

*Keynote Paper*

## **TRANSPORT PROCESSES AND THERMODYNAMIC IRREVERSIBILITIES IN DROPLET COMBUSTION**

**S.K. Som\***

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

**Abstract** The literature in droplet and spray combustion is abundant. For an overall understanding of the scientific progress in the field, a brief review of the spectrum of models pertaining to transport processes and thermodynamic irreversibilities in droplet combustion has been presented.

### **1. INTRODUCTION**

The theory of evaporation & combustion of liquid fuel droplets and sprays, because of its inherent impact on various industrial processes, has undergone a phenomenal progress over last two decades. The theoretical progress includes the appearance of different physical models, the development of general purpose computer code capable of solving model equations and enhanced computer capabilities. Experimental progress involves the development of improved instrumentations (e.g. laser-doppler anemometry, light scattering methods etc.) for evaluating model predictions. The large number of both experimental and computational works carried out in the field with enhanced facilities have contributed well to the scientific understanding of the subject. It is really difficult, at this stage, to present even the conclusive results of important work pertaining to different aspects of the subject in a compact form. A review of the classical work in the field up to middle or late eighties have been well documented by [Faeth, 1977, 1983, 1987], [Law, 1983] and [Sirignano, 1983, 1988]. The present paper highlights, in brief, some of the profound aspects of the transport processes and thermodynamic irreversibilities in droplet and spray combustion in the light of physical understanding and conclusive information as provided in literature till date.

### **2. THEORIES & MODELS ON TRANSPORT PROCESSES**

#### **2.1 Objective**

The rate of evaporation and burning of a liquid fuel spray in a gaseous environment is mainly controlled by the transport processes in gas and droplet phases which, in turn, are guided by the velocity, temperature and species concentration fields along with the transport properties in both the phases. Therefore, most of the works in the field of droplet and spray combustion pertain to the understanding of transport processes. Because of expensive and time consuming testing, and

Email: \*sksom@mech.iitkgp.ernet.in

severe penalties of test failures, the current interest in the field focuses mainly on the development of comprehensive numerical models. As a result, many established software codes of spray combustion like CONCHAS, CONCERT, KIVA, EPSIO etc. are available for their uses in specific purposes. The present section of the review will mention briefly some modelling aspects of the transport processes in vapourizing droplets.

#### **2.2 Droplet Models**

**Droplet and gas phase flow:** The nature of gas flow past a vapourizing liquid droplet has been investigated by several workers. The major assumptions in the flow models are (i) the droplets remain spherical because of low values of Weber number encountered in the situations of interest and (ii) the gas phase flow around the drop is quasi-steady, since the characteristic time for development of the gas phase flow field is two to three orders of magnitude less than the droplet life time.

The interesting features in the flow of gas over a vapourizing droplet in motion are (i) the large non-uniform outward radial flow at droplet surface (ii) the internal circulation in the droplet phase flow and (iii) the droplet translation relative to Stefan flow at droplet surface.

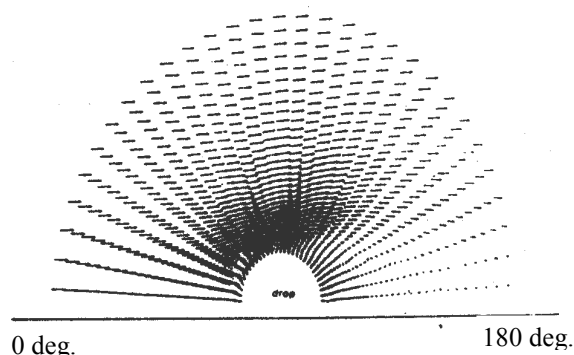
An evaporating drop experiences a large non-uniform outward radial flow at its surface due to evaporation. The outward radial flow decreases both the frictional and pressure drag on the droplet and contributes to an additional drag component due to momentum transport at the interface, which is much less compared to other drag components.

The droplet phase flow field depicts a Hills type spherical core vortex surrounded by a viscous boundary layer and internal wake. The internal circulation decreases with an increase in the outward radial velocity at droplet surface. The normal component of velocity at the droplet surface in the liquid phase is negligibly small as compared to that in the gas phase because of high ratio of droplet to gas phase density.

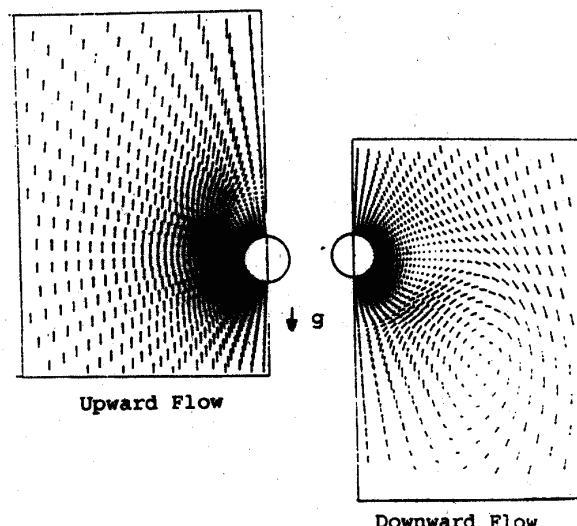
The typical values of droplet diameter and its slip velocity conform to a laminar flow of gas around the droplet. However, the expansion of gaseous combustion products in near vicinity of the droplet causes an additional turbulence in local gas phase over and above the inherent free stream turbulence.

The influence of buoyancy in gas phase flow field around large drops depends upon the relative magnitudes of inertia and buoyancy force. The buoyancy force arises due to both temperature and concentration gradients. A typical Froude number based on drop diameter and free stream velocity becomes the criterion for the influence of buoyancy driven flow over forced flow. Typical gas phase flow fields past vapourizing droplets under different situations are shown in Figs.1, and 2.

**Temperature field:** The simplest classical picture of temperature and species concentration distributions in gas and droplet phases refers to the spherico-symmetric model of droplet evaporation and combustion. A thin flame combustion model was employed for the purpose. The classical approaches for the solution of droplet phases employ "thin skin model" "uniform temperature model" and "uniform state model". In the solution of conservation equations of energy and species concentration, the droplet-gas interface is assumed to be thermodynamic equilibrium with negligible temperature jump due to finite rates of evaporation. The pressure of fuel vapour at droplet surface is considered as the thermodynamic vapour pressure at the interface temperature. Furthermore, the effect of surface tension is neglected in determining the phase equilibrium. The assumptions are generally satisfactory for atmospheric pressure and above for drops having diameters greater than 1  $\mu\text{m}$ . While the flow and transport in the continuous phase are quasi-steady, drop heat up is unsteady. Uniform gas phase properties either at film condition or at condition corresponding to 1/3 -2/3 mixing rule are employed in the solution of conservation equations. The variations in gas phase



**Fig. 1 Typical Gas Phase Velocity Field Around a Vapourizing Droplet at Steady State** after [Biswal, et al. 1999]  $Re_i$  (initial droplet Reynolds number) = 40,  $T_\infty$  (free stream temperature) = 3.0(900 K), Fuel: n-hexane

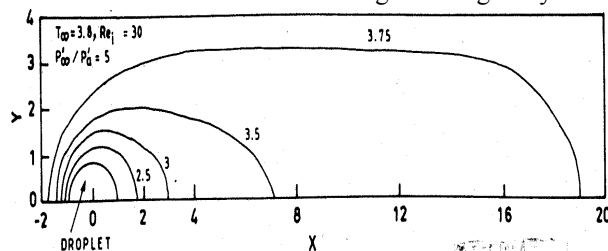


**Fig. 2 Typical Gas Phase Velocity Field Around a Burning Droplet in Mixed Convection** after [Ghosal, 1993]  $Re_i = 20$ ,  $Fr_i$  (initial Froude number) = 1.2,  $T_\infty = 4.0(1200 \text{ K})$ , Fuel: n-hexane

properties are usually taken care of through adjusting parameters in model validation by experiments. The steady state temperature field for a vapourizing droplet without burning is shown in Fig.3.

The internal circulation one dimensionalizes the temperature distribution within the drop. The asymptotic steady state drop temperature corresponds to the wet-bulb temperature of free stream ambience in case of droplet evaporation, while a gradual droplet heat-up near to its boiling temperature takes place in case of droplet combustion. The droplet heat-up time increases with ambient pressure, while the ambient temperature and droplet Reynolds number have marginal influence on droplet transience.

The combustion of a single isolated droplet under realistic conditions *in* practical combustors occurs in several different modes involving a wide range of physical and chemical processes. The theoretical treatments employ different model assumptions for transport processes and chemical kinetics. Transport model extends from thin flame spherico-symmetric combustion to the realistic situation of combustion with the occurrence of wake in the aft region at high Reynolds



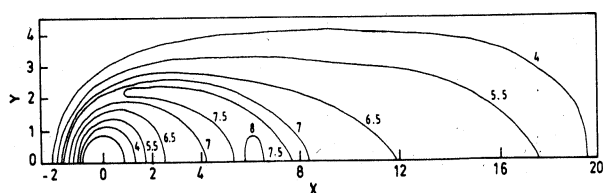
**Fig. 3 Steady State Temperature Field Around a Vapourizing Droplet** after [Dash et al. 1991]  $Re_i = 30$ ,  $T_\infty = 4.0$ , Fuel: n-hexane

number characterised by separated flow. For gas phase chemical reaction, either fast chemistry assumption or finite rate reaction of Arrhenius type is considered. The multistep chain propagating and chain branching reactions are represented by a single step global reaction in generating the source interaction terms in gas phase conservation equations. For hydrocarbon fuels, the assumption of a global reaction step in predicting the droplet lifetime and other performance parameters is fairly accurate.

In forced convection situations, the gas phase temperature field shows an envelope flame whose shape and stand off distance depend mainly on ambient pressure and free stream temperature. A typical isotherm in a droplet combustion in forced flow is shown in Fig.4. The influence of buoyancy makes a considerable change in the flame shape. While the shape of flame in aiding flow is an upright envelope type, the flame in opposing flow at high Reynolds number takes a typical inverted hat shape. The flame shape, is strongly influenced by droplet Reynolds number.

The phenomenon of ignition is closely related to the aerodynamic conditions of the ambience, gas phase temperature and fuel vapour concentration fields. It has been recognised by several workers that the pertinent parameters influencing the ignition are free stream temperature, ambient pressure, droplet Reynolds number and a typical Damkohler number. There is a minimum diameter at a given free stream temperature below which spontaneous burning is not possible. The threshold drop diameter is an inverse function of free stream temperature but a direct function of ambient pressure and 'droplet Reynolds number.

**Multicomponent droplets:** A number of investigations have been made on multicomponent droplet and mainly on binary component fuel droplet with widely varying fuel volatilities. While the gas phase transport processes remain almost the same, the diffusion in liquid phase shows interesting results. During evaporation of a two-component fuel droplet, the more volatile component evaporates first from the surface, yet remains inside the core. This is because the diffusion in liquid phase is much slower than that in gas phase. The concentration of more volatile component at the surface reduces to a negligible value within the period of droplet transience, and steady state droplet temperature exceeds the boiling



**Fig. 4 Typical Temperature Field in a Droplet Combustion in Forced Flow** after [Dash et al. 1991]  
 $Re_i = 30$ ,  $T_\infty = 4.0$ , Fuel: n-hexane

point of pure lighter component at ambient pressure. The temperature and evaporation histories are controlled by the heavier component, while the ignition characteristics are controlled by the lighter component. However, the rapid mixing model assumption predicts the complete evaporation of the lighter component first, leaving the fuel drop as a single component with the heavier one, as happens in case of distillation.

**Interfering droplets:** The transport processes in droplet arrays have been investigated by several workers to identify the influence of neighbouring drops on the vapourization rate of an individual drop. The results are usually provided in terms of an interaction coefficient defined as the ratio of mass burning rate of an interacting drop to that of an isolated drop. Reduction in mass burning rate due to droplet interference is inversely proportional to the inter drop distance. For drops of unequal sizes, the effect is more for smaller drop than that for the bigger drop. For unequal sized drops, interaction coefficient for the bigger drop is directly proportional to the radius ratio, while that for the smaller drop bears an inverse relationship with radius ratio.

For evaporating droplets, whether subjected to slow or rapid evaporation, the presence of a neighbouring droplet increases the surrounding fuel vapour concentration and thus it is expected that the vapourization rate would monotonically increase with inter-drop distance attaining the isolated drop value asymptotically.

In case of burning droplet system, the presence of the flame introduces two effects : competition, for available oxygen and heat loss reduction. Thus it may be expected that, with the increase in inter-drop distance, the burning rate, starting from a value less than that of an isolated drop, increases to a maximum above the value of isolated drop and subsequently decreases to the isolated drop value.

**Transport coefficients:** Information on transport processes in gas-droplet flow have been furnished in terms of transport coefficients by a number of workers. A number of correlations for average drag coefficient with Reynolds number for a non-evaporating liquid drop was suggested by [Clift et al. 1978]. The drag force on a evaporating liquid drop is smaller due to Stefan flow and is taken care of in the correlation for non-evaporating drops through the use of a transfer number B. One of the most widely used relations is that due to [Renksizbulut and Yuen, 1983] as

$$C_D (1 + B)^{0.2} = \frac{24 (1 + 0.2 Re^{0.63})}{Re}$$

However, values of  $C_D$  under many situations correlate well with the standard drag curve without the need for a B number correction provided Reynolds number (Re) is defined on the basis of mixture viscosity

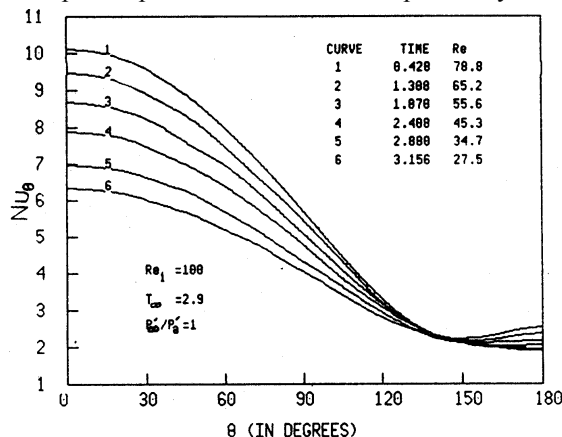
(1/3 -2/3 rule) and free stream density. This was originally suggested by [Yuen and Chen, 1976] and was explained in the light of counter weighing effects of marginal increase and decrease in pressure drag and friction drag respectively. The evaporation drag is less by orders of magnitudes as compared to pressure and friction drags.

The variations in local Nusselt number  $Nu_\theta$  over the droplet surface show different pictures for droplet evaporation (Fig.5 & 6) and droplet combustion [Dash et al. 1991]. In case of droplet evaporation, the rate of heat transfer is maximum at the forward stagnation point. The typical variations in  $Nu_\theta$  in droplet combustion are attributed to the fact that the self initiation of burning is exhibited due to rapid gas phase reactions in the rear side of the droplet and then progresses to the forward side to create an envelope flame.

Regarding the correlations of average Nusselt number (Nu) for steady state droplet evaporation, the widely referred empirical equation due to [Ranz and Marshall, 1952] with a B number correction follows as

$$Nu(1+B) = 2 + 0.66 Re^{0.5} Pr^{0.33}$$

The accuracy of the equation under different situations of droplet vaporization have been reported by several

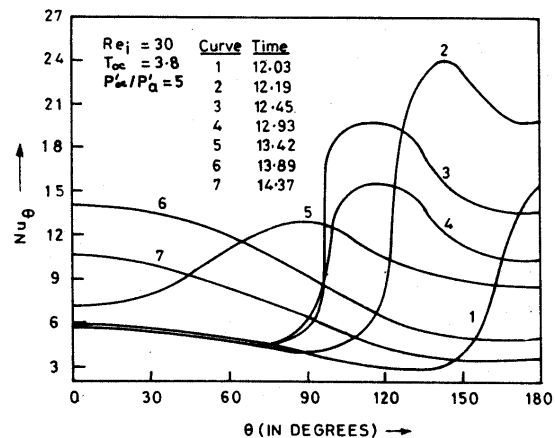


**Fig. 5 Variation of Local Nusselt Number for Evaporating Water Drop** after [Dash et al. 1991]  $Re_1 = 100, T_\infty = 3.0$

workers from both numerical and actual experiments of droplet evaporation and combustion under different situations. Another equation in popular use is that due to [Rensizbulut and Yuen, 1983] and follows as

$$Nu(1+B)^{0.7} = 2 + 0.57 Re^{0.5} Pr^{0.33}$$

Both the equations conform the typical  $d^2$  law and  $d^{3/2}$  law for mass burning rate of droplet in a quiescent and convective ambience respectively. A fair agreement in predicting Nu, in the transient period of droplet heating, from the steady state equations requires a modified value of heat of vapourization for the liquid due to the heat flux in the drop to be used in those equations. It has also been recognised [Biswal et al. 1999] that the drag



**Fig. 6 Variation of Local Nusselt Number for Burning n-hexane Drop** after [Dash and Som, 1991]  $Re_1 = 30, T_\infty = 4.0$

and heat transfer laws for uniform slip velocity are well applicable in case of accelerating (or retarding) drops due to droplet drag exerted by local surroundings.

**Consideration of turbulence:** The free stream turbulence has a influence on the transport laws of individual drops. It is generally agreed that the relative turbulence intensity is the most important factor in representing the effect of turbulence on heat and mass transport rates, while the scale of turbulence assumes a secondary role. The enhancement in transport coefficients depends upon the range of Reynolds number and may vary from 1% to 20%.

However, there is a little information available concerning simultaneous fluctuations of velocity, temperature and concentration in local gas phase on transport rates of drops, particularly in environment representative of spray combustion process.

The continuous gas phase is invariably turbulent for practical sprays and other dispersed flows. Most of the computational work employ standard or modified k-ε turbulence model with density-weighted (Favre) averaged quantities, in conjunction with the conserved-scalar formalism for scalar properties. It has been recognised that the use of Favre averages, rather than, Reynolds (time) average is helpful for density variable flows. Questions arise for the use of standard k-ε model for recirculating flows in continuous gas phase. However, it has been reported [Strugess and Syed, 1990], [Nikjooy and Mongia, 1991] and [Datta, 1998] that neither any modified version of k-ε model nor the higher order Algebraic Stress Model (ASM) can provide pronounced improvement in the predictions of flow field. Though Reynolds Stress Model (RSM) is capable of reproducing major features of highly anisotropic swirling recirculating flows with greater accuracy, the computational complexity and time requirement with RSM is sufficiently large.

The turbulent dispersion of drops in gas phase is considered through a stochastic separated flow model. However, when the particle mass loading in the spray is sufficiently small ( $< 0.5\%$ ) the particles can be assumed to have negligible effect on mean and turbulent gas phase properties.

### 3. THERMODYNAMIC IRREVERSIBILITIES AND EXERGY ANALYSIS

#### 3.1 Objective

An important aspect in the investigation of a thermal system is the thermo- dynamic irreversibility and the consequent loss of exergy in the physical processes encountered by the system in operation. The term exergy ascribes the quality of energy and is defined, according to the second law of thermodynamics, as the maximum part of the energy obtainable as useful work with respect to a reference environment. In any natural process, involving conversion and transfer of energy, exergy is continuously destructed due to the irreversibilities associated with the process. Spray combustion is a phenomenon in which the chemical energy stored in fuel is converted to thermal energy through various physical and chemical processes like vapourisation of liquid fuel, turbulent transport and mixing, chemical reaction and thermal radiation. While combustion efficiency describes the performance of the process of combustion in terms of the quantity of energy converted from the fuel burnt, second law or exergetic efficiency describes it in terms of the conservation of the quality of energy during such conversion. Thus, from the view- point of energy economy, efficient droplet or spray combustion process should be guided not only by the combustion efficiency, but also by its exergetic efficiency. Hence, the need of investigating the sources of irreversibilities in a spray combustion process and determination of exergetic efficiency of the process vis-a-vis its combustion efficiency becomes apparent in providing thermodynamic information to decide upon the optimum design and operating parameters of a combustion system leading to an overall system economy in the scenario of energy management.

#### 3.2 Droplet Models

The work of [Dash et al., 1991] 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 were characterised by the rate of entropy production in the transport processes and were determined "from the numerical solutions of the entropy conservation equation along with the conservation equations of heat, mass and momentum trans- ports in both the phases. A break-up of entropy generation rate due to different modes of transport processes in gas and liquid phases depicts that the entropy generation rate due to viscous dissipation is negligibly small because of very low Eckert numbers encountered in these cases.

Irreversibilities in droplet phase are also found to be quite insignificant compared to those in the gas phase. The most significant contribution in the total entropy generation rate is due to the conduction of heat and its coupled effect with mass transfer in the gas phase. The rate of entropy production decreases continuously at a rate lower than the decreasing rate of droplet surface area. A numerical correlation of entropy generation rate with pertinent dimensionless input parameters follows as [19]

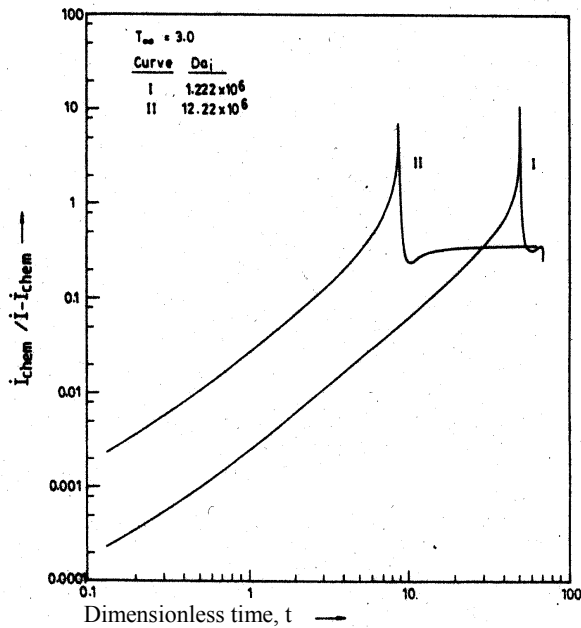
$$\frac{E}{a^2} = 714.5 \frac{(M_\infty / M_v)^{1.02} B^{1.29}}{(\text{Re} \cdot \text{Pr})^{0.66}}^{-0.72}$$

where  $E$  ( $= E' / \rho_\infty \cdot R \cdot u \cdot a_i'^2$ ) is the dimensionless entropy generation rate,  $\rho$  is the density,  $R$  is the gas constant,  $u$  is the flow velocity,  $a$  is the droplet radius,  $\text{Re}$  is the Reynolds number of flow past the droplet,  $\text{Pr}$  is the Prandtl number of gas flowing around the droplet and  $\alpha$  is the transfer number. The subscripts  $\alpha$  and  $i$  refer to the free stream condition and initial state of the droplet respectively.

The identification of irreversibility components in droplet combustion requires the determination of entropy generation in a chemically reacting flow. Pertinent information on entropy production and exergy balance in the process of droplet combustion in both quiescent and convective ambience have recently been reported by [Dash and Som, 1991], [Puri, 1992] and [Hiwase et al., 1998]. 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 instant of ignition. The interesting outcome of this fact, as mentioned by [Hiwase et al., 1998] in relation to a spherico-symmetric model of droplet burning, is that, in a typical diffusion controlled droplet combustion process in which the rate of chemical reaction is much faster than the rates of diffusion of heat, mass and momentum, the irreversibility rate has, in contrast, a lower value due to chemical reaction than that due to diffusion processes taken together. This is shown in Fig.7. In a convective ambience, the total entropy generation rate per unit droplet surface area increases as the burning of droplet progresses and reaches its highest value at the end of droplet life when both the entropy generation rate and droplet surface area become extremely small.

The important feature in the exergy analysis of droplet and spray combustion process is the consideration of chemical availability of the fuel along with its thermomechanical counterpart. A. typical variation in exergetic efficiency, for the process of a n-hexane droplet combustion in a quiescent ambience of air, with initial Damkohler number  $\{Da_i\}$  at various free stream temperatures ( $T_\infty$ ) is shown in Fig.8. The parameter  $Da_i$ , physically signifies the ratio of characteristic

thermal diffusion to chemical reaction time. A variation in  $Da_i$  for any given fuel, under fixed values of initial gas phase properties, implies a variation in the initial diameter of the droplet. The upper flat portions of the curves ( Fig. 8) correspond to the process of droplet vapourization without burning in the gas phase, while the lower flat portions pertain to the steady state combustion of droplet. A conclusive information from this figure suggests the choice of a low value of  $Da_i$  and a high value of free stream temperature for the process of droplet combustion from the view point of energy economy in relation to efficient utilization of energy resources. In a convective ambience, the minimum

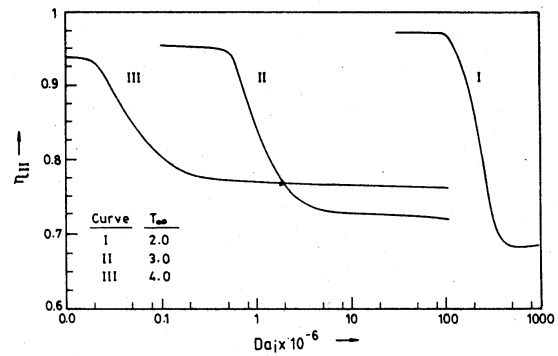


**Fig.7 Temporal Histories of the ratio of Chemical Irreversibility ( $I_{chem}$ ) to Thermomechanical Irreversibility in the Process of Droplet Combustion in Quiescent Medium** after [Hiwase et al., 1998]

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.

### 3.3 Spray Models

The entropy generation rate in case of spray evaporation or spray combustion is composed of two parts, namely (i) the entropy generation in the evaporation of discrete droplets in their local surroundings due to interphase transport processes 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 exergy balance and the second law analysis of a spray evaporation



**Fig. 8 Second Law Efficiency in a Droplet Combustion Process** after [Hiwase et al., 1998]

process in a gaseous surrounding with uniform free stream were reported by [Som et al., 1990] and [Som and Dash, 1993]. The entropy generation rate in the evaporation of a liquid spray is initially very large and then decreases with the axial distance of the spray as the evaporation of the liquid phase goes on. The rate of entropy generation is augmented with an increase in the ratio of free stream to initial droplet temperature or with a decrease in the initial Reynolds number of the spray based on initial droplet velocity and Sauter mean diameter of the initial PDF of the spray.

The variation of exergetic or second law efficiency of a spray evaporation process, as predicted by [Som et al., 1990] and [Som and Dash, 1993] depicts different kinds of picture. The second law efficiency ( $\eta_{II}$ ) evaluated using "discrete droplet model" shows an initial increase in  $\eta_{II}$  with the free stream temperature ( $T_\infty$ ) followed by an almost constant value thereafter. This implies physically an optimum value of  $T_\infty$  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 ( $\eta_{II}$ ). Under this situation,  $\eta_{II}$  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 and Som, 1999a,b] provide a comprehensive information on energy and exergy balance in a spray combustion process in a gas turbine combustor. The inlet air pressure has a marked influence in decreasing the irreversibility due to interphase transport process ( $I^d$ ), while the irreversibility in the continuous gas phase ( $I^g$ ) is almost uninfluenced by the air pressure. At high air pressure, the value of  $I^d$  is relatively lower than the value of  $I^g$ , while the picture is reversed at lower pressure of ambient air. This can be attributed to a reduction in droplet vapourization rate because of a reduction in mole fraction of fuel vapour at

droplet surface with an increase in local pressure at a given local temperature. An increase in inlet air temperature increases the irreversibility in the interphase transport processes, while the gas phase irreversibility remains almost the same.

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 between 90-98% under usual operating conditions. The destruction of 30-50% of the chemical availability of fuel during a combustion process was reported by [Dunbar and Lior, 1994]. A comparative picture of exergetic efficiency and combustion efficiency in a gas turbine combustion process at different values of operating parameters is shown in Table-I. 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. While, at a low pressure of 100 kPa, an increase in inlet swirl increases the exergetic efficiency ( $\eta_{II}$ ) and reduces the combustion efficiency ( $\eta_c$ ), the trends are reversed when the combustor pressure is increased to a value of 600 KPa. At low pressure, the adverse effect of reduced droplet penetration due to an increase in inlet air swirl plays the dominant role in reducing  $\eta_c$  and increasing  $\eta_{II}$ . However, at higher pressure the droplet penetration is as such low and hence the favourable effect of enhanced mixing of fuel vapour in the gas phase due to an increase in inlet air swirl plays the prominent role in reducing the value of  $\eta_{II}$  and increasing the value of  $\eta_c$ . The optimum operating condition for a spray combustion process leading to an overall fuel economy is the trade off between efficient energy conversion and minimum exergy destruction. A fine spray with larger

**Table I: A Comparative Picture of Combustion Efficiency and Exergetic Efficiency in a Gas Turbine Combustion Process** after [Datta and Som, 1999],

$P_i$  = Inlet pressure, S = Inlet Swirl number,  $\psi$  = Spray cone angle

$P_i$ kPa	S	$\Psi$ degree	$\eta_c$ %	$\eta_{II}$ %
100	0.37	80	97.6	54.9
100	0.76	80	95.3	57.2
600	0.37	80	87.2	75.7
600	0.76	80	91.3	71.8
100	0.76	60	91.5	62.7
100	0.76	100	95.6	48.8

cone angle burning in a high pressure and high temperature air results in an increased combustion efficiency along with a high exergetic efficiency too.

#### 4. CONCLUDING REMARKS

In spite of a continuous development of the theory of vapourization and combustion of droplets and sprays for several decades, there are still gaps in our understanding of certain aspects of the field. For example, (i) the influence of free stream turbulence on transport laws of individual droplets, (ii) the droplet interactions in actual spray, (iv) suitability of proper turbulence model in carrier phase computations and considerations of both way turbulent inter- actions between droplets and gas phase, (v) consideration of gas and droplet phase radiation, (vi) consideration of, chemical kinetics of chain propagating or chain branching combustion reactions and (vii) detailed exergy analysis in droplet and spray combustion deserve attention for further studies. Due to complicated nature of gas-droplet flow, most of the information leading to an understanding of physics of the problem should come from experiments and through the model validations with experiments. Therefore the classical field of "droplet and spray combustion" still offers new challenges to the researchers in the field of fluid mechanics and heat and mass transfer.

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