10D.1 *HOT TOWERS FORMATION – A SIMPLE PLUME RISE MODEL*

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1. INTRODUCTION

Hurricane intensification has been studied by scientists for decades and one phenomenon that appears to always accompany the intensification is the presence of hot towers of cumulous clouds that stretches to 15 km high, touching the top of the troposphere (Figure 1a &b). The hypothesis of Hot towers was first proposed in 1958 by Riehl and Malkus (Anthes, 1999), who wrote in conclusion from their observations that

"..neither a gradual land mass circulation nor simple convective diffusion can transport heat upward to balance losses aloft and we postulate a mechanism of selective buoyancy with undiluted cloud towers…." and

"….considering the ascent of narrow warm towers through an environment…"

Their hypothesis has been confirmed by scientists (Thompson and Gutro, 2004; Anthes, 1999; Braun, 2007) to accompany intensification of hurricanes. In 1999, Anthes concluded in his review that without hot towers, hurricane would not exist. The mechanism of Hot towers formation as explained in the recent NASA video (Braun, 2007) that is shown on *Youtube* identifies the differential speeds of vortices around the tower wall as the cause. Hot towers are described as 'express elevators' for rising moist air at the advanced stage of hurricane activity where it intensifies.

An alternative hypothesis is being propounded here that hot towers exist long before the intensification of hurricanes takes place, by carrying out a simulation in a calm surrounding without the latent heat release of moist air, to see whether an 'express elevator' or 'corridor of hot air rise' can be formed without the ferocious vortices.

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If an 'express elevator' can be predicted by the simulation, then the hypothesis is probably worth investigating further. The 'effective plume-chimney' is here identified with the 'express elevator', in that a column of hot air meets no resistance in rising up the atmosphere.

To begin the enquiry into the hypothesis, it is necessary to compare the plumes over a heated flat plate as studied in a laboratory by Fishenden and Saunders (1950) in Figure 2a, which was adapted by Chu (2002, 2006a) for forced draft air-cooled heat exchangers operating under natural convection (Figure 2b), and that given by Garbell in 1947 (Anthes, 1999) as shown in Figure 2c. One can immediately see the striking resemblance of the three.

The model to be described here was originally developed for plume rise in the atmosphere (Figure 3), then applied successfully to laboratory and industrial scale heat exchangers [Chu, 1986-2006b]. There is no reason why in the light of the laboratory results the model cannot be applied back in its original field of atmospheric phenomena.

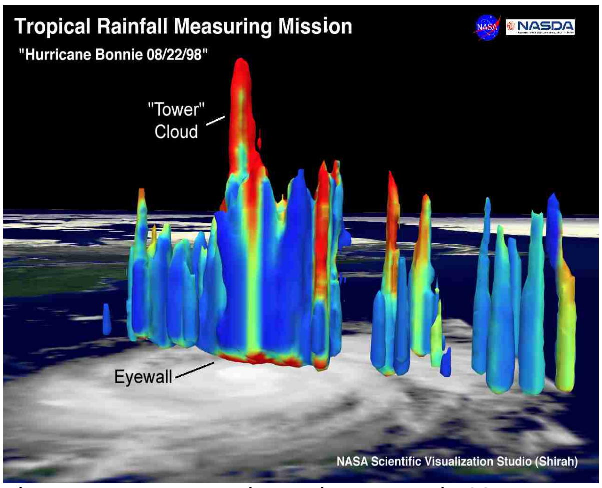

Figure 1a: Hot Towers in Hurricane Bonnie 22 August 1998 spotted by NASA TRMM satellite (Thompson and Gutro, 2004)

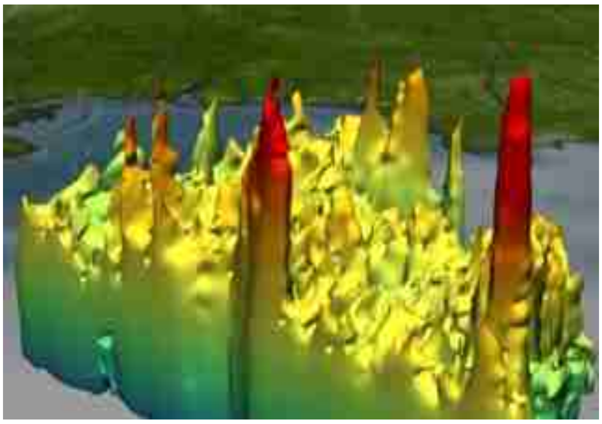

Figure 1b: Hot Towers in Hurricane Katrina with Clouds completely removed (Dewitt, 2005)

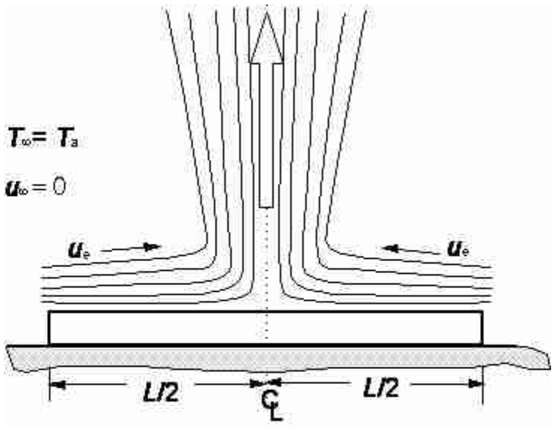

Figure 2a: An upward facing heated flat plate

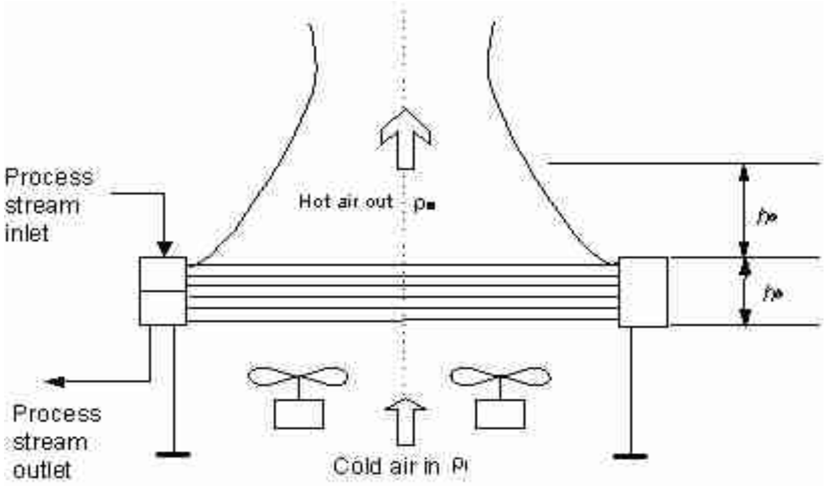

Figure 2b: A Forced Draft Air-Cooled Heat Exchanger Operating under Natural Convection

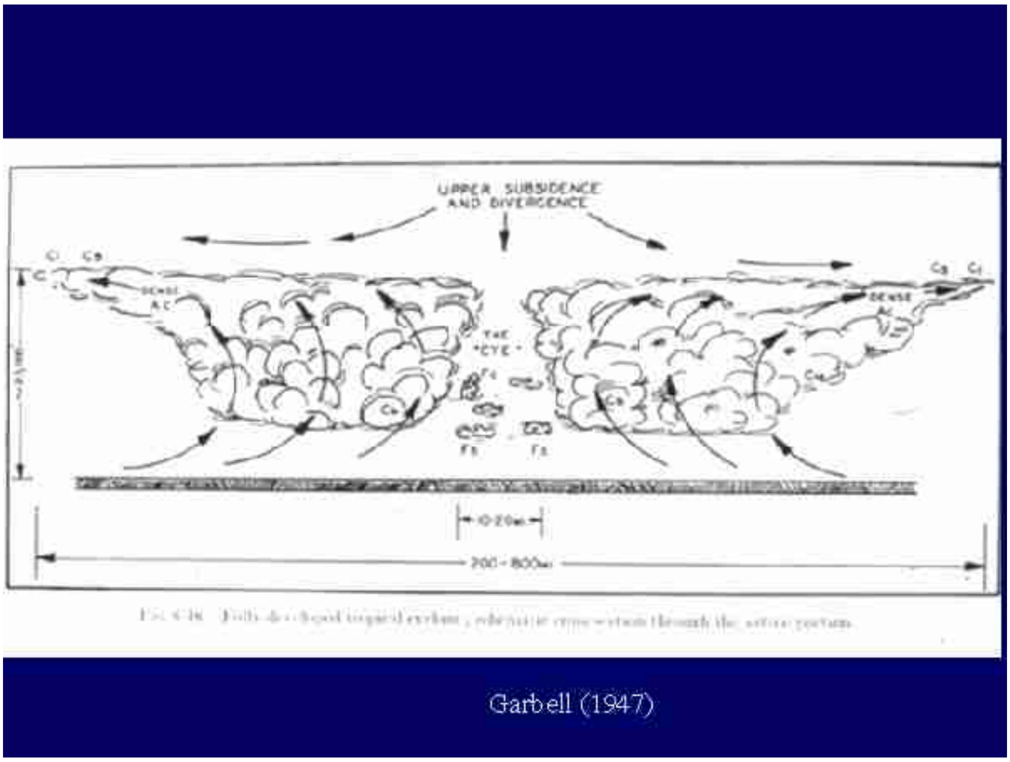

Figure 2c: Fully developed tropical cyclone schematic diagram showing the convergence and divergence of the plume over a source width of 200 – 800 miles (320 – 1280 km) [Anthes, 1999]

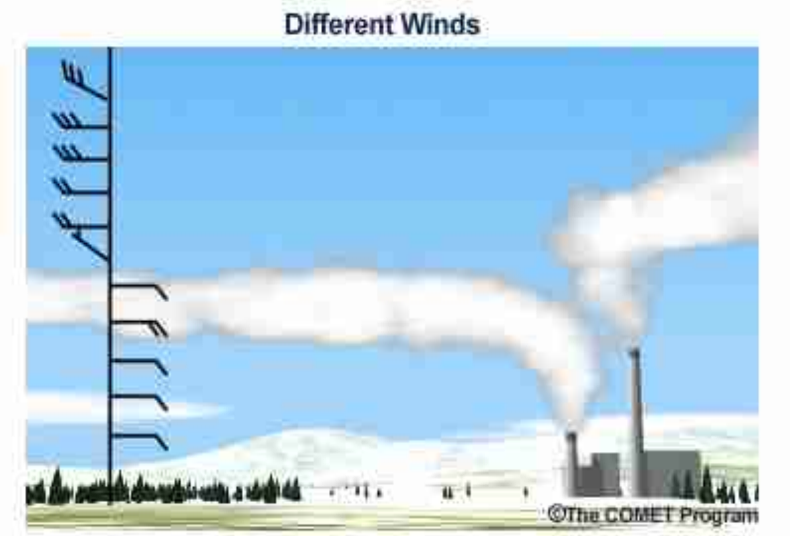

Figure 3: Plume Rise Dispersion Study (http://meted.ucar.edu/dispersion/afwa/txt/sect4.htm)

2. THEORY OF EFFECTIVE PLUME-CHIMNEY

In a world where everything happens instantaneously, air surrounding a horizontal heated hot plate rushes in and mixes efficiently to ensure that the pressure difference caused by the buoyancy effect is nullified, an equilibrium situation. This is nearly achieved with small face-dimension hot or cold plates (Figure 4a).

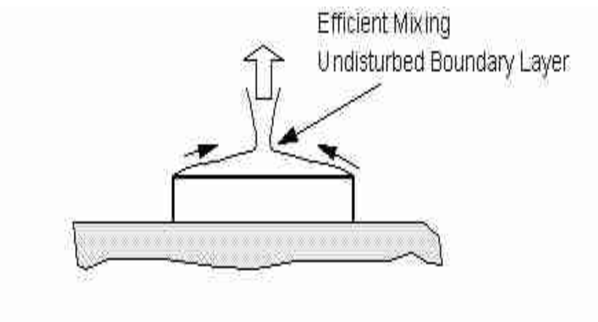

Figure 4a: Heated Flat Plate of Small Face Dimensions

As the flat plate dimensions increase for the same process conditions, the equilibrium is disturbed until a steady state occurs where there is a constant pressure difference between the core of the plume and the ambient air. This is brought about by the buoyant plume diverting the entrained ambient air upwards, disallowing an equilibrium to be established (Figure 4b).

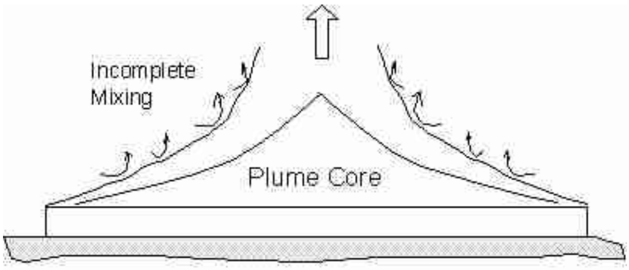

Figure 4b Heated Flat Plate of Large Face Dimensions

It is by taking advantage of this non-equilibrium that one can create an 'Effective Plume-chimney' that is invisible, that penetrates through the bulk fluid by opening an 'express highway' for a rising fluid in a natural convection process. Up until the year 2002, the empirical Doyle and Benkly (1973) formula had been the only method available in the open literature to attempt to exploit this effect by estimating the 'effective plume-chimney height' (EPCH) of an air-cooled heat exchanger operating under natural convection. It appears that no other heat transfer work has been found to try to capitalize on this effect. Scorer (1959), an atmospheric scientist, whose work inspired the initial plume research by Chu (1986) to investigate several possibilities of physically measuring an EPCH for application in forced draft air-cooled heat exchangers, suggested the necking point of a converging plume to be the height with chimney effect. A converging plume occurs with a criterion of

Fr < $5\lambda^2/8\alpha$ at the source according to the analysis by Morton (1959), where λ is the ratio of density and velocity radii and α is the entrainment coefficient. This criterion was met at both the laboratory and industrial scales. At first it was experimentally determined using a laboratory size air-cooled heat exchanger that h_o was negligibly small. Data from a fullsize industrial heat exchanger of 2.0 x 3.1 m^2 face area and fitted with three hardware chimney heights of 0.30, 1.22 and 2.44 m appeared to support the laboratory result reasonably well (Chu et al, 1988). However by further qualitative consideration it was eventually recognised that assuming the EPCH to be negligibly small when simulating a forced draft air-cooled heat exchanger with large face dimensions can lead to a very conservative result. An equation for predicting the EPCH was therefore developed by Chu (2002) and found to compare within acceptable error of the data obtained at an industrial test rig. Currently, a project is in progress at Universiti Malaysia Sabah for parameterizing these effects in a specially built air duct, to validate the Chu (2002, 2006a) equations.

Since the concept is derived on the basis of a horizontal heated flat plate of sizable dimensions, it is therefore not illogical to apply the EPCH on natural convection phenomena that occur over objects or surfaces of similar geometrical characteristics, namely oceans, forest fire, nucleate pool boiling vessels and forced draft air-cooled heat exchangers. For a mesoscale or larger plume source (10 -1000km) it was found necessary to develop a method that is not susceptible to scale such as an integral model derived from conservation of mass, momentum and energy equations to predict EPCH. Figure 5 shows a satellite image taken by the AMSR-ENASA_Aqua_Satellite over the period of 1June-18 September 2005, showing that such a source is not inconceivable.

Because the heat source is still the predominant source of energy to the storm, the primary thermal characteristics of the plume are not expected to change significantly from conception to fully-developed hurricane. However, modifications by the coriolis forces and other factors that are beyond the scope of this paper, do intensify the updraft and the wind speeds around the eye.

3. PLUME RISE MODEL OF MORTON, TAYLOR AND TURNER (1956)

The model of Morton, Taylor and Turner (1956) is a classic one-dimensional plume rise analysis.
For this exercise the plume is considered dry, and there is no crosswind. The density of the ambient atmosphere is taken at sea level and assumed to obey the barometric formula throughout the troposphere (Table 1).

The basic assumptions in the solution are:

- Boussinesq approximation,
- loss of momentum from turbulent eddies is negligible,
- entrainment of surrounding air occurs at the rate of 0.116 of the axial velocity throughout the plume rise,
- a uniform profile of velocity and temperature runs across the flow area, or alternatively called 'Top hat'. (Figure 6)

By making these assumptions, the effect is to make conservative predictions, so that the calculated wind speed will be less than the actual case which receives the assistance of latent heat release, which is subject to modification by coriolis forces and terrain.

The equations are:

Volume
$$\frac{d(\pi r^2 u)}{dx} = 2\pi r \alpha u \quad (1)$$

Momentum
$$\frac{d(\pi r^2 u^2 \rho)}{dx} = \pi r^2 g(\rho_e - \rho) \quad (2)$$

Buoyancy flux
$$\frac{d\{\pi r^2 u(\rho_e - \rho)\}}{dx} = 2\pi r \alpha u(\rho_e - \rho_{e1}) \quad (3)$$

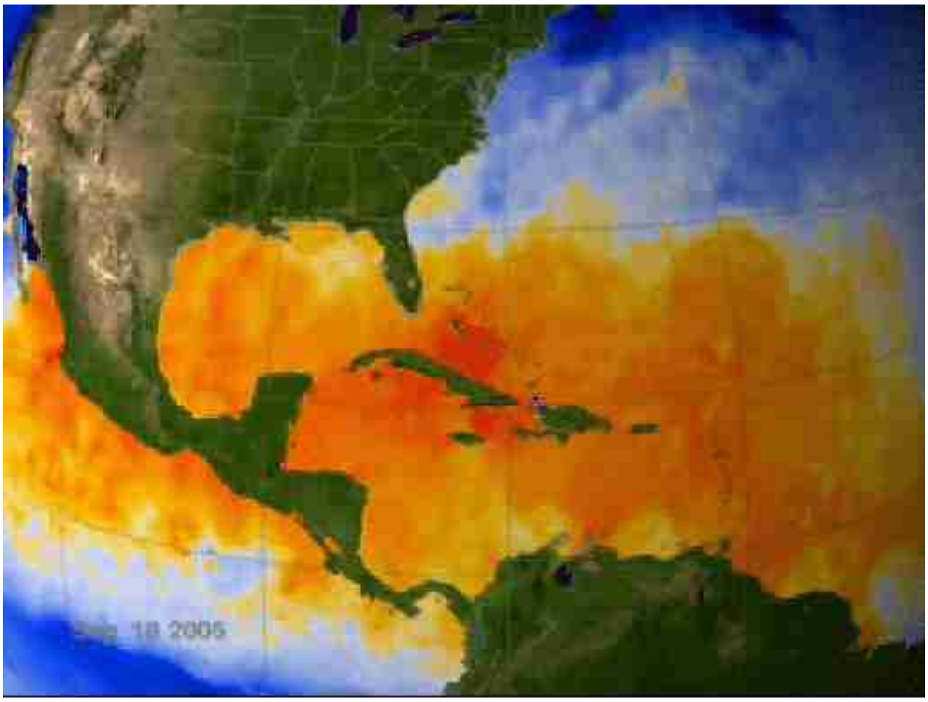

Figure 5: Every area in yellow, orange or red represents 82 degrees F or above. Note the cooler blue water left behind by hurricanes Dennis, Emily, and Katrina. The data came from the Advanced Microwave Scanning Radiometer (AMSR-E) instrument on NASA's Aqua satellite. (Dewitt, 2005)

Table 1: Barometric formula data (Wikipaedia, 2008)

Height x (m)	Density ρ_e (kgm^{-3})
0	1.225
11000	0.36391
20000	0.08803
32000	0.01322

Curve-fitted by a cubic polynomial
$\rho_e = 1.225 - 4 \times 10^{-14} x^3 + 4 \times 10^{-9} x^2 - 0.000x$ ($R^2 = 1$)

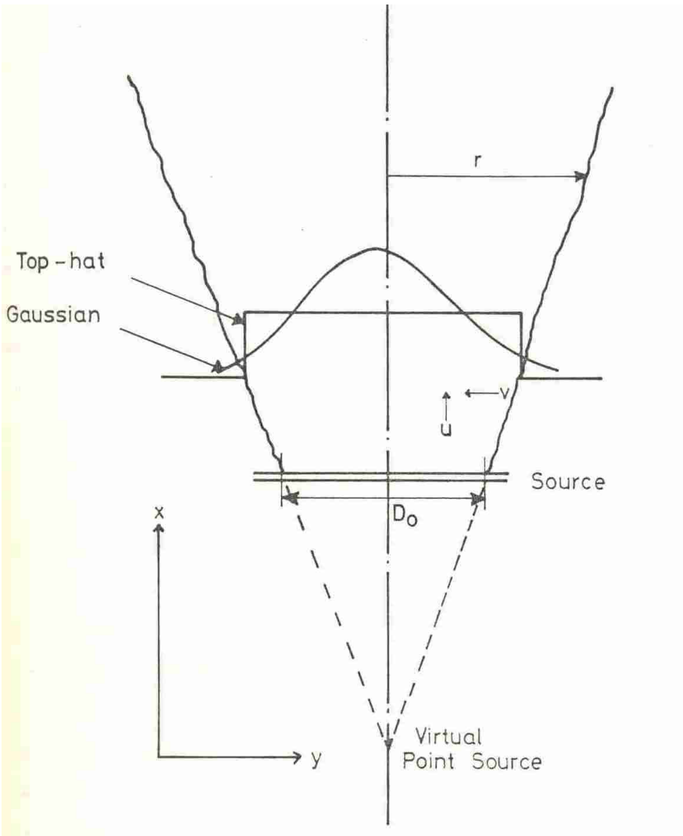

Figure 6: Top hat profile

4. NUMERICAL CALCULATIONS

The equations are solved numerically by marching-forward calculations at the conditions of: source diameter = 1000km, source temperature = 27°C, surrounding ambient air temperature = 15°C, and the axial velocity at source is merely 0.05 ms^{-1}. For the first 25 metres of height, the step size is 0.001m, then increased to 5m per step until 12.5km high. The reference density ρ_e is calculated from the barometric formula (Table 1; Wikipaedia, 2008).

The results are as expected, i.e. the plume necks at around 5km high, of the order of magnitude that the TRMM satellites have spotted of the 'Hot Towers' at 10-15km. The rising wind speed appears to reach over 200km/h, of similar magnitude as the large fire plume calculations by Nielsen and Tao (1965). Figures 7 to 10 display the diameter, velocity and buoyancy profiles of the plume versus height.

5. CONCLUSION

The hypothesis proposed here on the formation of Hot Towers by the natural convective mechanism of a large plume source that opens up an 'express highway' because of the inability of entrainment to drown out the rising warm air, appears to be supported by using a simple plume integral model on a dry basis, in a calm surrounding, to predict the tower height to be at 5 km by equating it to EPCH, the necking height in this case, and the rising wind speed reaching over 200 km/hr in the column. The converging plume behaves to a certain degree like a giant hardware chimney in the atmosphere up to the EPCH. The Hot Towers phenomenon should be observable though not visibly, but thermally, at the inception of a tropical cyclone, and should not be necessary to wait until the advanced stage of intensification.

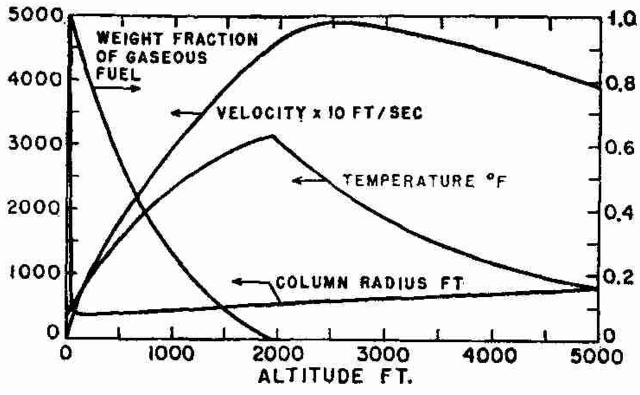

FIG. 3. Predicted variation with altitude of conditions within plume. Fuel gas generation rate, 0.0135 lb/ft^2 sec; gas temperature at ground, 350°F; ground radius of column, 5000 ft; entrainment coefficient, 0.17; atmosphere lapse rate, 0.005355°F/ft.

NOMENCLATURE

D_o	Dimension of plume at source	m
Fr	Froude number = $\frac{u_{co}^2}{D_o g\left(\frac{\rho_e-\rho}{\rho}\right)}$	(-)
g	Gravitational acceleration, 9.81	ms^{-1}
h_b	Bundle depth of a forced draft air-cooled heat exchanger	m
h_o	Effective plume-chimney height of a forced draft air-cooled heat exchanger	m
L	Horizontal plate breadth	m
r	Plume radius	m
T	Plume exit temperature	K
T_a	Ambient temperature	K
T_∞	Temperature at infinity from the square plate centreline	K
u	Plume axial velocity(vertical)	ms^{-1}
u_{co}	Centreline axial velocity at source	ms^{-1}
u_∞	Entrainment velocity at infinity from the square plate centreline	ms^{-1}
v	*Radial velocity of plume*	ms^{-1}
x	Axial length in vertical direction	m
y	Radial dimension of plume	m
α	Entrainment coefficient	(-)
λ	Ratio of velocity radius to density radius	(-)
ρ	Hot air density	kgm^{-3}
ρ_e	Ambient air density	kgm^{-3}
ρ_{e1}	Ambient air density at Reference point	kgm^{-3}
ΔT	Temperature difference between the exit and the ambient air	K

Subscripts

i	inlet
o	outlet

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