

# Turbulent combustion of sprays

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## EXTENDED ABSTRACT

Combustion characteristics of liquid sprays are profoundly influenced by two aerothermochemical roles played by two-phase turbulent processes. First of all, the interphase exchange of mass, momentum and energy are essential sub-processes in the developments of combustion and the construction of the flow structures in liquid sprays. The effects of turbulence on the droplet gasification have been evaluated by experimental data by accounting mean convection. There is a persistent belief that no turbulence effects are expected to change the vaporization rate if the scales of energetic eddies are greater than the droplet size. However, little numerical simulations of the gasification are available to confirm the view described above. Recent study by Goklap et al [1] reveals strong effects of turbulence on the average vaporization rate of single droplet, in the energetic turbulent length scales those are larger than the droplet initial diameter. At increased pressure, wherein the turbulence of small scales are excited because of high Reynolds number at reduced kinematic viscosity, the droplets gasification will be affected by smaller scale eddies. How the gasification rate depends on the turbulent eddy interaction remains as one of the most important issues in current droplet and spray combustion theory. Thus, the laws of droplet in turbulent environment with the full range of eddy scales, from Komogorov scale to larger length scales need to be established. Secondly, the turbulent modulation of the carrier gas in response to the fluctuations of dispersed phase significantly alters the structures of the turbulence. To be specific, turbulence modulation refers to the *direct effects* of turbulent interaction, which result in the following phenomena in the carrier gas:

- (i) Modulation of turbulent energy spectrum due to increased local shear rates in the region of wave legthes comparable to the interdrop distance and droplet size [2][3].
- (ii) Modulations of turbulent kinetic energy,  $\kappa$ , energy dissipation rate,  $\epsilon$ , turbulence integral length scales,  $l$ , and the turbulent viscosity,  $\mu_T$ . [4]. Such modulation affects the flow structures and combustion characteristics.
- (iii) Modulation of interfacial exchange rates of scalar and vector properties in the broad ranges of Reynolds number.
- (iv) Modulation causes the reduction in the turbulent intensities and increased trends of anisotropic flow in the vicinity of dense dispersed flow [5].

For the reasons described above, the comprehensive assessments of the effects of the interfacial exchange and turbulent modulation have significant bearing on the understanding of the dilute dispersed flow [6].

Despite of impressive research efforts which have successfully resolved number of outstanding issues and served to enhance the qualitative understanding of spray combustion, the critical mechanisms of droplet gasification in turbulent environment and turbulent modulation

in practical sprays have not been well understood to aid in the determination of the spray flow field structure and combustion characteristics. In particular, the mechanisms contributing modulations, nature of the interlinkages between sub-mechanisms, the strength of the modulation mechanisms and the parameters affecting the extent of modulation have not been identified to facilitate genuine understanding of these complex phenomena. Recent developments in turbulent combustion of gaseous fuel have succeeded, in a great measure, in predicting the flame structure of the turbulent pre-mixed and non-premixed combustion of gaseous fuel, see for example [7] [8] [9]. However, review of the literature reveals that the two-phase turbulent combustion has not yet reached to the status of accomplishments of single-phase combustion. The basic difficulties encountered in the turbulent combustion of two-phase reacting flows are twofold: first factor is the complexities associated with two-phase interaction and second is the lack of the comprehensive solutions that could provide basic information of all the sub-mechanisms of droplet gasification and complex two-phase interaction that contributing modulations and their prospective governing parameters.

The objective of this article is to present an axiomatic theory of the interfacial exchange of a droplet in turbulent environment and the two-phase flow structure under the effects of modulation of the carrier gas. Specifically, the analysis covers the predictions of the laws of droplet gasification, the flow structure and combustion characteristics under the influence of the modulations of turbulent kinetic energy and the rate of energy dissipation. The theory serves to identify all the sub-mechanisms and the rigorous analytical assessments of the extent of modulation by each sub-mechanism. The analysis adapts the recently developed canonical theory [10][11] to provide explicit analytical expressions of the flow variables, velocity, temperature, and turbulent properties of interest, in terms of participating aerothermochemical processes: convection, transport processes, phase change and chemical reaction occur in turbulent spray flow environment. The canonical theory, developed for general flow systems governed by a set of non-linear conservation equations, analytically determine the eigenfunctionals of the equations under given Dirichlet type boundary conditions and prescribed initial conditions. The eigenfunctionals expressed by potential functions of three different geometrical configurations in three-dimensional flow give both the flow field solutions and the interface exchange rates by appropriate selection of the terminal points of the potentials. The theory can be applied to the non-linear, multi-dimensional and time dependent parabolic and elliptic partial differential equations.

Analytical study of gasification of droplet moving in a turbulent environment accounts the variation in the relative importance of molecular and turbulent transport processes from the droplet surface outwardly. The difficulty associated with the analytical determination of gasification is fully appreciated by observing that the turbulent viscosity,  $\mu_T$ , is related with the turbulent length scale, kinetic energy and rate of energy dissipation, as described in turbulence models. For example,  $\mu_T = C_1 \rho \kappa^{1/2} l$ , or  $\mu_T = C_\mu \rho \kappa^2 / \epsilon$ , where  $C_1$  and  $C_\mu$  are constants,  $l$  the turbulent length,  $\kappa$  the turbulent kinetic energy, and  $\epsilon$  the rate of energy dissipation. Hence, the effects of variation of the turbulent viscosity on the gasification rate depend on the variation of these turbulence properties, i.e.,  $\kappa$ ,  $\epsilon$  and  $l$ . These latter properties must be calculated from appropriate turbulent kinetic energy, rate of dissipation and turbulent length scale equations.

Turbulent flow structures of sprays and their dependence on the turbulent modulations are analyzed to identify the key factors affecting the axial and radial developments of the vector and scalar properties. The flow structure depends on the mean flow related interaction and

turbulent fluctuation induced modulation of turbulent kinetic energy and dissipation rate. Henceforth the turbulent viscosity variation serves to modulate the development of the overall flow and combustion. The analysis aims to establish the explicit functions: axial and radial, mean flow as well as turbulent fluctuations induced modulation. The analysis emphasizes the generality of the application for various turbulence models, i.e.,  $k-\epsilon$ ,  $k-\epsilon-g$ , or a type of averaging method used, for example, Reynolds average, and Favre average. The validity of the present methods has been assessed by comparing the results with the existing analytical, numerical and experimental results for a special case such as single droplet vaporization or group combustion of sprays [10] and existing experimental data on the flow structure of particle laden jet [5].

The article presents the following major results:

*(1) Gasification rate of a droplet in turbulent flow environment.*

The law of droplet gasification in turbulent flow environment is derived from the conservation equations of turbulent reacting flow. The effects of molecular and turbulent transport processes, turbulent kinetic energy and dissipation rates are taken into account in the formulation. Various factors including the effects of the variation of turbulent viscosity and the sizes of eddies on the gasification rate are also discussed. The results are compared with recent experimental data [1] to justify the validity of analytical result. In the limiting case of stationary droplet vaporizing in a uniform temperature environment, the present law gives the classical law of Spalding.

*(2) Turbulent flow structures and modulations in particle laden jets.*

The structure of the particle laden jets of steady axisymmetric configuration, i.e., the spatial distributions of velocity, temperature, turbulent kinetic energy, and the rate of dissipation are represented by axiomatic forms in such a manner that all the mechanisms contributing the flow structures appear explicitly in the exact axiomatic solutions. The mechanisms of turbulent modulation due to the fluctuations of relative velocity, temperature, droplet number density, turbulent kinetic energy, dissipation rate, and therefore turbulent viscosity are identified. The results are compared with the experimental data. The theoretical results shed light on the detailed interlinking mechanism among major modulation processes and provide genuine understanding of the structure of turbulent flows. The present approach distinguishes itself from the existing conventional means of numerical and experimental methods that yield numerical data upon which the deductive judgement is made on the underlining physical mechanisms. This conventional approach has been successful, yet it is often limited by many factors: accuracy and the limitation of the data and more importantly, the validity of the deductive judgement exercised on complex, intercoupled process. Present method provides solutions in explicit analytical forms such that the physical mechanisms contributing the flow field are transparent. The method serves to complement CFD by providing analytical protocols of elucidating the detailed physics of the results of CFD.

The article concludes with the discussions of the future research that aims to the understanding of basic problems including flamelets, collective interaction, group phenomena, eddy-droplet interaction in dense spray structures.

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