Int. J. Heat Mass Transfer. Vol. 32, No. 10, pp. 2000–2002, 1989
Printed in Great Britain

0017-9310/89 $3.00+0.00

Transport-related phenomena for clusters of drops

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(*Received* 31 *October* 1988 *and in final form* 3 *April* 1989)

INTRODUCTION

MEASUREMENTS performed in sprays characteristic of power systems show that sprays are composed of several regions [1]. Near the atomizer the drops might not be entirely formed and liquid sheets and filaments might still exist. There follows a region where the drops are already formed but have not yet been dispersed, so that they cluster together with a typical distance between the drops that is of the same order of magnitude as that of the average radius of the drops themselves. This region of the spray is called the dense spray region. Finally, further from this dense spray region there exists a region where the drops might still cluster, but in these clusters the distance between drops is much larger than the average radius of the drops. This region is called the dilute spray region.

In the dilute spray region drops are far apart from each other and thus when the spray is exposed to a convective flow, these drops practically behave like isolated drops in a convective flow. In contrast, in the dense spray regime, the drops are close to each other and thus their history is controlled by how much of the surrounding gas can enter in contact with them. This is to say that, unlike for drops belonging to dilute clusters of drops, transport phenomena are crucial in determining the behavior of drops belonging to dense clusters of drops because transport imposes limits on heat and mass transfer between the two phases. These phenomena pertain to indirect interactions and they can control the motion of drops, their heat-up time, evaporation, ignition and combustion.

Previous work [2–5] pointed out some important consequences of these indirect interactions. Two models of turbulent transport were used in ref. [5] in order to investigate the importance of turbulent transport from the surroundings to the cluster. Because of the global aspect of the model in which all the drops were assumed to behave identically, the transport from the cluster to surroundings was modeled using a 'trapping factor'. Basically, the 'trapping factor' is a weighing factor which allows the modeling of intermediary situations between those of dilute clusters where evaporated mass was assumed to be trapped in the cluster and that of dense clusters where evaporated mass was assumed to escape to ambient. It was found [5] that whereas in the dilute regime turbulence is not a controlling parameter, in the dense regime it becomes the crucial control parameter. This is a fact well known by experimentalists and design engineers who locate turbulent enhancement devices near the injector where the spray is dense, rather than further down the combustor where the spray is dilute.

Since the transport processes between the cluster and its surroundings were found to be so important in the case of dense clusters, it was thought very important to improve the description of the transport of heat, mass and species from the cluster and its surroundings. This new model is described in detail in ref. [6] for electrostatically charged drops, and is used to calculate the results presented below for the special case of null charge. Due to the brief nature of the Technical Note, the nomenclature used here is the same as in refs. [5, 6].

The model developed in ref. [6] is similar to that of ref. [5] in that the drops and gas have two velocity components: a uniform axial component along the trajectory direction and a radial component. The difference between the two models is in the description of the radial velocity component. Whereas in ref. [5] a 'trapping factor' was used as discussed above, the new formulation uses the assumption of self-similarity in the radial direction as explained in detail in ref. [6].

RESULTS AND DISCUSSION

Calculations were performed using the models of refs. [5, 6] for n-decane drops evaporating in a spherical cluster surrounded by unvitiated ambient air at atmospheric pressure. The thermophysical constants used in the calculation have been listed in ref. [3].

Figure 1 shows a comparison of the results obtained with the two turbulence models for each one of the 'trapping factors' and similarity models. The evaporation time which is plotted vs the initial air/fuel mass ratio represents either the time when $R_1 = 0.05$ or the time at which saturation was obtained. As can be seen in Fig. 1 the discrepancy between the four sets of results is small in the lean mixture and dilute spray regime. This is because in this regime transport processes are not important in determining the evaporation time due to the fact that the drops are far apart and enough heat is available for their evaporation. As the initial mixture becomes rich the discrepancy between the 'trapping factor' and similarity models becomes larger. In contrast to the results obtained with the 'trapping factor' model, the similarity model predicts that turbulent transport is important even in the rather dilute cluster regime ($n^0 \simeq 5\times10^3\ \mathrm{cm}^{-3}$).

When ϕ^0 decreases further, the initial mixture becomes richer and the drop number density falls into the dense regime ($n^0 > 10^4\ \mathrm{cm}^{-3}$). As the initial drop number density is larger, turbulence becomes crucial in determining the evaporation time as it is clearly shown by both cluster models. However, the results become extremely sensitive to the cluster model itself because for example for $n^0 = 5\times10^4\ \mathrm{cm}^{-3}$ the 'trapping factor' model predicts saturation before complete evaporation whereas the similarity model predicts the opposite. It is expected that the regime of saturation before complete evaporation will be encountered with the similarity model at higher n^0. What this comparison shows is that global models such as those in refs. [2–5] can be expected to offer only a qualitative understanding. The quantitative predictions can be obtained only when the results of these global models can be compared with experimental observations. On the other hand experimentalists need information on what to measure, and where to make measurements. The present results show that in order to validate global models, measurements of evaporation times should be made in the dense cluster regime where the sensitivity is highest.

In Fig. 2 the evaporation time is displayed vs the initial radius of the cluster for an air/fuel mass ratio corresponding to a drop number density which is the dividing value for dense/non-dense sprays under the initial conditions shown in the legend. Both cluster models predict that turbulent transport effects are more important for smaller clusters. This is due to the smaller volume to surface ratio and thus

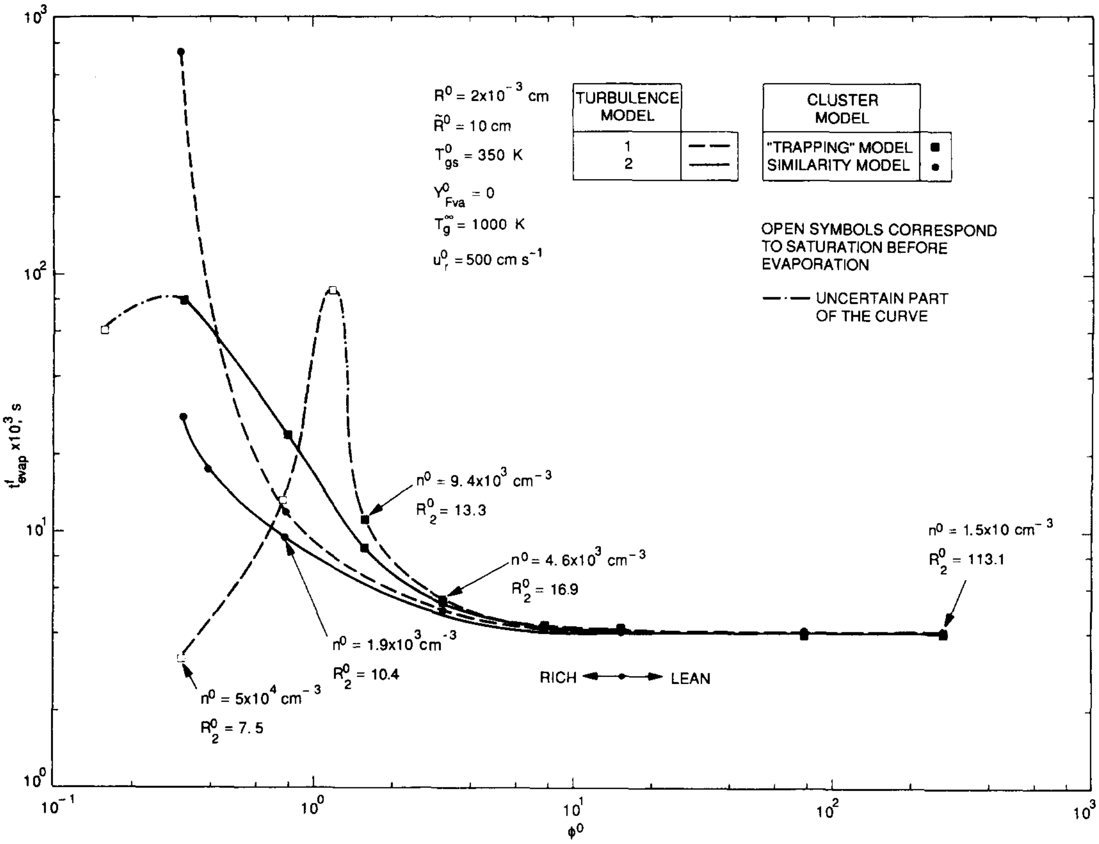

FIG. 1. Evaporation time vs initial air/fuel mass ratio: $T^0_{ga} = 1000$ K, $T^0_{gs} = 350$ K, $Y^0_{Fva} = 0$, $u^0_r = 500$ cm s^{-1}, $R^0 = 2\times10^{-3}$ cm, $\tilde{R}^0 = 10$ cm.

to the greater transport of hot unvitiated gas to the drops in order to promote evaporation. Although the qualitative predictions of the two cluster models are the same, quantitatively the similarity model predicts a smaller effect. Once again, experimental observations are needed to show the quantitative effect of turbulence, and these experiments should be performed in the small cluster regime where the sensitivity is highest.

The importance of the cluster model used is again illustrated in Fig. 3 where the final size of the cluster is compared with the initial size of the cluster for several initial cluster sizes. In all cases larger clusters contract more, relative to their initial size, than do small clusters. This is due to the heating of the drops and the consequent cooling of the gas phase. A smaller number of drops in a cluster results in less cooling of the gas phase at complete evaporation and shorter evaporation time; this is the case of the smaller clusters. A higher turbulence level will enhance transport of heat to the cluster and thus there will be less cooling and consequently less cluster contraction; this is the case of turbulence model 2. For small clusters and high turbulence levels the similarity model predicts that the cluster actually expands. This is another trend that needs experimental verification. In this case observations should be performed again in the small cluster regime.

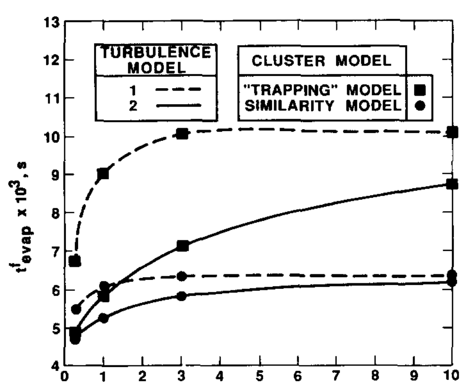

FIG. 2. Evaporation time vs initial cluster radius: $\phi^0 = 1.57$ ($n^0 = 9.44\times10^3$ cm^{-3}, $R^0_2 = 13.3$), $T^0_{ga} = 1000$ K, $T^0_{gs} = 350$ K, $Y^0_{Fva} = 0$, $u^0_r = 500$ cm s^{-1}, $R^0 = 2\times10^{-3}$ cm.

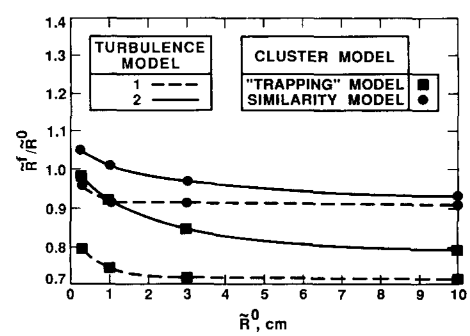

FIG. 3. Non-dimensional final cluster radius vs initial cluster radius: $\phi^0 = 1.57$ ($n^0 = 9.44\times10^3$ cm^{-3}, $R^0_2 = 13.3$), $T^0_{ga} = 1000$ K, $T^0_{gs} = 350$ K, $Y^0_{Fva} = 0$, $u^0_r = 500$ cm s^{-1}, $R^0 = 2\times10^{-3}$ cm.

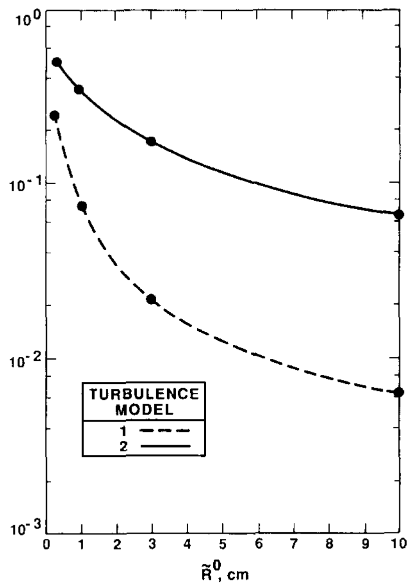

FIG. 4. Fuel loss ratio vs initial cluster radius obtained with the similarity model: $\phi^0 = 1.57$ ($n^0 = 9.44 \times 10^3$ cm^{-3}, $R_2^0 = 13.3$), $T_{ga}^0 = 1000$ K, $T_{gs}^0 = 350$ K, $Y_{Fva}^0 = 0$, $u_r^0 = 500$ cm s^{-1}, $R^0 = 2 \times 10^{-3}$ cm.

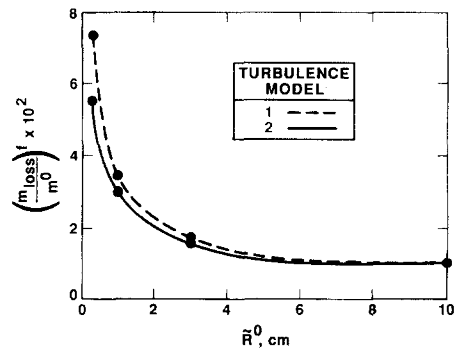

FIG. 5. Total mass loss ratio vs initial cluster radius obtained with the similarity model: $\phi^0 = 1.57$ ($n^0 = 9.44 \times 10^3$ cm^{-3}, $R_2^0 = 13.3$), $T_{ga}^0 = 1000$ K, $T_{gs}^0 = 350$ K, $Y_{Fva}^0 = 0$, $u_r^0 = 500$ cm s^{-1}, $R^0 = 2 \times 10^{-3}$ cm.

Finally, plotted in Figs. 4 and 5 are respectively the relative fuel mass loss and the relative total mass loss from the cluster at the end of evaporation. These results were obtained with the similarity model, which is believed to be the more accurate of the two cluster models. In the case of dense clusters, the relative fuel mass loss from the cluster is important because ignition outside of the cluster is expected [7] with only the ejected fuel participating in ignition. The fuel loss ratio depends strongly on the cluster size and the turbulence model. In contrast, the total mass ratio is nearly insensitive to the turbulence model for large clusters, with a larger sensitivity shown for smaller clusters. However, similar to the fuel mass ratio, the total mass loss ratio increases substantially as the cluster size decreases. The larger fuel loss and greater entrainment for smaller clusters may be attributed to their larger surface to volume ratio. It is important to notice that the present model does not account for vortical motion of the drops inside the cluster and thus the results predict a minimum amount of mass escaping from the cluster due to the lack of centrifugal force effects. In order to validate experimentally models such as those described above, rates of growth or decay of clusters are needed for comparison.

Acknowledgement—This work was supported by Air Force Office of Scientific Research, Army Research Office and Department of Energy–Energy Conservation and Utilization Technologies Programs through interagency agreements with National Aeronautics and Space Administration.

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