Irreversible entropy production in two-phase flows with evaporating drops

Nora A. Okong'o and Josette Bellan
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, MS 125-109
Pasadena, CA. 91109-8099

Abstract
A derivation of the irreversible entropy production, that is the dissipation, in two-phase flows is presented for the purpose of examining the effect of evaporative-drop modulation of flows having turbulent features. For single-phase single-species flows the dissipation has two components, one due to viscous effects and the other resulting from the heat flux. For two-phase flows with evaporation there are additional contributions to the dissipation from the source terms representing the interaction of the drops with the gas and from the species mass flux. To determine the importance of each of these terms, transitional states (i.e. states displaying turbulence characteristics) obtained from Direct Numerical Simulation (DNS) of a temporal three-dimensional mixing layer are analyzed. The analysis comprises three such states, one of which was created in absence of drops, and two others differing only by the initial mass loading; all other initial parameters are the same for the three layers. For each transitional state, comparisons are performed among volume averages and volume rms of all contributions both for the DNS and the corresponding filtered flow field. Additionally, the effect of the small scales is determined by calculating the difference between the DNS and the filtered flow field results. For finite mass loadings, the overwhelming contribution to the dissipation is from the energy source term, and it is specifically due to drop heating and evaporation. At the larger scales, this contribution to the dissipation is positive meaning that the drops reduce turbulence; however, at the small scales this contribution is negative, indicating that the drops enhance turbulence. The second largest contribution to the dissipation is due to the source terms associated with the chemical potential, and they enhance turbulence at the large scales and reduce it at the small scales. The viscous dissipation is only third in order of magnitude, being at least a factor of five and as much as a factor of seven smaller than the largest contribution. It is shown that the contribution due to the momentum source is about two orders of magnitude smaller than that of the energy source, and is negative at lower mass loading but becomes positive at higher mass loading as the evaporation term becomes dominant over drag in the momentum source. These results indicate that modeling of small scale turbulence phenomena should address the effects of evaporation additional to those of the viscous stresses.

Introduction
The effect of drop interaction with a turbulent flow in sprays has been a subject of long-standing controversy. Specifically, the interest is on the modulation of the flow by a multitude of drops, and its effect on evaporation and combustion. Most studies of particle interaction with flows were performed for solid particles or non-evaporating drops rather than the evaporative situation of interest to spray applications.

For example, early experiments [1], [2], [3], [4], [5] with solid particles of diameter \( d \leq 250\mu m \) or drops in free turbulent jets showed that the spreading rate of the jet decreases compared to equivalent gaseous jets and thus led to the conclusion that the particles reduced turbulence. Other experiments showed that there seems to be a size threshold below which particles suppress turbulence and above which they enhance it. Levy and Lockwood [6] found that particles having \( d \leq 250\mu m \) suppress turbulence of a free jet whereas particles with \( d \geq 500\mu m \) enhance turbulence. Both the effect of \( d \) and the mass loading were studied by Hardalupas et al. [7] who showed that turbulence decreases with increasing volume fraction of \( 40\mu m \) solid particles, whereas it increases with increasing volume fraction of \( 80\mu m \) solid particles. Gore and Crowe [8] categorized the particle size with respect to the Eulerian integral length scale, \( l \), and proposed that there is a critical value of \( d/l \approx 1 \) below which turbulence is suppressed and above which turbulence is enhanced; however, their experiments displayed some scatter, so that this simple relationship was not entirely justified by the data. Hetsroni [9] attributed the enhancement of turbulence by the particles to wake shedding when the particles have high Reynolds numbers. Yuan and Michaelides [10] confirmed the Hetsroni [9] postulate through a simple model whose predictions favorably compared to the experimental data of Tsuji et al. [11], of Modaress et al. [3] and of Levy and Lockwood [6]. Essentially, the Yuan and Michaelides [10] results agreed with those of Gore and Crowe [8] in that they showed that small particles attenuate whereas large particles enhance turbulence. More recently, Kulick et al. [12] studied the influence of solid particles in a downflow fully developed channel in air up to particle mass loadings of 80%. All particles were smaller than the Kolmogorov scale, and in all cases (i.e. independent of \( d \) or of the identity of the particle material) particles attenuated turbulence, with the degree of attenuation increasing with each.
of the mass loading and the Stokes number. Solid particles were also used in the experimental study of channel flow by Paris and Eaton [13] and the conclusion was that moderate mass loadings of 0.3-0.4 decrease the gas phase turbulence kinetic energy and viscous dissipation rate by as much as 85%, and that the attenuation of these quantities increases with mass loading. The only recent example of well-documented observations of drops in shear layers is that of Kiger and Lasberas [14], but in that study, conducted with drops smaller than the Kolmogorov scale, the mass loading was $O(10^{-2})$, so that their conclusion that the total dissipation due the drops is small is not surprising.

In the realm of numerical studies Squires and Eaton [15] investigated the two-way interaction of particles with flow in stationary, isotropic turbulence through Direct Numerical Simulation (DNS), a technique whereby the gas flow is resolved down to the Kolmogorov scale. However, because the flow was forced at the low wave numbers, adding energy equal to the dissipation, such results cannot reveal uncontroversial evidence about the modulation of the flow by the particles. Boivin et al. [16] also performed DNS of solid particles in isotropic turbulence for mass loadings up to unity and with particles sizes ranging from the Kolmogorov to the Eulerian scale. Similar to Squires and Eaton [15], Boivin et al. [16] added energy at the low wavenumbers, $k$, to maintain a statistically stationary flow but utilized ‘computational’ instead of actual particles. Boivin et al. [16] reported that the particles seem to increase the high $k$ portion of the turbulent kinetic energy spectrum, but that at the low $k$ the particles act to reduce the turbulent kinetic energy. Because of the addition of energy at the low $k$ and of the utilization of ‘computational’ particles, the results of Boivin et al. [16] must be interpreted with caution. Actual particles were used in the DNS of Sundaram and Collins [17] conducted for solid particles in isocytic decaying turbulence and in that of Druzhinin [18] for solid-particle-laden isotropic decaying turbulence. Their results add support to the indication that the addition of particles smaller that the Kolmogorov scale enhance turbulence at high $k$ and decrease it at low $k$, with this crossover point in $k$ space shifting towards larger numbers with increasing particle characteristic time. The particle characteristic time is defined as $\tau_p = \frac{d^2 \rho_p}{18 \nu \rho_g}$, so that the findings in [18] mean that the value of $k$ at which the enhancement/reduction crossover occurs increases with the diameter at particle-to-gas-phase specified density ratio, $\rho_p/\rho_g$, and specified gas kinematic viscosity, $\nu$.

Elghobashi and Truesdell [19] addressed the topic of solid particle-modulation of the flow but in the context of DNS of homogeneous turbulence, and similar to the method of [16] performed simulations with ‘computational’ particles, each representing 100 real particles. In [19] the volume loading was $O(10^{-4})$, however since the mass loadings were as large as 0.45, clearly, the use of computational particles affects the momentum and energy interaction of the particles with the flow. Therefore their finding that the particles reduce turbulence at low $k$ with the reverse occurring at high $k$, must be cautiously considered. Note-worthy, the findings of Elghobashi and Truesdell [19] for homogeneous turbulence are similar to those of Boivin et al. [16] for isotropic turbulence. Computational particles, each representing 45 actual solid particles were also used by Ahmed and Elghobashi [20] in DNS of turbulent homogeneous shear flows, and thus their results attributing the modulation of the flow by the particles to specific aspects of the vorticity dynamics modification should also be carefully scrutinized. The topic of drops in homogeneous turbulence was studied by Mashayek [21] for both non-evaporating and evaporating drops smaller than the Kolmogorov scale under the assumption that the enthalpy carried by the species diffusional fluxes is negligible in the heat flux with respect to the thermal conductivity contribution. Results pertaining to the modulation of the flow by the drops are reported for non-evaporating drops and confirmed the findings of other investigators that particles decrease turbulence; for evaporating drops, his finding is that the turbulence kinetic energy increases due to mass transfer.

Miller and Bellan [22] found that evaporating drops having an initial Stokes number (see exact definition below) of 1.02 in drop-laden mixing layers increasingly attenuated the fluctuation kinetic energy with increasing mass loading. In that study, the enthalpy of the diffusional fluxes was neglected in the heat flux with respect to the conductive contribution, just as in [21].

Thus, it is apparent that most studies focus on how solid particles modulate idealized turbulent flows, and that there are no equivalent thorough studies with evaporating drops in turbulent shear flows such as encountered in sprays. From the fundamental viewpoint, particles that are treated as point sources and that are in the Stokes regime cannot develop the wakes that Hetsroni [9] associated with turbulence enhancement at high drop Reynolds number. Thus, the size effect detected in all numerical studies performed in the Stokes regime must be associated with drag. We also note that investigations focussing on categorizing the modulation of the flow by the particles according to the drop characteristic time, or equivalently to the diameter, are meaningless in the context of evaporating drops because even if one initially considers drops of equal diameter, the interaction of the drops with the flow will result in different drop evaporation rates, and therefore a size polydispersity. The only meaningful question that can be asked for sprays is whether a polydisperse collection of drops attenuates or enhances turbulence, and to inquire about the physical mechanisms leading to these effects.

To address the question of turbulence modification by evaporating drops in a spray, we take as a representative configuration that of a three-dimensional (3D) temporal mixing layer laden with evaporating drops. The strategy is to create transitional states (i.e., states embedding turbulence features) using DNS and to analyze them in order to elucidate the underlying physics.
Mathematical model

The governing equations are formulated in the Eulerian framework for the gas and in the Lagrangian framework for the drops. This representation is justified by the volumetrically small loading (≈ 10^-3); however, there is no restriction on the mass loading which can be substantial due to the very high density ratio of the liquid and carrier gas (O(10^3)). The drops are treated as point sources of mass, momentum, and energy, this representation being consistent with drops smaller than the Kolmogorov scale (see discussion in [16]). The carrier gas and vapor emanating from the drops are assumed calorically perfect. The model follows the general development of Miller and Bellan [22] [23], with two notable exceptions. First, and most important, the enthalpy carried by the species diffusional fluxes is no longer assumed negligible in the heat flux with respect to the thermal conductivity contribution, resulting in additional terms in the gas energy equation. To our knowledge, only Réveillon and Vervisch [24], who conducted a study of drops in freely decaying turbulence using ‘computational’ drops, included the species enthalpy contribution in the heat flux. The importance of these terms is examined elsewhere [25] and it is determined that they govern the heat flux at the low gas-to-drop temperature difference conditions of the DNS. These low-temperature conditions are selected in order to foster interactions between the drops and flow and obtain a transitional state representative of these interactions. Second, the pressure gradient contribution is included in the species mass flux, but its contribution is found to be negligible with respect to Fick’s term [25]. Due to space restrictions, only that part of the model needed for the present purposes is presented, and the reader is referred to the detailed derivation of Okong’o and Bellan [25].

The focus of this investigation is on the modulation of the flow by the drops. This subject can be best treated by considering the flow dissipation, that is the irreversible entropy production [26]. Following the derivation of the entropy equation by Okong’o and Bellan [27], a parallel derivation described elsewhere in detail [28] leads to the following result: If \( g \) is the rate of irreversible entropy production, then

$$
g = g_{III} + g_{II} + g_{kine} + g_{chpot} + g_{visc} + g_{temp} + g_{mass}, \tag{1}$$

where

$$
g_{III} = \frac{S_{III}}{T}, \quad g_{II} = -\frac{u_i S_{II,i}}{T}, \tag{2}$$

$$
g_{kine} = \frac{\mu}{T} \left( 2S_{ij} S_{ij} - \frac{2}{3} S_{kk} S_{ll} \right), \tag{3}$$

$$
g_{visc} = \frac{\lambda}{T^2} \frac{\partial T}{\partial x_j} \frac{\partial T}{\partial x_i}, \tag{4}$$

$$
g_{temp} = \frac{R_C R_V}{Y_C Y_V (R_V Y_V + R_C Y_C)} \frac{3}{2} \frac{v_{ij} v_{ij}}{\rho D}, \tag{5}$$

$$
g_{mass} = \int C_{p,V} (T) \frac{dT}{T} - \int \frac{R_V dp}{p} \tag{6}$$

and \( (h_V - T s_V) \) is the chemical potential of the vapor; \( S_{ij} \) is the strain rate

$$
S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right); \tag{8}$$

where \( h_V, Y_V \) are the mass fractions of the carrier gas and vapor \( (Y_C + Y_V = 1) \); \( R_V = R_C / Y_V \) and \( R_C = R_u / Y_C \) where \( R_u \) is the universal gas constant and \( W \) represents the molar weight; \( j v_{ij} \) is the vapor mass diffusional flux; \( \lambda \) is the thermal conductivity; \( \mu \) is the viscosity and \( D \) is the diffusion coefficient. As in Miller and Bellan [22] [23]

$$
S_I = -\dot{m}_d, \tag{9}$$

$$
S_{II,i} = -[F_i + \dot{m}_d v_i], \tag{10}$$

$$
S_{III} = -[F_i v_i + Q + \dot{m}_d \left( \frac{1}{2} v_i v_i + h_{V,s} \right)], \tag{11}$$

where \( h_{V,s} = C_{p,V} T_d + h_0 \) is the vapor enthalpy at the droplet surface; \( \dot{m}_d = \rho m_d / dt \) is the single drop evaporation rate; \( v_i \) is the drop velocity; \( F_i \) is the body force on the drop due to drag and \( Q \) is the individual drop heating rate due to convective heat transfer. Expressions for \( \dot{m}_d, F_i \) and \( Q \) appear elsewhere [22] [23].

Inspection of eq. 1 shows that the gas phase dissipation has several origins. First, the surface of each drop represents a boundary for the gas phase and thus sources of mass, momentum, species and energy at those boundaries represent sources of dissipation, as embodied in \( g_{III}, g_{II}, g_{kine} \) and \( g_{chpot} \). Noteworthy, the source terms contain contributions due to the kinetic energy of the drops, embedded in \( S_{III} \), and due to the kinetic energy of the gas evolving from the drop surface, \( (1/2) u_i u_i S_I \). Phase change is consistently taken into account for the drops, as contained in \( S_{II} \), and for the gas, through \( (h_V - T s_V) S_I \). The terms \( g_{visc}, g_{temp} \) and \( g_{mass} \) contain the dissipation due to transport phenomena associated with fluxes and are positive definite.

Results

To investigate the specifics of flow modulation by the drops, we analyzed and compared results from three DNS of a 3D temporal mixing layer whose initial conditions are listed in Table 1. The comparison bears on databases obtained at transitional states whose general characteristics are displayed in Table 1. The resolution adopted for the
simulations (see Table 1) ensured that all scales were resolved, manifested by smooth turbulence energy spectra [25]. The three DNS differ by the initial mass loading, which is 0, 0.2 and 0.5. In TP500a2 and TP500a5, the simulations were initiated with drops randomly distributed throughout the lower stream with uniform number density and a uniform drop temperature, $T_d$. The initial drop slip velocity with respect to the gas was null, and the initial drop size distribution was polydisperse being specified by a Gaussian distribution for the Stokes number, $St = \tau_d U_0/\omega_{d,0}$, where $\Delta U_0 = 2U_0$ is the initial mean velocity difference between streams with $U_0$ calculated from the specified freestream initial Mach number $M_{c,0} = U_0/\sqrt{R_C T_0 C_p C/\bar{C}_v C}$ where $T_0$ is the initial uniform temperature of the gas, $C_p C$ is the heat capacity of the carrier gas at constant pressure and $\bar{C}_v C$ is the carrier gas heat capacity at constant volume, $\delta_{\omega,0} = \Delta U_0/\langle \delta u_1/\delta x_2 \rangle$ is the initial vorticity thickness where the brackets $\langle \rangle$ indicate averaging over homogeneous ($x_1 - x_3$) planes, the initial condition for $u_1$ is presented in [22], and $\tau_d = \delta^2 \rho_i / (18 \nu)$ where $\rho_i$ is the liquid density corresponds to $\tau_p$ defined above. The momentum thickness based Reynolds number, $Re_m$, is defined using the momentum thickness

$$\delta_m = \frac{1}{\theta_1 - \theta_2} \int_{-L_{2,\min}}^{L_{2,\max}} \left( -\theta_2 + (\rho u_1) \right) (\theta_1 + (\rho u_1)) dx_2,$$

where $\theta_1 = \langle \rho u_1 \rangle_{x_2=-L_{2,max}}$ and $\theta_2 = \langle \rho u_1 \rangle_{x_2=-L_{2,min}}$, $L_{2,max} = L_2/2$ and $L_{2,min} = L_2/2$.

The strategy of the investigation is to conduct a comparison between SP500 and TP500a2 which should reveal the role of the drops, and an analysis of the results from TP500a2 and TP500a5 which should elucidate the role of the mass loading, $ML$. The data is compared from the perspective of the volume average and rms budget of eq. 1. The information is presented in Table 2 for SP500, Table 3 for TP500a2 and Table 4 for TP500a5. The terms in the tables are arranged according to decreasing rms of the DNS flow field.

For SP500 the dissipation has only two components, $g_{visc}$ and $g_{temp}$. Due to the compressible nature of the flow, $g_{temp}$ is not null, however it is much smaller than $g_{visc}$ due to the very small temperature gradients. Along with DNS results, labeled as “Unfiltered”, we also display equivalent results from calculations with the filtered flow field denoted “Filtered”, using a box filter with $\Delta = 4\Delta x$, where $\Delta x$ is the maximum computational grid spacing. The filtered results are indicative of the large scale behavior. The dissipation of these large scales can be seen to be only about half of the DNS. Subgrid Scale (SGS) models are precisely meant to palliate this shortcoming of the larger scale resolution by re-inserting the ‘lost’ dissipation. The third column listing of Table 2, obtained by taking the difference between the DNS and the filtered computation, shows what the contribution of the SGS terms would have to be in order to recover the DNS results. For the SP calculation the SGS terms would have to increase the dissipation, both the average and rms, and this augmentation is comparable in magnitude to the filtered term for the average and much larger than the filtered term for the rms. The larger magnitude of the SGS rms compared to that of the filtered terms is expected since the smaller scales are those responsible for the fluctuations associated with turbulence.

A striking difference with the SP500 situation can be seen when inspecting the equivalent results obtained for the TP500a2 and TP500a5 databases. The largest term is $g_{III}$, due to the energy contribution of the evaporating drops and is positive on average, meaning that turbulence is reduced. However, the average SGS term is negative independent of $ML$ and its magnitude increases with $ML$. This means that the energy addition to the flow due to the drops enhances turbulence at the small scales. An estimate of the primary contribution to $g_{III}$ reveals that $\left[ - (Q + m_d \rho_v \nu_1) \right]$ is one order of magnitude larger than the remaining terms $\left[ -(F_1 + m_d \nu_1 \nu_1/2) \right]$, and therefore that this energy addition is overwhelmingly of evaporative (i.e. thermodynamic) rather than dynamic nature.

The next term in magnitude contributing to $g$ is $g_{ch,pet}$ which arises from the chemical potential of the evaporating drops and is negative on average, indicating that it enhances turbulence. The SGS scales associated with it have though a positive contribution in average, and therefore diminish turbulence.

The largest term not related to evaporation is the viscous dissipation term $g_{visc}$, which is third in order of importance and is about an order of magnitude smaller than the two larger terms. Noteworthy, the contribution of the SGS $g_{visc}$ terms is larger than that of the filtered terms both for the average and the rms, thus showing a departure from the SP500 simulation where only the rms term was larger and indicating their importance in reproducing the results of the DNS.

For TP500a2 the smallest term is $g_{kine}$ and the next larger term is $g_{temp}$, but with increasing $ML$ this order of the two smallest terms is reversed. Also, for TP500a2, $g_{III}$ is small compared to $g_{visc}$, having about one-third the rms, and is negative on average. In contrast, for TP500a5 $g_{III}$ approaches the magnitude of $g_{visc}$ and is positive on average. Thus it seems that drag combined with momentum due to the vapor entering the gas phase ($g_{III}$) destroy entropy (i.e. enhance turbulence) at lower $ML$, but create it (i.e. reduce turbulence) at higher $ML$. This effect is understandable if one considers the sign of the two terms in $g_{III}$: $F_1 > 0$ whereas $m_d \nu_1 < 0$, and since $g_{III} = u_1 (F_1 + m_d \nu_1)/T$, it is clear that on the volumetric average $g_{III} > 0$ if the drag dominates the evaporation rate, whereas $g_{III} < 0$ if the evaporation rate dominates drag. The results show that for $ML = 0.2$ drag dominates the evaporation rate, but with increasing $ML$ a reversal occurs as the contribution from evaporation now dominates drag. Also of importance is the observation that as $ML$ increases, the contribution of the SGS terms in $g_{III}$ becomes increasingly important. For example, for TP500a2 the filtered average $g_{III}$ has the same sign as that of the DNS but is about a factor of three larger in magnitude.
for TP500a5, the filtered $g_{II}$ has the opposite sign and is of same magnitude as that of the DNS.

Overall, the bulk of the irreversible entropy production is associated with the drop evaporation and viscous stresses, whether for the DNS solution, the filtered flow field or the small scales. Noteworthy, the average small scale contribution of the two largest terms has the opposite sign of the respective DNS and filtered flow field. Thus, the small scale effect of the energy sources is to decrease the dissipation, and therefore enhance the turbulent aspect of the flow, whereas the effect of viscosity and the enthalpy due to evaporation is to increase the dissipation. These results extend into the realm of evaporating drops the information obtained from experimental results [1] [2] [3] [4] [5] [6] [7] [8] showing that particles smaller than the Kolmogorov length will attenuate turbulence. In those experiments, the particles were solid and there was no phase change, and therefore $g_{II}$ did not contain the important contribution of $[-(Q + \tilde{m}_d h_{V,a})]$, which are the leading terms in $S_{III}$. We have already established that drag as well as the momentum and kinetic energy of the vapor entering the gas phase ($g_{III}$, $g_{I,kine}$) are negligible contributors to dissipation. Our results indicate that caution must be exercised in generalizing experimental results obtained with solid particles to the different setting of evaporating drops, and in generalizing low or high $ML$ findings.

Conclusions

A study is presented of the interaction of evaporating drops with a flow displaying turbulent features. The results originate from an analysis of transitional states obtained from Direct Numerical Simulations of drop-laden temporal mixing layers. Three transitional states from simulations with different mass loadings are considered. In one simulation there are no drops; the other two simulations differ only by the mass loading and are initialized with a polydisperse Gaussian drop-size distribution. The method of analysis consists in developing an expression for the irreversible entropy production, which is the dissipation, and calculating its volumetric budget in terms of the average and rms. Such calculations are conducted for the flow field obtained from the Direct Numerical Simulation representing the unfiltered solution and also for a flow field obtained by filtering the unfiltered solution. The examination of the budget for the filtered flow field reveals the approximation of the dissipation that would be obtained if only the larger scales of the flow were considered. Furthermore, by taking the difference between the unfiltered and filtered results, one may detect the behavior of the small scales.

The expression for the dissipation shows that in two-phase flows with phase change there are two types of contributions to it: source terms originating from the boundary of each drop and the classical flux terms associated with the viscous, temperature and species mass flux effects; for single-phase single-species turbulent flows there are only the viscous and heat flux effects. The source terms comprise energy contributions due to drop heating, due to the enthalpy of the vapor entering the gas phase, due to drag work, due to the kinetic energy of the drops, due to the kinetic energy of the evaporated mass entering the gas phase and due to the chemical potential of the vapor entering the gas phase. The momentum based source contains terms due to drag and to the momentum of the evaporated vapor. Examination of the volume averages shows that the sum of the energy terms due drop heating, to the enthalpy of the vapor entering the gas phase, to drag work and to the kinetic energy of the drops overwhelms all other terms in the dissipation, whether at the unfiltered, filtered of small scale level. Among the four terms in this contribution, the sum of the first two terms is larger than that of the last two terms by one order of magnitude. At the larger scale, this largest contribution attenuates the flow turbulence whereas at the small scale, it enhances flow turbulence. The next large contribution is due to the chemical potential term, and adds turbulence at the large scales while removing it at the small scales. The viscous dissipation is only third in order of importance and is a factor of five to seven smaller than the largest term; its effect is to decrease turbulence at all scales and its small scale contribution is larger than its large scale one. These three larger contributions to the dissipation increase with increasing mass loading. The next contribution to the dissipation is that from the momentum source and is at least one order of magnitude smaller than the viscous contribution. Unlike the larger terms, the momentum source average is negative at the smaller mass loading, but positive at the higher mass loading indicating a crossover in the contributions of drag and momentum of the drop-released vapor which dominates at higher mass loadings. The remaining terms may have averages of the same magnitude as the momentum source term, but their rms is considerably smaller.

The impact of these results is quite clear. So far, small scale modeling for describing turbulence in sprays has been focused on modeling the viscous stress effect, emulating the typical modeling strategy from single-phase flows. Our findings indicate that this may be an incorrect strategy, in that the dissipation due to the source terms may overwhelm that associated with viscous effects. These results were all obtained for transitional states of drop-laden mixing layers. Future studies will show whether these results are also typical of the interaction of evaporating drops with fully developed turbulent flows.

Acknowledgment

This research was performed at the Jet Propulsion Laboratory (JPL) of the California Institute of Technology, under the sponsorship of the U.S. Department of Energy (DOE), with Mr. Neil Rossmeisul (DOE Headquarters) and Mr. D. Hooker (DOE Golden Center) serving as contract monitors, under an agreement with the National Aeronautics and Space Administration. Computational resources were provided by the supercomputing facility at JPL.
References


[28] Okong'o, N. A. and Bellan, J., Consistent Large Eddy Simulation of a temporal mixing layer laden with evaporating drops. II: A priori study, to be submitted for publication, 2002
\(N_1, N_2, N_3\) are the number of grid points in \(x_1, x_2\) and \(x_3\) directions corresponding to \(L_1=0.2m, L_2=0.22m, L_3=0.12m\)
\(t_{tr}\) is the dimensionless transition time, \(t^* = t \Delta U_0 / \delta_{w,0}; \delta_{w,0} = 6.85 \times 10^{-3}m; Re_m = \rho_0 \Delta U_0 \delta_m / \mu\)

For all cases: \(M_c,0=0.35, Re_0 = \rho_0 \Delta U_0 \delta_{w,0}/\mu=500, T_0=375K\); For TP cases: \(T_d,0=345K\)

Initial \(St\) given by a Gaussian distribution (mean 3, standard deviation 0.5).

### Table 1: Initial conditions and transition times.

<table>
<thead>
<tr>
<th>Run</th>
<th>(ML)</th>
<th>(N_d)</th>
<th>(N_1 \times N_2 \times N_3)</th>
<th>(t_{tr}^*)</th>
<th>(Re_m, tr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP500</td>
<td>0</td>
<td>0</td>
<td>256\times 288\times 160</td>
<td>100</td>
<td>1290</td>
</tr>
<tr>
<td>TP500a2</td>
<td>0.2</td>
<td>227722</td>
<td>256\times 288\times 160</td>
<td>100</td>
<td>1414</td>
</tr>
<tr>
<td>TP500a5</td>
<td>0.5</td>
<td>569305</td>
<td>256\times 288\times 160</td>
<td>105</td>
<td>1361</td>
</tr>
</tbody>
</table>

### Table 2: Entropy production of unfiltered and filtered flowfields, case SP500 at \(t^* = 100, \Delta = 4\Delta x\).

<table>
<thead>
<tr>
<th>Term</th>
<th>Unfiltered Average Rms</th>
<th>Filtered Average Rms</th>
<th>Difference (SGS) Average Rms</th>
</tr>
</thead>
<tbody>
<tr>
<td>(g_{visc})</td>
<td>1914 4305</td>
<td>1054 2040</td>
<td>860 2594</td>
</tr>
<tr>
<td>(g_{temp})</td>
<td>16 50</td>
<td>7 16</td>
<td>9 38</td>
</tr>
<tr>
<td>(g)</td>
<td>1390 4329</td>
<td>1601 2048</td>
<td>869 2610</td>
</tr>
</tbody>
</table>

### Table 3: Entropy production of unfiltered and filtered flowfields, case TP500a2 at \(t^* = 100, \Delta = 4\Delta x\).

<table>
<thead>
<tr>
<th>Term</th>
<th>Unfiltered Average Rms</th>
<th>Filtered Average Rms</th>
<th>Difference (SGS) Average Rms</th>
</tr>
</thead>
<tbody>
<tr>
<td>(g_{III})</td>
<td>15996 47358</td>
<td>18097 57925</td>
<td>-2101 15990</td>
</tr>
<tr>
<td>(g_{I, chem})</td>
<td>-9353 29332</td>
<td>-10621 35792</td>
<td>-1269 9813</td>
</tr>
<tr>
<td>(g_{visc})</td>
<td>3718 9003</td>
<td>1781 3557</td>
<td>1937 6149</td>
</tr>
<tr>
<td>(g_{II})</td>
<td>-111 3181</td>
<td>-298 3558</td>
<td>187 1196</td>
</tr>
<tr>
<td>(g_{mass})</td>
<td>289 1157</td>
<td>147 467</td>
<td>142 835</td>
</tr>
<tr>
<td>(g_{temp})</td>
<td>169 543</td>
<td>71 179</td>
<td>92 410</td>
</tr>
<tr>
<td>(g_{I, kine})</td>
<td>80 342</td>
<td>89 380</td>
<td>-9 106</td>
</tr>
<tr>
<td>(g)</td>
<td>10789 23513</td>
<td>9265 24192</td>
<td>1524 8394</td>
</tr>
</tbody>
</table>

### Table 4: Entropy production of unfiltered and filtered flowfields, case TP500a5 at \(t^* = 105, \Delta = 4\Delta x\).

<table>
<thead>
<tr>
<th>Term</th>
<th>Unfiltered Average Rms</th>
<th>Filtered Average Rms</th>
<th>Difference (SGS) Average Rms</th>
</tr>
</thead>
<tbody>
<tr>
<td>(g_{III})</td>
<td>26765 74878</td>
<td>31811 94735</td>
<td>-5046 31801</td>
</tr>
<tr>
<td>(g_{I, chem})</td>
<td>-15119 47339</td>
<td>-17929 58595</td>
<td>2810 18393</td>
</tr>
<tr>
<td>(g_{visc})</td>
<td>3469 8039</td>
<td>1646 3205</td>
<td>1823 5444</td>
</tr>
<tr>
<td>(g_{II})</td>
<td>303 7392</td>
<td>-301 8928</td>
<td>604 3813</td>
</tr>
<tr>
<td>(g_{mass})</td>
<td>317 1323</td>
<td>164 552</td>
<td>153 953</td>
</tr>
<tr>
<td>(g_{I, kine})</td>
<td>128 536</td>
<td>145 609</td>
<td>-17 194</td>
</tr>
<tr>
<td>(g_{temp})</td>
<td>153 512</td>
<td>65 183</td>
<td>88 374</td>
</tr>
<tr>
<td>(g)</td>
<td>16017 34440</td>
<td>15601 39467</td>
<td>417 13329</td>
</tr>
</tbody>
</table>
