THERMODYNAMICS OF DROPLET AND SPRAY COMBUSTION

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S.K. Som

Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur, India

Extended Abstract

The literature in droplet and spray combustion is abundant. The attention has been paid mostly on the various aspects of the transport processes and predictive models for transport coefficients and rate of vaporization of droplets and sprays. From the viewpoint of energy economy, efficient droplet or spray combustion process should be guided not only by the combustion efficiency, but also by its exergetic efficiency that focuses the sources of irreversibilities in a spray combustion process. However, a relatively less information is available on this important thermodynamic aspect, namely, the identifications of thermodynamic irreversibilities and the subsequent exergy analysis in the process of droplet and spray combustion. The present paper highlights this thermodynamic aspect of droplet and spray combustion through a brief review of relevant work in the field with particular references to the pioneering contributions of the present author.

Droplet Models

The work of Dash et al [1] is probably the pioneering work in ascertaining the sources of irreversibilities in course of evaporation of a single component liquid fuel droplet in a high temperature convective gaseous medium. The thermodynamic irreversibilities, being characterised by the rate of entropy production in the transport processes, were determined in their work from the numerical solution of the entropy conservation equation along with the conservation equations of heat, mass and momentum transports in both the phases. A numerical correlation of entropy generation rate with pertinent dimensionless input parameters can be written after Dash et al [1] as

$$\frac{E}{a^2} = 714.5\frac{(M_\infty/M_V)^{1.02}B^{1.29}}{\left(Re.Pr^{0.66}\right)^{-0.72}} \tag{1}$$

where $E\ (= E'/\rho_\infty\ R\ u\ a_i'^2)$ is the dimensionless entropy generation rate, ρ is the density, R is the gas constant, u is the flow velocity, a' is the initial droplet radius, $a\left(= a'/a_i'\right)$ is the dimensionless droplet radius, Re is the Reynolds number of flow past the droplet, Pr is the Prandtl number of gas flowing around the droplet and B is the transfer number. The subscripts ∞ and i refer to the free stream condition and initial state of the droplet respectively. M_∞ and M_V are respectively the molecular weights of free stream gas and fuel.

The identification of irreversibility components in droplet combustion requires the determination of entropy generation in a chemically reacting flow. The pertinent information on entropy production and exergy balance in the process of droplet combustion in both quiescent and convective atmosphere have recently been reported by Dash and Som [2], Puri [3] and Hiwase et al [4]. It is observed from their work that the entropy generation rate due to chemical reaction is of the same order as those due to heat conduction and combined heat and mass convection. However, the entropy generation rate due to heat conduction in gas phase is still the dominant factor, though the entropy generation due to chemical reaction shoots upto a higher value at the onset of ignition. Hiwase et al [4] suggested the choice of a low value of Damkohler number and a high value of free stream temperature for the process of droplet combustion in a quiescent atmosphere from the view point of energy economy in relation to the efficient utilization of energy resources. In a convective medium, the minimum entropy generation for the burning of a fuel droplet corresponds to an optimum transfer number which is directly proportional to the square of the relative velocity and inversely proportional to the heat release rate and the temperature difference between the droplet and its surrounding flow.

Spray Models

The entropy generation rate in case of spray evaporation or spray combustion process comprises two parts, namely (i) the entropy generation in the evaporation of discrete droplets in their local surroundings due to the transport processes at the liquid-vapor interface and (ii) the entropy generation due to transport processes and chemical reaction in the continuous carrier phase. A break-up of the sources of irreversibilities in a spray combustion process shows equal order of magnitudes for the irreversibility contributed by local interphase transport processes and that contributed by the transport processes and chemical reactions in continuous gas phase.

The variation of exergetic or second law efficiency of a spray evaporation process, as predicted by Som et al [5] and Som and Dash [6] depicts different kinds of picture. The second law efficiency (η_{II}) evaluated using "discrete droplet model" shows an initial increase in (η_{II}) with the free stream temperature (T_∞) followed by an almost constant value thereafter. This implies physically an optimum value of T_∞ above which the evaporation of spray is not thermodynamically justified, since the increase in the rates of exergy transfer and that in its destruction become almost equal. However, the picture is different when the "two phase separated flow model" is used to evaluate the second law efficiency (η_{II}). Under this situation, η_{II} shows a monotonically decreasing function of free stream temperature and an increasing trend with initial Reynolds number of the spray. The optimum values of free stream temperature and spray Reynolds number should be chosen on the basis of an overall economy which is a trade-off between the length of evaporation and total irreversibility of the process.

The recent investigations of Datta [7] and Som and Sharma [8] provide a comprehensive information on energy and exergy balance in a spray combustion process in a gas turbine combustor. The exergetic efficiency in a typical spray combustion process lies between 50-70% while the combustion efficiency in case of a gas turbine combustion lies within 90-98% under usual operating conditions. The destruction of 30-50% of the chemical availability of fuel during a spray combustion process has been reported by Dunbar and Lior [9]. The interesting feature observed, in this context, is that the qualitative trends of the influence of inlet swirl number of incoming air on exergetic efficiency and combustion efficiency are exactly the opposite when the combustor pressure is changed from a lower to a higher value.

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