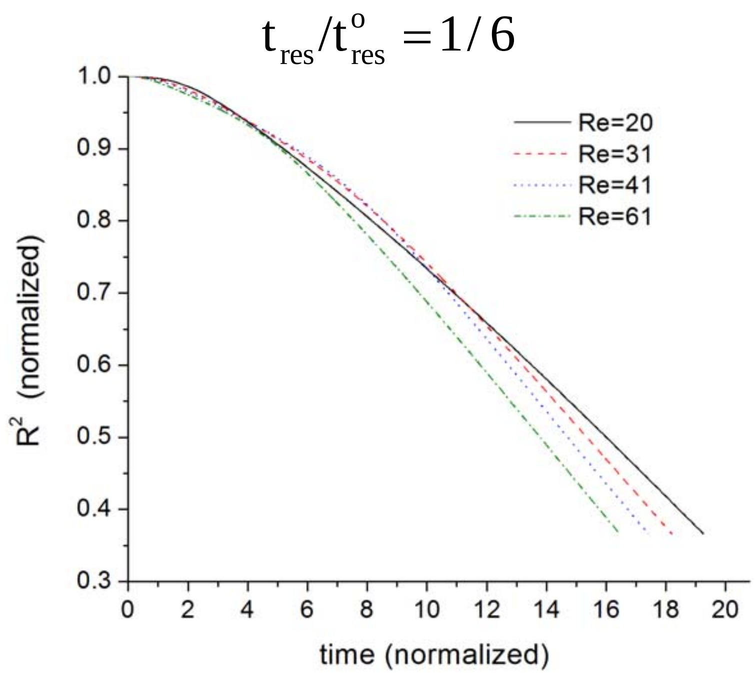




Comparisons of Radius squared, relative gas-droplet velocity, Nusselt number and Sherwood number for three cases with different array configurations and droplet spacing. The peaks in Nu and Sh are due to initial adjustment and ignition. (d_0=50microns, $\mathrm{Re} = 3.4$)

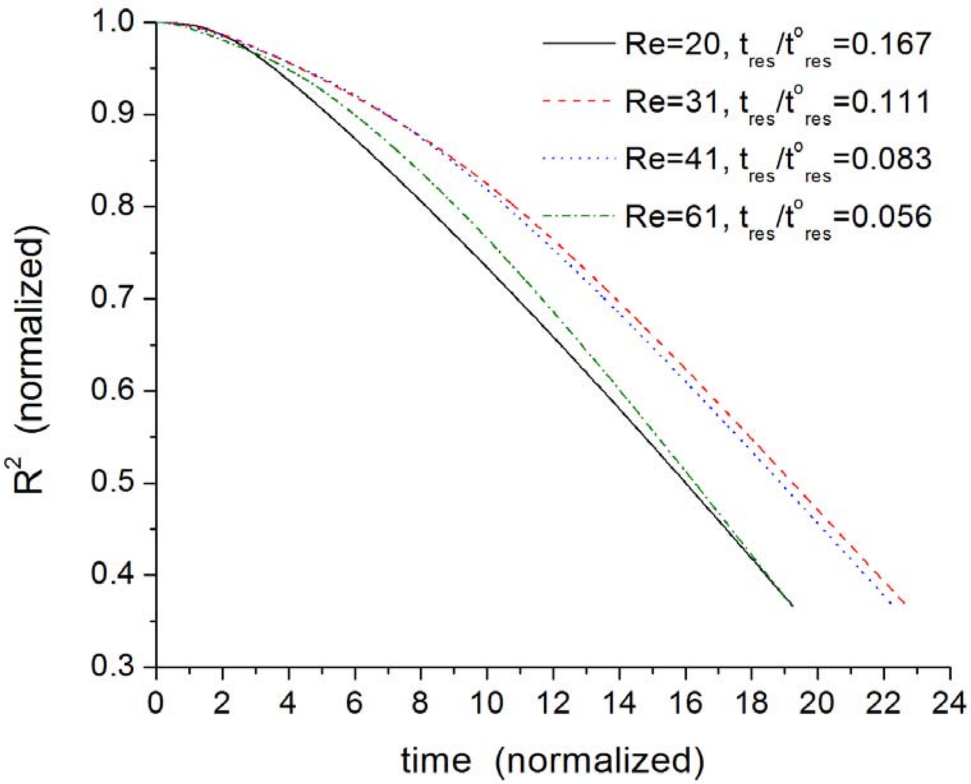
Different initial residence time or Reynolds number (infinite periodic configuration)





Comparisons of Radius squared amongst different initial residence time with the initial Reynolds number held as 20, and amongst different initial Reynolds number with the initial residence time held as 1/6. Increase in the residence time results in more complete burning, greater heating, and faster vaporization of the droplet. Increase in Reynolds number results in greater convective heating but extends the flame further downstream.

Different initial relative velocity



Comparisons of Radius squared for different initial relative velocity under the same initial diameter. As the initial relative velocity is increased, the initial residence time is decreased and the initial Reynolds number is increased, so this plot can be explained from the previous two plots.

Summary

- The flames are combined or separate depending on the droplet spacing, the Reynolds number, and the droplet surface temperature. Large Reynolds number or small residence time makes the flames tend to transit from envelope flames to wake flames.
- The vaporization rates are greater for larger droplet spacing, the configuration with less droplets, or higher initial Reynolds number, due to smaller droplet interactions or stronger forced convection.
- Greater initial residence time leads to higher burning rate, especially around the value at which the envelope-wake flame transition occurs.
- As the initial relative velocity is increased, the burning rate may be decreased around the envelope-wake flame transition due to decrease in the initial residence time.