THEORETICAL STUDIES ON SOME ASPECTS OF DROPLET AND SPRAY EVAPORATION

SYNOPSIS

Evaporation of atomised liquid sprays in a hot convective gaseous medium is associated with the power industry using liquid fuel combustion and also with the process industry in the field of spray drying. The entire success of these processes are centered around the physical understanding of the basic mechanism of atomisation of liquid and of the evaporation histories of the resulting spray in a stream of surrounding hot gas. While on one hand , the generation of a spray of preassigned characteristics, is guided by the hydrodynamics of flow inside the nozzle and the hydrodynamic instability of the moving liquid sheet or jet in the surrounding medium culminating in formation of droplets,the effective operation of the entire spray evaporation on the other hand is dictated by the kinematics and thermal interactions of the droplets with the surrounding convective medium. Moreover,the thermodynamic analysis of spray evaporation also plays an important role in the optimisation of the process with respect to the efficient transfer of energy, in particular- in relation to its application in the power sector.

Literature review on spray generation shows that a good number of theoretical and experimental studies are available both in relation to the hydrodynamics of flow inside the nozzle and also to the process of atomisation through the hydrodynamic instability of the high speed liquid sheet or jet in the surrounding medium. These involve predictions of spray characteristics as a function of pertinent input parameters - namely, the injection conditions , nozzle geometry and the properties of the liquid and the surrounding medium.

In the field of spray evaporation in a hot convective gaseous medium, a large number of work- both empirical and theoretical in nature are available, relating to the studies of heat, mass and momentum transport of a single evaporating drop and to the studies of spray modelling - either on the basis of discrete droplet behaviour or on the basis of localised homogeneous flow. From a wide review of the literature in this field it appears that certain aspects of spray evaporation have not yet received adequate attention and require to be analysed further. A few such aspects can be summarised and classified as follows :

I . Prediction of transport coefficients of an evaporating liquid drop by a theoretical analysis through the use of the fundamental conservation equations.

II . Description of a generalised mathematical model depicting the interactions between the evaporation and the performance characteristics of spray through the relative influences of all the pertinent input parameters involved in the process.

III. Thermodynamic analysis in evaluating the total irreversibilities associated with the process of spray evaporation and its optimisation with respect to the total energy transfer.

IV . Basic understanding of the mechanism of augmenting the transport processes from an evaporating liquid drop by the incorporation of free stream turbulences.

This thesis is therefore directed towards a theoretical investigations into the different aspects of droplet and spray evaporation as mentioned above and has been presented under the following broad heads:

A. Numerical prediction of heat and mass transfer coefficients of an evaporating liquid drop in creeping flow.

B. Investigations into the performance characteristics of an evaporating atomised spray in a uniform stream of hot gas.

.1 Influence of downstream distance on drop size characteristics

.2 Evaporation , drop size and spatial dispersion characteristics of liquid spray containing dissolved solids

.3 Second law analysis of spray evaporation

C. Dynamics of a liquid droplet , and evaporation histories of droplets and sprays in periodically fluctuating free stream motion

.1 Drag resistance on a liquid sphere in creeping flow with a periodically fluctuating free stream motion

.2 Kinematics and evaporation histories of droplets and sprays in a periodically fluctuating free stream motion

A brief description on the work listed above is given below :

A. NUMERICAL PREDICTION OF HEAT AND MASS TRANSFER COEFFICIENTS OF AN EVAPORATING LIQUID DROP IN CREEPING FLOW

Heat and mass transfer coefficients of an evaporating liquid sphere in a 2-dimensional creeping flow have been predicted from numerical solutions of energy and species continuity equations. The hydrodynamic flow field of the gaseous phase surrounding the drop has been taken as that of a steady 2-dimensional creeping flow around a liquid sphere (Hadamard - Rybczynski solution) superimposed with a purely radial flow field originating from the diffusion of the liquid vapour into the surrounding and the continuous displacement of the liquid-vapour interface (droplet radius). The temperature and the vapour concentration fields around the droplet at any instant has been mapped in $r-\theta$ plane from the solutions of energy and species continuity equations.The solutions to these conservation equations have been obtained by the finite difference technique with the alternating direction implicit scheme alongwith the relavant initial and boundary conditions of the problem. The average Nusselt and Sherwood numbers at any instant have been calculated from the surface integral of the local transfer coefficients determined from the respective gradients at different points on the surface. Finally, the steady state values of the average Nusselt and Sherwood numbers alongwith their variations with Peclet and Lewis numbers have been predicted. The results have been compared with the existing empirical informations on the respective transport coefficients of an evaporating liquid sphere in very low ranges of Reynolds number (compatible to creeping flow).

B. INVESTIGATIONS INTO THE PERFORMANCE CHARACTERISTICS OF AN EVAPORATING ATOMISED SPRAY IN A UNIFORM STREAM OF HOT GAS

A non-evaporative spray is usually characterised by the drop size distribution and spatial dispersion features,while for an evaporating spray,in addition to above,the rate of evaporation (based on its interaction with the surrounding stream) alongwith the entropy generation histories are important parameters for its characterisation. While the studies on the rate of evaporation, spatial dispersion and drop size distribution characteristics give an insight into the basic dimensions of the chamber, the second law analysis aided by the entropy generation histories will lead to the concept of optimisation of the process in relation to the efficient transfer of energy. The work under this head is aimed at carrying out studies on these aspects of spray evaporation and has been presented as below :

B.1 Influence of downstream distance on drop size characteristics

Numerical studies have been made to evaluate the drop size distributions and mean drop diameter of an atomised liquid spray at various downstream distances in a uniform stream of hot gas. With the help of a unified spray evaporation model, developed for the present purpose, both the theoretical drop size distribution and the same that could have been obtained in practice by light scattering measurement technique, have been determined numerically at different downstream sections perpendicular to the axis of the spray. Variations of mass mean drop diameter with the axial distance for any atomised spray, specified by the Rosin - Rammler equation as its initial size distribution function, has been established. Finally, the influences of all the pertinent input parameters controlling the dispersion and evaporation of the spray on the mass mean diameter - distance histories have been recognised. A comparative picture of the influence of downstream distance on actual mass mean diameter and that which could have been obtained from light scattering measurement technique, for both non - evaporative and evaporative atomised sprays is one of the interesting predictive features of this problem.

B.2 Evaporation, drop size and spatial dispersion characteristics of liquid spray containing dissolved solids.

A numerical model expressed in nondimensional form has been developed to describe the evaporation, drop size and spatial dispersion histories of an atomised liquid spray containing dissolved solids in a stream of hot gas. The model utilises the empirical equations (as described in literature) of transport processes for discrete drops and is based on the assumption of gradual accumulation of solid particles in the core. It incorporates a generalised scheme, developed for the purpose of updating the liquid and the surrounding gas properties due to changes in temperature and concentration of the constituents. The evaporation and the mean drop diameter histories of sprays along the distance for all the pertinent input parameters like initial liquid concentration, Reynolds number of spray, ratio of surrounding to droplet initial temperature have been studied in this problem.

B.3 Second law analysis of spray evaporation

Second law anlysis for an evaporating atomised liquid spray is made in a uniform parallel stream of hot gas.

With the help of the numerical model for spray evaporation, as described earlier, an exergy (available energy) analysis has been carried out to determine theoretically the entropy generation histories of the evaporating spray. The total rates of heat transfer and associated irreversbilities for complete evaporation of the spray has been calculated. A merit function M, defined as

$$M = \frac{\text{rate of total exergy transferred}}{(\text{rate of total exergy transferred} + \text{rate of total exergy destroyed})},$$

has been evaluated for various values of pertinent input parameters,namely the initial Reynolds number, $Re_i (= 2\rho_i^g v_i \bar{r}_i / \mu_i^g)$ and the ratio of ambient to inital droplet temperature, $\theta'_\infty (= \theta_\infty / \theta_i)$. Finally, from the influences of Re_i and θ'_∞ on the merit function and on the length of complete evaporation conclusions have been drawn in the light of the thermodynamic optimisation of the process.

Though it has been felt that the thermodynamic optimisation in relation to exergy transfer is not of prime practical importance in the evaporation of atomised sprays of liquid containing dissolved solids, associated with the process of spray drying, the entropy generation histories,representing the irreversibility characteristics of the process has been presented for a theoretical understanding of the phenomena.

C. DYNAMICS OF A LIQUID DROPLET AND EVAPORATION HISTORIES OF SINGLE DROPLET AND SPRAYS IN PERIODICALLY FLUCTUATING FREE STREAM MOTION

Incorporation of free stream turbulences in the flow field is one of the conventional methods of augmenting the transport processes. In relation to the evaporation of droplets and sprays, the diffusion of vapour (generated from the drops)and its expansion in the free stream also induce a fluctuating velocity field alongwith that already imposed in the main stream to enhance the rate of evaporation. The mechanism of spray evaporation under this situation is guided by the physical response of the discrete droplets to such changes in relation to their transport processes. In order to throw light under such conditions on the aspects of spray evaporation, an attempt has been made,through a periodic simmulation of free stream turbulence,in this work and is presented in the following problems.

C.1 Drag resisitance on a liquid sphere in creeping flow with a periodically fluctuating free stream motion

Theoretical studies have been carried out to evaluate the drag resistance on a liquid sphere in creeping flow ($Re \to 0$) with a periodically fluctuating free stream motion over a uniform mean value. Drag coefficient on the sphere has been calculated from the pressure and velocity distributions at its surface obtained from the analytical solution of the Navier-Stokes equations. The results are presented in terms of a fractional error ϵ ,defined as the relative change of the instantaneous drag coefficient in the unsteady case from that computed from the steady state drag law (Hadamard - Rybczynski solution) with Reynolds number based on instantaneous velocity, assuming a quasi-steady situation. It is observed that ϵ executes a periodic function of time with a shift of phase from that of the periodic free stream fluctuation. A decrease in $u'_\infty(u_\infty/\bar{U}_\infty)$, $\overline{Re}(2a\bar{U}_\infty\rho/\mu)$ and an increase in $L'(u_\infty/\omega a)$, decreases ϵ at any instant. It has been concluded that as L' increases gradually towards the order of 1 or more,even the maximum values of ϵ fall to negligible quantities for moderate values of velocity amplitudes of the fluctuating component - thus justifying the use of the steady state drag law (based on instantaneous velocity) to evaluate the drag coefficient.

C.2 Kinematics and evaporation histories of droplets and sprays in a periodically fluctuating free stream motion

Influence of free stream turbulence on the kinematics and evaporation characteristics of a single droplet alongwith spray evaporation has been recognised through a simplified numerical model with a periodic simmulation of free stream turbulence. For a continuous injection of single drops the periodic free stream conditions induces a periodic motion (with the same frequency as that of the free stream) on both the non-evaporative and evaporative drops at any downstream section. The amplitude-distance history for a non-evaporative drop exhibits that the amplitude of drop velocity increases sharply to a maximum value, within a very short distance from the plane of injection and gradually flattens or decreases and then attains a constant value(depending upon the frequency). In contrast,in the case of the evaporating drop the amplitude of droplet velocity instead of attaining a constant value goes on increasing monotonically in its entire life time . Regarding the influence of free stream fluctuation on spray evaporation, it is found that an increase in the ratio of velocity amplitude of fluctuating component to the mean value of the free stream ($u'^{\infty} = u^{\infty}/\bar{U}^{\infty}$) enhances the evaporation rate with a consequential decrease in the length of evaporation.The frequency of free stream fluctuation however has a negligible effect on the evaporation history of sprays.