Abstract

Turbulent plumes are commonly encountered in both natural and engineering flows. One of their most significant applications is in atmospheric flows, where clouds are modeled as a combination of multiple plumes evolving in a stratified environment. As the moist air parcel rises up, it becomes saturated and the water vapor condenses, leading to the release of latent heat. This additional buoyancy due to latent heat release in clouds is typically modeled in the laboratory as the volumetric heating of plumes. Atmospheric stability also plays a critical role in the evolution of clouds as it determines the rate at which the density of the atmosphere varies in the vertical direction. Cloud convection typically occurs within a stably stratified environment, which consists of layers of vertically varying densities in the atmosphere. In this study, we investigate the behavior of volumetrically heated plumes in a stratified medium using both RANS modeling and large eddy simulations. The evolution of mean and turbulent statistics of heated plumes are examined in detail.

We first conducted numerical simulations of the forced plume in a stratified medium using the Reynolds-Averaged Navier-Stokes (RANS) equations paired with the standard k-ϵ turbulence model. This approach allowed us to perform many simulations at much lower computational cost when compared to large eddy simulations. We systematically varied the background stratification and examined how the flow statistics vary with the stratification. This also allowed us to validate the RANS simulations against the reported experimental data. We compared the maximum height, mean centerline velocity, and turbulence statistics such as shear production and dissipation rate. Mean velocity profiles obtained from RANS simulations showed good agreement with the experimental data when the background is unstratified i.e. when the density of the ambient is uniform. However, mean flow statistics for a stratified medium showed considerable deviation between the RANS simulations and experimental data. We found that as the stratification strength increased, the maximum height of the plume decreased. This suggests the importance of atmospheric stability in limiting the vertical development of clouds. Further, we examined how the turbulence energy budget varies with the background stratification strength. We noted that for stronger stratification levels, the residual of the turbulence kinetic

energy budget increased. This suggests a greater non-homogeneity in the flow, indicating the limitations of the assumptions made in RANS models. Overall, the RANS modeling was effective in studying the mean flow quantities for weakly stratified and unstratified mediums, however, at higher stratification strengths significant improvements in the modeling are required.

In the second part of this study, we performed large eddy simulations (LES) of the forced plume subjected to volumetric heating in a stratified medium. The heating is computationally modeled by adding a source term to the energy equation near the plume equilibrium height. We validated our LES methodology by comparing the mean flow statistics and the entrainment rate coefficient with previous experimental study, for an unstratified medium. We performed a systematic study by varying two key parameters in the evolution of heated plumes. First is the heating rate which determines the rate at which energy is added to the system due to latent heat release, and the second parameter is the background stratification which determines the rate at which the background density varies in the vertical direction. In our study, we considered a similar range of heating rates as observed in cumulus clouds. We found that the addition of heat accelerated the plume due to additional buoyancy leading to an increase in the mean axial velocity. Mean velocity profiles were found to preserve their Gaussian structure in the heating zone, however, the temperature profile shows a double hump structure. At the same time, the turbulent kinetic energy and vorticity magnitude decreased in the heating zone due to the disruption of coherent structures caused by heating. The entrainment rate increases at the start of the heat injection zone (HIZ), but then drastically reduces towards the end of the HIZ. We observed that as the plume rises above the heating zone, it restores its Gaussian shape for temperature. Also, the vorticity magnitude and turbulence kinetic energy (TKE) increased above the heating zone. Interestingly, the kinetic energy spectrum reveals different scaling behaviors: κ_z^{-3} for an unheated plume and $\kappa_z^{-11/5}$ for a heated plume.

On the other end, increasing the background stratification is found to counteract the effects of volumetric heating by suppressing the maximum plume height and turbulence levels. The entrainment coefficient is observed to decrease with an increase in stratification strength for a given heating rate. Primary difference between the stratified and unstratified mediums is that in the unstratified medium where the

density of the ambient is uniform, plumes rise asymptotically without any maximum height. However, in a stratified medium where the plume encounters continuously varying density layers, the density of the plume at a certain height matches with the ambient, and the plume starts to spread laterally with the maximum height of the plume slightly above the neutral layer. In the case of a heated plume, due to additional buoyancy provided by the heating, the plume has a new neutral layer and reaches a new maximum height above the heating zone.

Next, we investigated the entrainment dynamics of a forced plume with volumetric heating using energy-consistent entrainment relations. We decomposed the entrainment coefficient into different components for both unheated and heated plumes. The closure of the energy-consistent approach is compared to the total entrainment coefficient with the standard entrainment hypothesis.

According to the energy consistent entrainment relation, there are three contributors to the entrainment coefficient, 1) contribution from the turbulence energy production, 2) contribution from the buoyancy effects, 3) contribution due to departure from self-similarity. In the unstratified medium, turbulence energy production is found to be the primary driver of the entrainment in unheated plumes, while for the heated plumes, the contribution from the turbulence energy production reduced, and the buoyancy emerged as the dominant factor driving the entrainment within the HIZ and beyond. In the stratified medium, the entrainment coefficient for the unheated plume due to the buoyancy effects is negative in the neutral layer. However, the release of latent heat leads to additional buoyancy, thus the contribution of buoyancy to the entrainment coefficient becomes less negative. As a result, the cumulative entrainment coefficient goes from a negative value (detrainment zone) to a positive value (entrainment zone) towards the end of HIZ. As the stratification strength increases, the contribution from the turbulent production to the entrainment coefficient increases. We also found that the deviation from expected self-similar behavior was more pronounced as the stratification strength increased.