Laboratory Studies of Anomalous Entrainment in Cumulus Cloud Flows

Sourabh S. Diwan\textsuperscript{1}, Roddam Narasimha\textsuperscript{1}, G.S. Bhat\textsuperscript{2} and K.R. Sreenivas\textsuperscript{1}

\textsuperscript{1}Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore
\textsuperscript{2}Indian Institute of Science, Bangalore

Abstract

Entrainment in cumulus clouds has been a subject of investigation for the last sixty years, and continues to be a central issue in current research. The development of a laboratory facility that can simulate cumulus cloud evolution enables us to shed light on the problem. The apparatus for the purpose is based on a physical model of cloud flow as a plume with off-source diabatic heating that is dynamically similar to the effect of latent-heat release in natural clouds. We present a critical review of the experimental data so far obtained in such facilities on the variation of the entrainment coefficient in steady diabatic jets and plumes. Although there are some unexplained differences among different data sets, the dominant trend of the results compares favourably with recent numerical simulations on steady-state deep convection, and helps explain certain puzzles in the fluid dynamics of clouds.

1. Introduction

Clouds are listed among the most urgent scientific problems requiring attention by the IPCC (2007); more effective cumulus parameterization schemes can significantly enhance understanding of tropical circulations and could improve predictions (for example) of the Indian monsoons. Convective clouds represent a set of complex interactions among microphysics, flow turbulence and radiation (Randall et al. 2003). They involve multiple phases, some of which change into each other releasing or absorbing considerable quantities of heat. However cloud-scale dynamical processes, in particular the entrainment and mixing that affect microphysics, remain puzzles despite numerous studies over the last six decades.

Early models for entrainment in cumulus clouds can be traced to a hypothesis due to G I Taylor (1945), who proposed that a convection current rising with a velocity $u$ in the atmosphere leads to an entraining current of velocity $\alpha u$ flowing from the surrounding atmosphere into the main rising current. The factor $\alpha$ here, after appropriate non-dimensionalization, is called the entrainment coefficient $\alpha_E$ (Turner 1973). Attempts at developing a model for cloud flows assuming a constant value for $\alpha_E$ were however not successful (Emanuel 1994).

In a series of studies bearing on the fluid dynamics of cumulus clouds (Bhat & Narasimha 1996 (BN henceforth); Venkatakrishnan et al. 1999) the problem has been tackled as one in free turbulent shear flows, in particular jets and plumes, subjected to off-source diabatic heating. This heating simulates latent heat release in natural clouds due to phase changes in $\text{H}_2\text{O}$. A dynamical similarity parameter in the form of a non-
dimensional heat release number (BN) provides the volumetric heat generation in the laboratory flow has an effect similar to that of latent heat release in natural cumulus clouds. A brief review of studies up to 2008 is available in (Narasimha & Bhat 2008). More recent developments are reported in Narasimha et al. (2011).

Experimental data on entrainment in diabatically heated jets and plumes are now available from five sources. The apparatus used in all these cases is virtually the same, both in principle of simulation and physical dimensions. Our objective here is to present a brief critical review of these data. For this purpose we make estimates of $\alpha_E$ defined as

$$\alpha_E = \frac{dm}{d\beta} \frac{\pi \rho b U_c}{2},$$

where $m$ is the total mass-flow rate in the flow, $z$ is vertical coordinate, $b$ is velocity width (it can either be $b_m$, where $U(b_m) = U_c / 2$ or $b_{ue}$, where $U(b_{ue}) = U_c / e$, $U$ and $U_c$ are mean local and centerline velocities respectively, and $\rho$ is fluid density.

2. The experimental arrangement

![Figure 1. Line diagram of experimental setup.](image)

The canonical cloud flow studied here is basically a round turbulent plume or jet. The current version of the apparatus (Figure 1) built for the purpose represents a considerable enhancement in capability over the original version (BN). The off-source diabatic heating is achieved through ohmic losses generated in the plume fluid, which is water rendered electrically conducting ('active') by addition of acid. A high-frequency variable voltage supply drives current through the plume within a cage of six electrodes made of a net of steel wires. The appropriate non-dimensional parameter for fluid-dynamical simulation of the diabatic heating experienced by the cumulus clouds is the heat-release number (BN),

$$G = \left( \frac{\beta g / \rho C_p}{Q / b_b U_b^3} \right)$$

where $\beta$ is coefficient of thermal expansion of the cloud fluid, $g$ is acceleration due to gravity, $C_p$ and $\rho$ are respectively specific heat at constant pressure and density of the ambient fluid, $Q$ is off-source volumetric heating rate, and $b_b$ and $U_b$ are length and
velocity scales, e.g. at condensation level in the cloud or beginning of heat generation in the apparatus. In the atmosphere $Q$ is $O\ (1\ Wm^{-3})$ and $G = 0.1–2$ (Narasimha et al. submitted). The same range of values of $G$ can be obtained in water subjected to a heating rate of $O\ (4\ MWm^{-3})$, which over a volume of order $250\ cm^3$ is a manageable 1-2 kW. The heat ‘injection’ zone (HIZ) extends over a selected height range in the plume (Figure 2), over which flow is accelerated by the enhanced buoyancy due to heating.

3. **Data analysis**

Making accurate measurements of the velocity field presents several difficulties. (i) The total duration of any given run is limited to about 15 minutes, because of the diffusion of dyed, active plume fluid into the ambient deionized fluid. This not only affects flow visualization, but also reduces the resistivity of the ambient fluid, thereby adversely affecting the parameters of the fluid electrical circuit. (ii) Velocity measurement between electrodes is affected by the narrow inter-electrode spacing and optical reflection from the electrodes. (iii) The entraining velocity is relatively low, and highly variable in both space and time due to the presence of coherent structures. Therefore long averaging times are required for obtaining reliable results, especially when the HIZ is short (fewer coherent structures subjected to heating).

For these reasons the scatter in entrainment data is appreciable. Analysis requires some smoothing of data, especially for obtaining $\alpha_E$ which involves a derivative of the mass flux. The smoothing is usually a shape-preserving spline interpolation scheme, ensuring that the smoothed curve is always within the error bars of the measured values.

The results from each data set are now briefly reviewed. Because of space limitations it is not possible here to treat each data set in detail. However a longer report (Diwan et al. 2011), setting out the detailed analyses, is available on request from the corresponding author (RN).

3.1 **Bhat and Narasimha (1996; BN)**

This study presents flow visualization and LDV measurements. Velocity and width data are reported at two slightly different values of $G$, respectively 4.4 and 4.7. This small difference in the numerical value of $G$ however will not affect the trend in $\alpha_E$. Velocity profile widths can also be inferred from measured scalar widths (BN). In general the flow width first grows slightly more rapidly than in the unheated case just above the bottom of HIZ (shown by black solid line), and later on drops below it.

BN found the axial velocity profiles (normalized by local width and centreline velocity) to be approximately Gaussian slightly beyond the HIZ, and the dye concentration (through the pixel-intensity) to be Gaussian even inside the HIZ. The mass-flow-rate is obtained by assuming Gaussian velocity profiles. The resulting volume-flow-rate ($m/\rho$) is shown in Figure 2.
Figure 2 (a) Variation of volume-flow rate (data from BN) with \( z \) corresponding to the data in Figures R1 and R2. Solid line corresponds to growth in unheated flow. (b) Mass-flow rate obtained using variable \( \beta \) model; reproduced from Narasimha and Bhat (2008).

It is clear from figure 2 that the effect of heating is to increase the mass-flow rate from the corresponding unheated value inside and beyond the HIZ. This is consistent with the mass-flow-rate variation presented by Narasimha and Bhat (2008) obtained by using what BN called a variable \( \beta \) model to convert scalar width into velocity width (also shown in Figure 2). Thus the mass-flow-rate in the heated jet is indeed higher than in the unheated jet in their experiments (not lower as inferred for the BN data by Agarwal and Prasad (2004). The reason is that flow acceleration dominates over shrinking spread rates. This does not imply that \( \alpha_E \) always goes up (see Section 4).

3.2 Venkatakrishnan (1997; VT)

We consider two data sets here, first for the jet and second for the plume. For both the volume-flow rate is obtained by direct integration of measured velocity profiles.

3.2a Jet:

Jet volume flow data are shown in Figure 6.

Figure 3 Mass flow rate as a function of \( z \) from figure 3.19 in VT for the jet. For details see the accompanying text.
The error bars are drawn from data in Venkatakrishnan et al. (1999) on measurement uncertainties in the experiments.

3.2b Plumes

The volume-flow rate data for the plume are broadly similar to those for the jet.

![Figure 4: Mass-flow rate as a function of z from figure 4.20 in VT for the plume.](image1)

3.3 Agarwal and Prasad (2004; AP)

AP have performed Particle Image Velocimetry (PIV) measurements on off-source heated jets. The experimental setup is virtually the same as used by BN. As we shall see in Section 4, the AP data agree with other data in some respects but disagree in others. A detailed discussion of their data is available in the report of Diwan et al. (2011). Here we confine our discussion to the volume-flow-rate data reported by AP and shown in Figure 5. Because of the scatter in the data, more than one choice of a smoothed curve through the data is possible. Figure 5 shows two such faired curves which represent more or less extreme options.

![Figure 5: Mass-flow rate as a function of z with two faired curves for AP.](image2)
3.4 L. Venkatakrishnan et al. (2003; VK)

VK did PIV measurements on a jet with off-source heating in a setup similar to that used by BN. They have reported values of $\alpha_E$ by directly measuring the radially inward velocity at the jet edge. The $\alpha_E$ values extracted from Figure 7 from VK are reproduced in Figure 6. They have not reported any measurements inside the HIZ due to difficulty associated with the presence of heater electrodes. VK obtained a value of 0.057 for $\alpha_E$ in the unheated jet, which matches well with the values reported in the literature (0.054 – 0.058).

3.5 Summary plot

Figure 6 is a summary plot showing the entrainment coefficient values from the five data-sets mentioned above. Note that the data-set in Venkatakrishnan et al. (1999) has not been included here since the experimental conditions therein were broadly similar to those in VT, which contained more experiments suitable for the present analysis.

![Figure 6](image_url)

Figure 6 Summary plot of variation of $\alpha E$ with $z$ for the five datasets discussed above. For the symbols see the accompanying text.

Each data set in Figure 6 is represented by a band indicating the range of uncertainty due to the various reasons mentioned earlier. Note that all the values of $G$ quoted in Figure 6 are with the ‘1/e-velocity’ width. Because of the normalization used, the ordinate in Figure 6 is unaffected by the definition of $b$.

4. Discussion and Conclusions

The summary plot on the entrainment coefficient is clear on certain issues, but leaves others open.

The first notable conclusion is that all data available to date agree on certain effects of diabatic heating. Immediately after the injection of heating the flow momentum width and the mass flow tend to increase, but the entrainment coefficient itself tends to retain its earlier value. With increasing height but still in HIZ $\alpha_E$ reaches a maximum. Thereafter, towards the end of and beyond HIZ $\alpha_E$ goes down, sometimes
rapidly, all the way to zero. In the similarity model $\alpha_E$ would have remained constant; the experiments show that changes in $\alpha_E$ can be substantial and even dramatic.

Current understanding of the entrainment process considers it as consisting of three distinct stages: engulfment of ambient fluid by coherent structures present in the flow, drawing the engulfed fluid into stretched and squashed shapes that vastly increase interface area between ambient and main flow (by stirring or mingling action), culminating in real mixing at molecular level. Computer simulations on the effect of off-source heating on a jet (Basu and Narasimha 1999) show that it takes a few eddy turnover times for heating to affect the organization within a coherent structure, but that it is eventually disrupted. Flow visualization studies also support this picture. This provides the explanation for the little change in $\alpha_E$ as heating commences, and the final drop to zero beyond the HIZ. The maximum in-between is due to large acceleration in the flow due to heating before the disruption stage.

It has recently been shown (Narasimha et al.2011) that the variation in $\alpha_E$ shown in Figure 5 is consistent with simulations of deep tropical convection using a cloud-resolving model (Romps and Kuang 2010).

A major conclusion from these studies is that diabatic heating plays a key role in the entrainment dynamics of cumulus clouds.

References

Agarwal, A. & Prasad, A. K. 2004 Evolution of a turbulent jet subjected to volumetric heating. *J. Fluid Mech.* 511:95-123.

Basu, A.J. & Narasimha, R. 1999 Direct numerical simulation of turbulent flows with cloud-like off-source heating. *J. Fluid Mech.* 385:199-228.

Bhat, G. S. & Narasimha, R. 1996 A volumetrically heated jet: large-eddy structure and entrainment characteristics. *J. Fluid Mech.* 325:303-330.

Diwan, S.S., Narasimha, R., Bhat, G.S. & Sreenivas, K.R. 2001 Laboratory investigations of the dynamics of anomalous entrainment in cumulus-cloud flows. *EMU Report, JNCASR*.

Emanuel K (1994) *Atmospheric Convection.* Oxford Univ. Press, Oxford.

IPCC 2007 In: *Climate Change 2007: The Physical Science Basis.* Contribution of Working Group I to the Fourth Assessment Report, IPCC (Ed. Solomon, S.D. *et al.* ) Cambridge Univ. Press.

Narasimha, R., Diwan, S.S., Duvvuri, S., Sreenivas, K.R. & Bhat, G.S. 2011 Laboratory simulations show diabatic heating drives cumulus-cloud evolution and entrainment, Submitted.
Narasimha, R. & Bhat, G. S. 2008 Recent experimental and computational studies related to the fluid dynamics of clouds. In: Kaneda Y (ed.) Computational Physics and New Perspectives in Turbulence, Springer 313-320.

Randall, D.A., Khairoutdinov, M., Arakawa, A. & Grabowski, W. (2003) Breaking the cloud parameterization deadlock. Bull. Amer. Met. Soc. 84:1547-1564.

Romps, D.M. & Kuang, Z. 2010 Do undiluted convective plumes exist in the upper tropical troposphere? J. Atm. Sci. 67:468:484.

Taylor, G.I. 1945 Dynamics of a mass of hot gas rising in air. LA Report 235 (US Atomic Energy Commission).

Turner, J. S. 1973 Buoyancy effects in fluids. Cambridge Univ. Press, London

Venkatakrishnan, L. 1997 Development of a plume with off-source volumetric heating. PhD thesis, Indian Institute of Science, Bangalore.

Venkatakrishnan, L. & Bhat, G. S. Narasimha R 1999 Experiments on a plume with off-source heating: Implications for cloud fluid dynamics. J. Geophy. Res. 104(D12):14271-14281.

Venkatakrishnan, L., Elavarasan, R., Bhat, G. S., Krothapalli, A. & Lourenco, L. 2003 Particle image velocimetry study of a cloud-like flow. Curr. Sci. 85:778-785.