Dynamics and entrainment of plumes induced by fire sources

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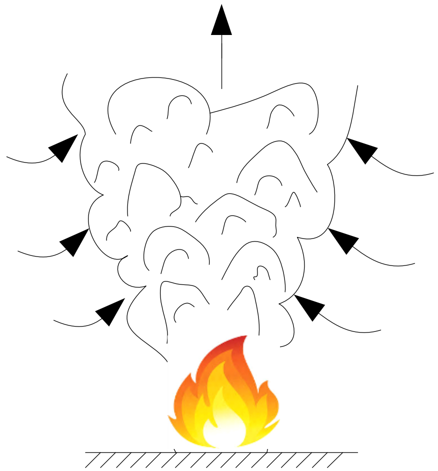
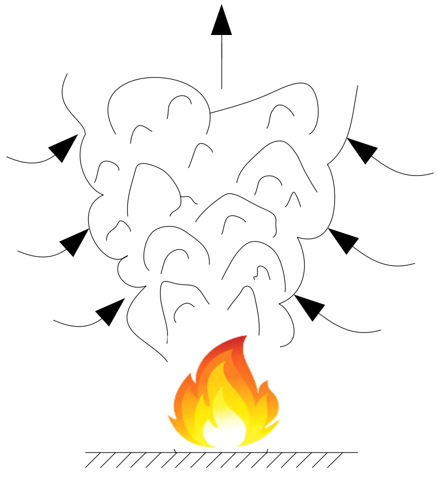
Visualization of the experimental plume

Equivalence between fire and densimetric plumes



$$\dot{H} = Q_s C_p \rho_s (T_s - T_{amb})$$

Equivalence between fire and densimetric plumes



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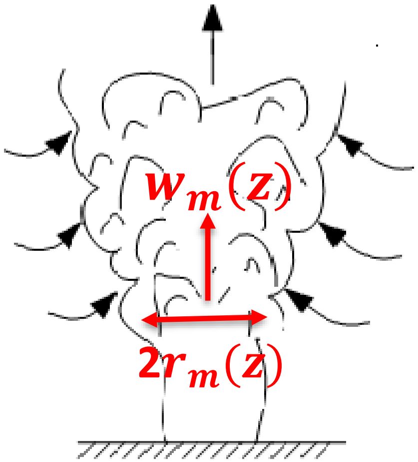


$$F = Q_s \frac{g(\rho_{amb} - \rho_s)}{\rho_{amb}}$$

- Assuming smoke acts as a perfect gas:

$$F = \frac{g}{\rho_{amb} T_{amb} C_p} \dot{H}$$

- The plume's dynamic is described in terms of integral quantities:

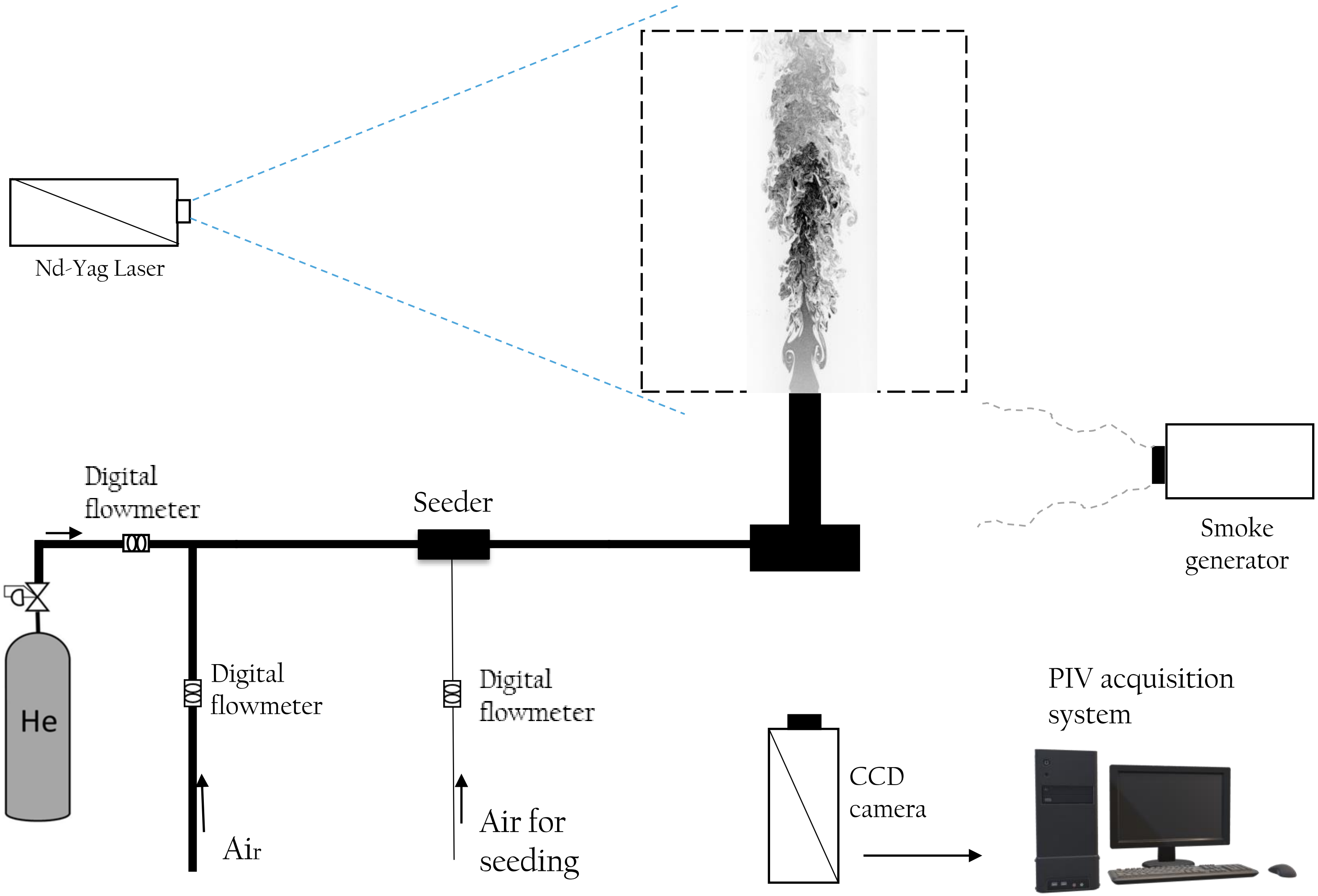
$$Q(z) \equiv 2\int_0^\infty \bar{w} r dr \qquad G(z) \equiv 2\int_0^\infty \bar{\rho}\bar{w} r dr \qquad M(z) \equiv 2\int_0^\infty \bar{w}^2 r dr \qquad F(z) \equiv 2\int_0^\infty \frac{g(\rho_{amb} - \bar{\rho})}{\rho_{amb}} \bar{w}\, r dr$$

$$r_m(z) = \frac{Q}{M^{1/2}} \qquad w_m(z) = \frac{M}{Q} \qquad \rho_m(z) = \frac{G}{Q}$$

Adimensional groups

- Scaled Richardson number : $\Gamma = K \frac{FQ^2}{M^{5/2}}$
  - $\Gamma = 0$ Pure jet
  - $\Gamma = 1$ Pure Plume
- Density Ratio: $R = \frac{\rho_s}{\rho_{amb}}$
  - $R > 0.8$ Boussineq
  - $R < 0.8$ Non Boussineq
- Reynolds number: $Re = \frac{2M_s^{1/2}}{\upsilon}$

PIV set-up

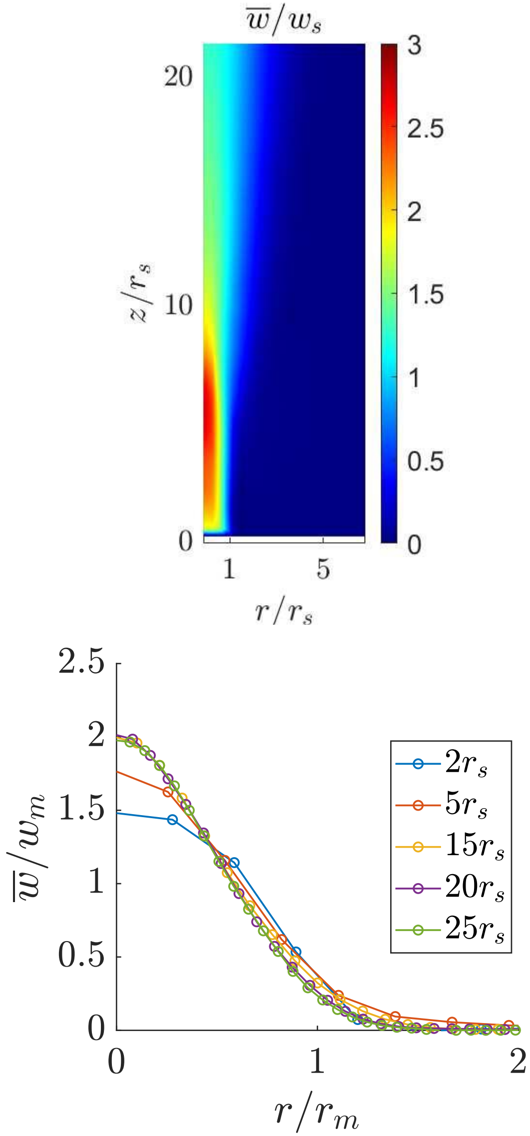

Nd-Yag Laser
Digital flowmeter
Seeder
Smoke generator
He
Digital flowmeter
Digital flowmeter
Air
Air for seeding
CCD camera
PIV acquisition system

Source conditions

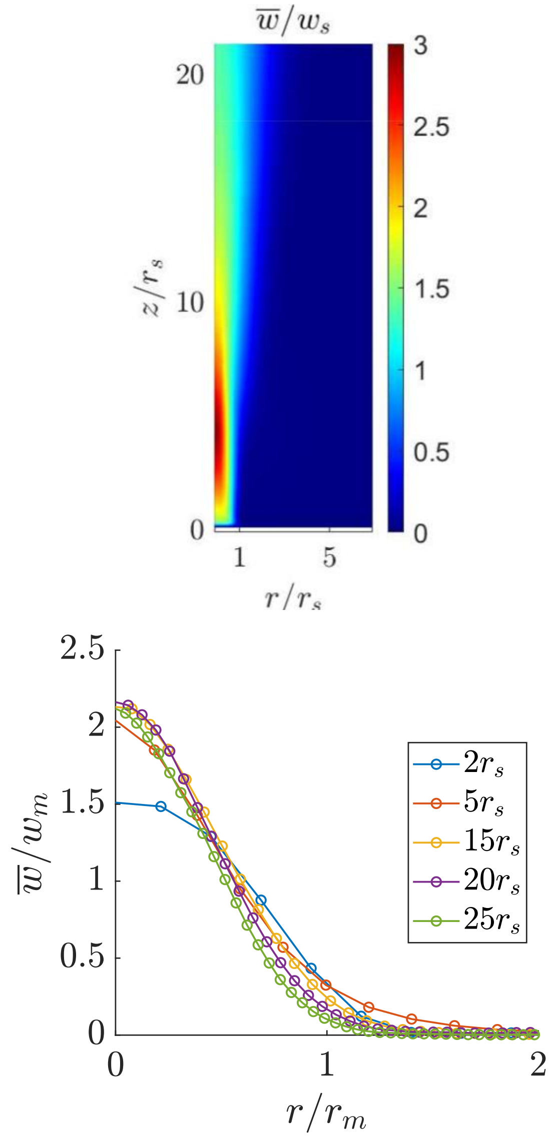
- 3 different test cases with **increasing** Reynolds number
- At the source, the plumes are **pure** (Γ=1) and non-Boussinesq (R=0.2).
- The helium molar fraction in the mixture is χ_{He}=0.93

	Plume 1	Plume 2	Plume3
Re	260	450	820
Γ	1	1	1
ρ_s/ρ_{amb}	0.2	0.2	0.2
Source diameter $D[cm]$	3.5	5	7.5
Exit velocity $U[m/s]$	0.82	0.98	1.2
Image field height	44.6	31.2	20.8
Number of recorded images	1400	1400	1400

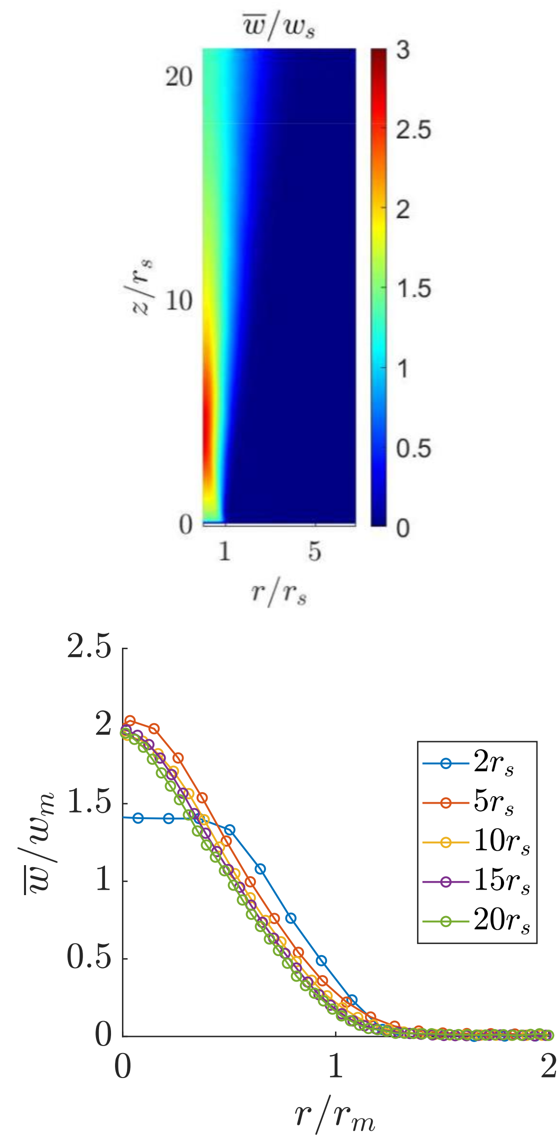
Mean vertical velocity



Re_{260}

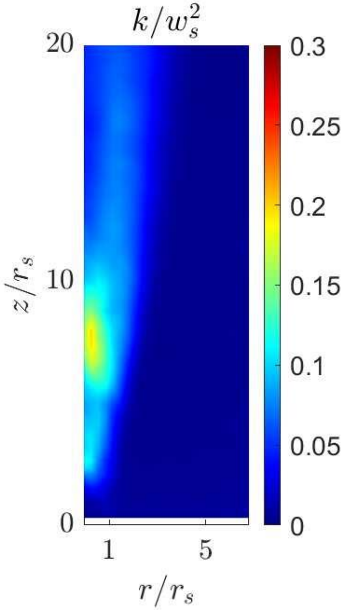


Re_{450}

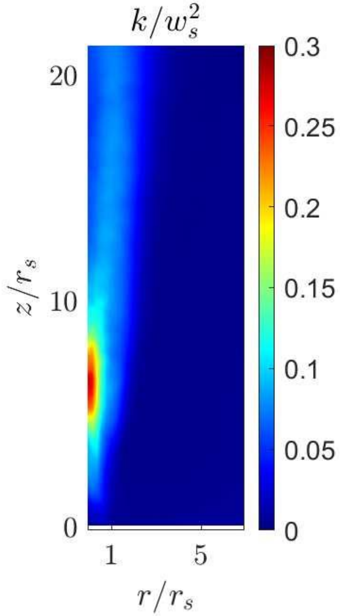


Re_{820}

Turbulent Kinetic Energy



Re_{260}



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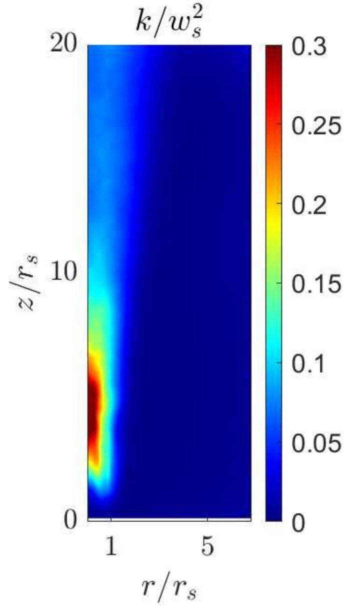

Re_{820}

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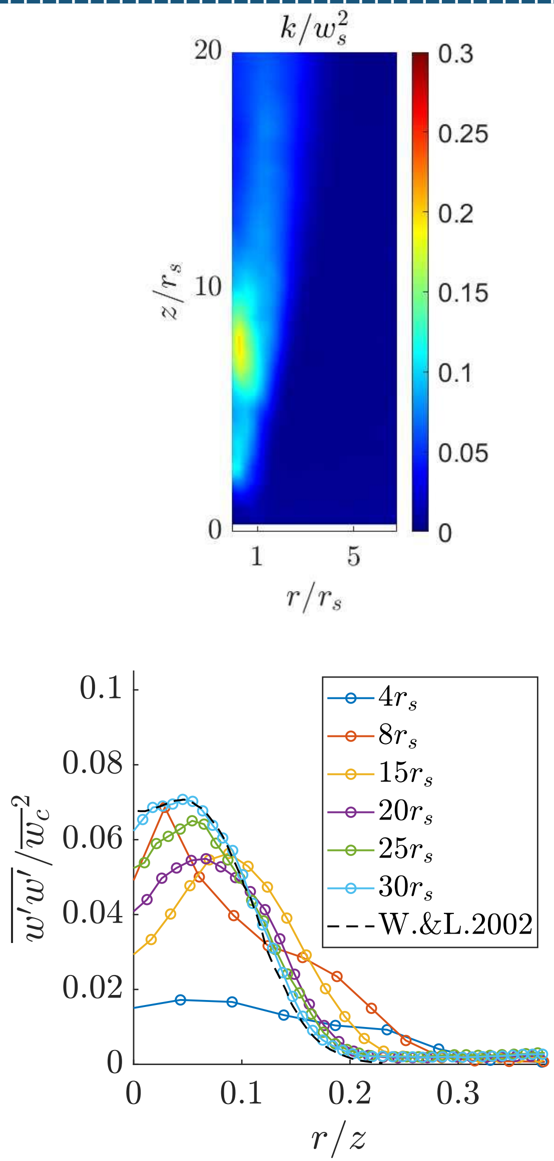
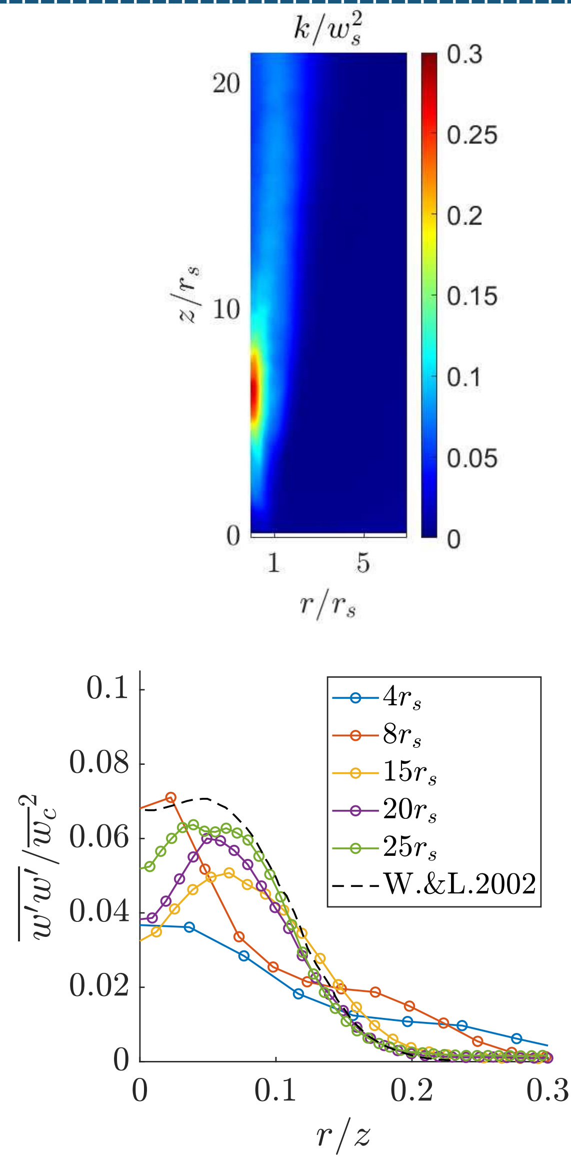
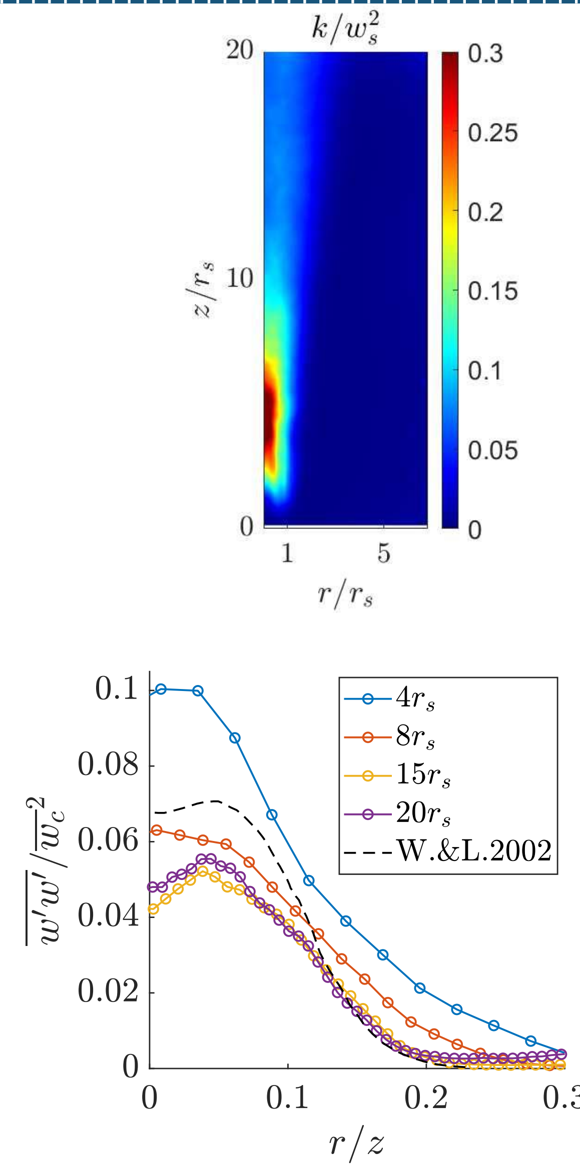


Re_{260}

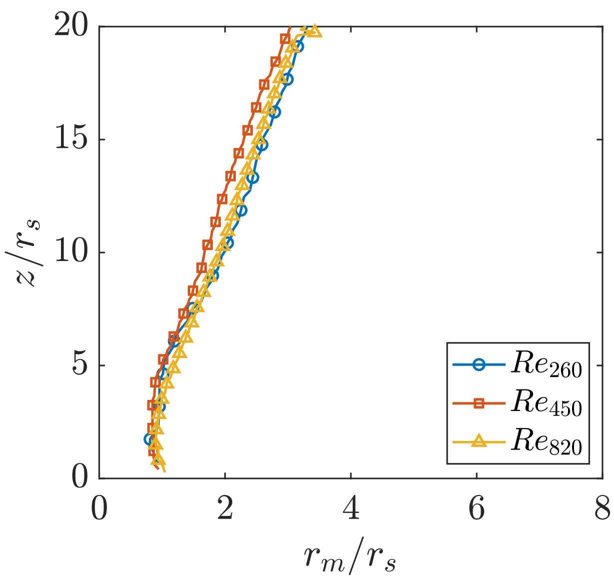


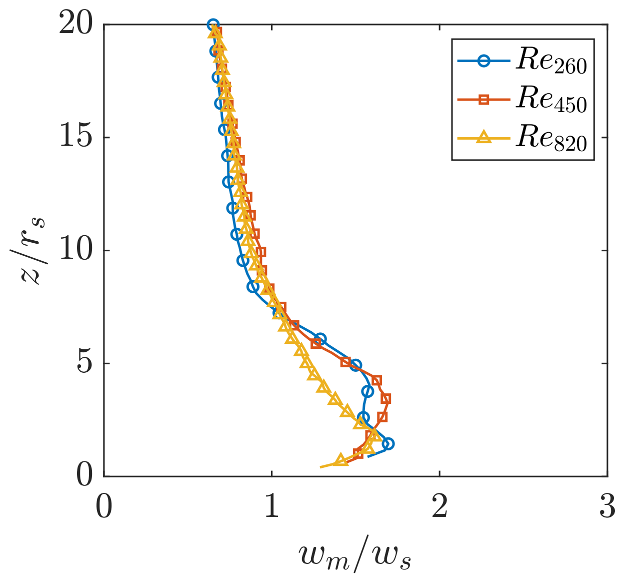
Re_{450}

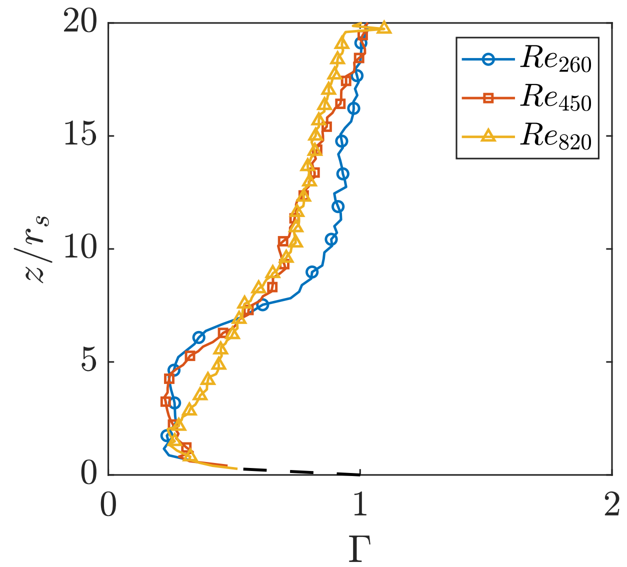


Re_{820}

Characteristic scales







$$r_m = \frac{Q}{M^{1/2}}$$

$$w_m = \frac{M}{Q}$$

$$\Gamma = K\frac{FQ^2}{M^{5/2}}$$

- Plume *necking* near the source, then linear spreading.
- Strong acceleration near the source, the plumes become *forced* and return asymptotically to the *pure plume* condition.

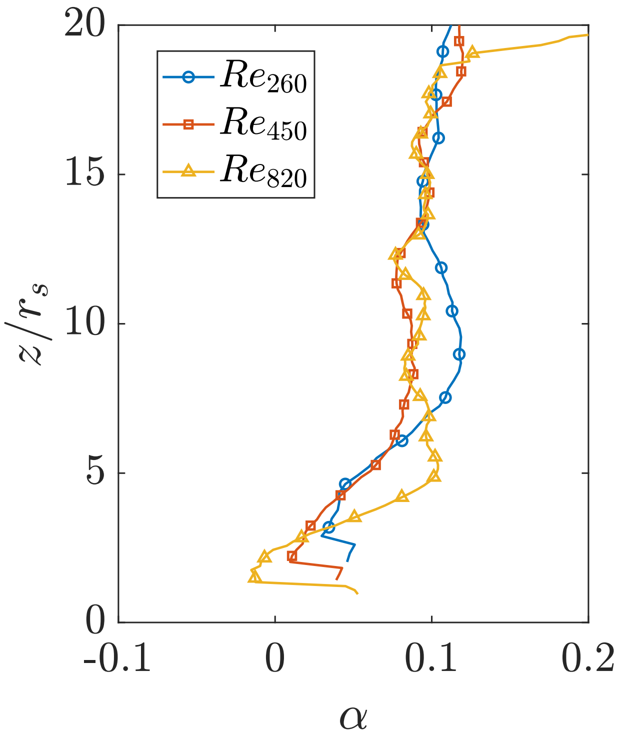
Entrainment coefficient

- As shown in *Viggiano et. al 2017* and *Salizzoni at al. 2022*, for non-Boussinesq jets, Reynolds statistics $(\bar{x})$ are equivalent to Favre statistics $\left(\tilde{x} = \frac{\overline{\rho x}}{\bar{\rho}}\right)$.

$$[r\bar{u}]_0^\infty + \int_0^\infty \frac{\partial}{\partial z}(\overline{w})rdr = 0$$

$$\alpha r_m w_m = -r_\infty u_\infty$$

$$\alpha = \frac{dQ}{dz}\frac{1}{2r_m w_m}$$



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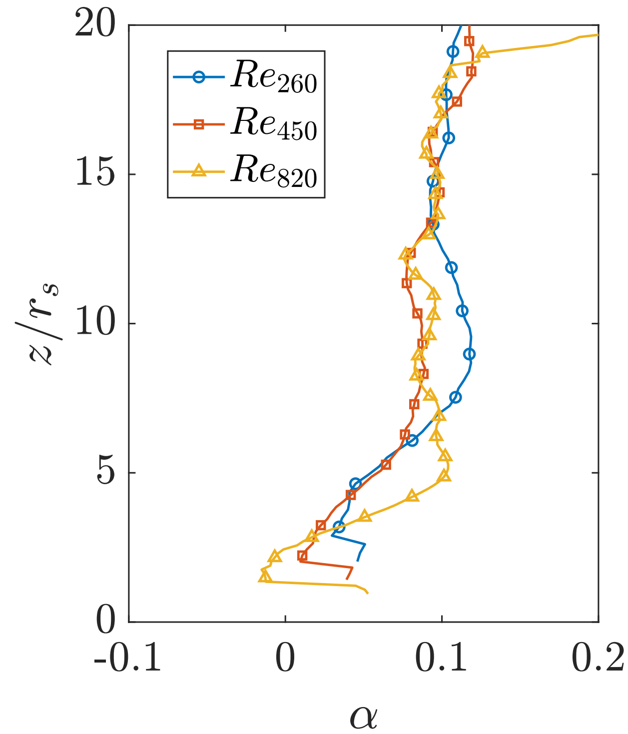
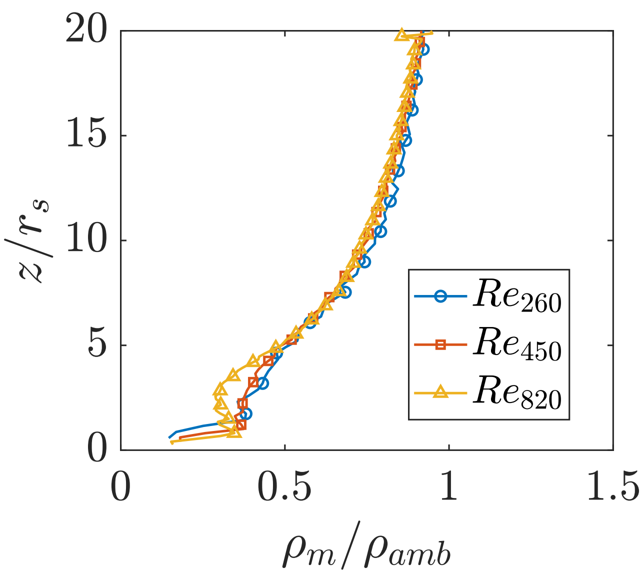


$$[r\bar{u}]_0^\infty + \int_0^\infty \frac{\partial}{\partial z}(\overline{w})rdr = 0$$

$$\alpha r_m w_m = -r_\infty u_\infty \qquad \alpha = \frac{dQ}{dz}\frac{1}{2r_m w_m}$$

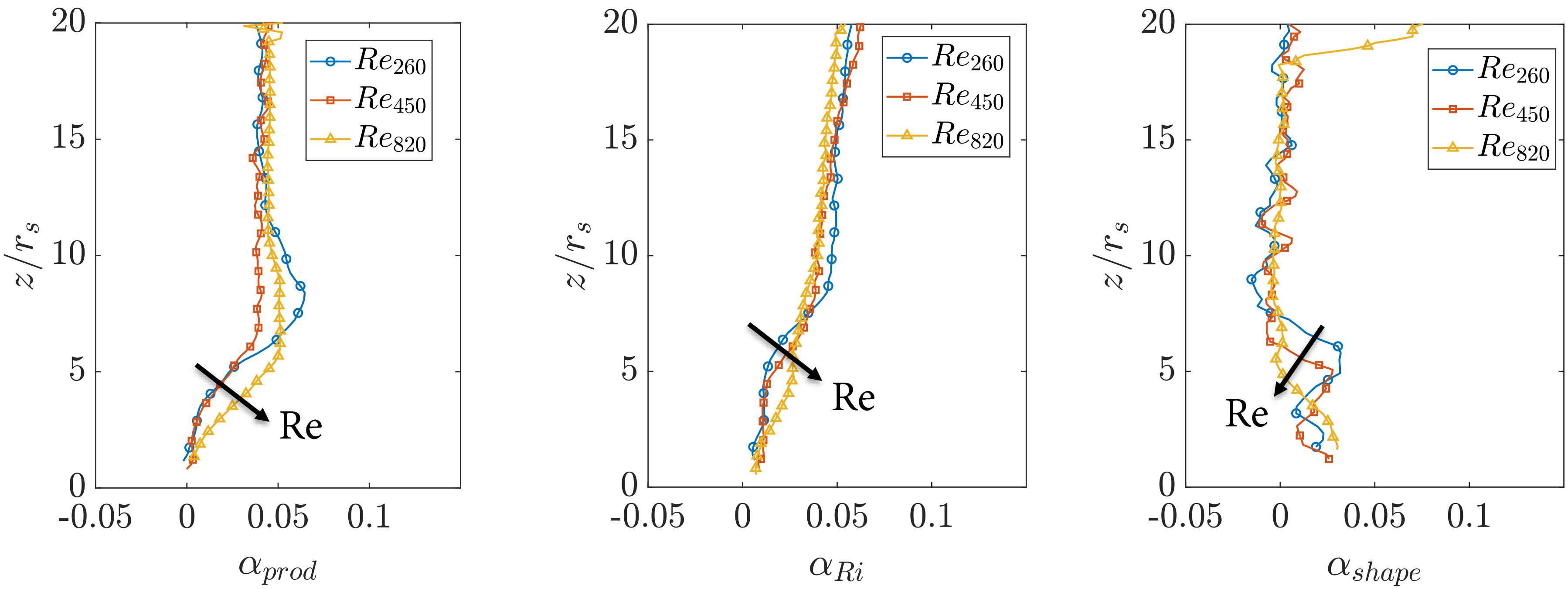


- Plugging the α value in the mass conservation equation, it's possible to reconstruct the characteristic density ratio $R = \frac{\rho_m}{\rho_{amb}}$.

Entrainment Relation

$$\alpha_E = \alpha_{prod} + \alpha_{Ri} + \alpha_{shape}$$

Van Reeuwijk, Craske 2015, JFM
Van Reeuwijk et al. 2016, PRFluids



$$\alpha_{prod} = -\frac{\delta_g}{2\gamma_g}$$

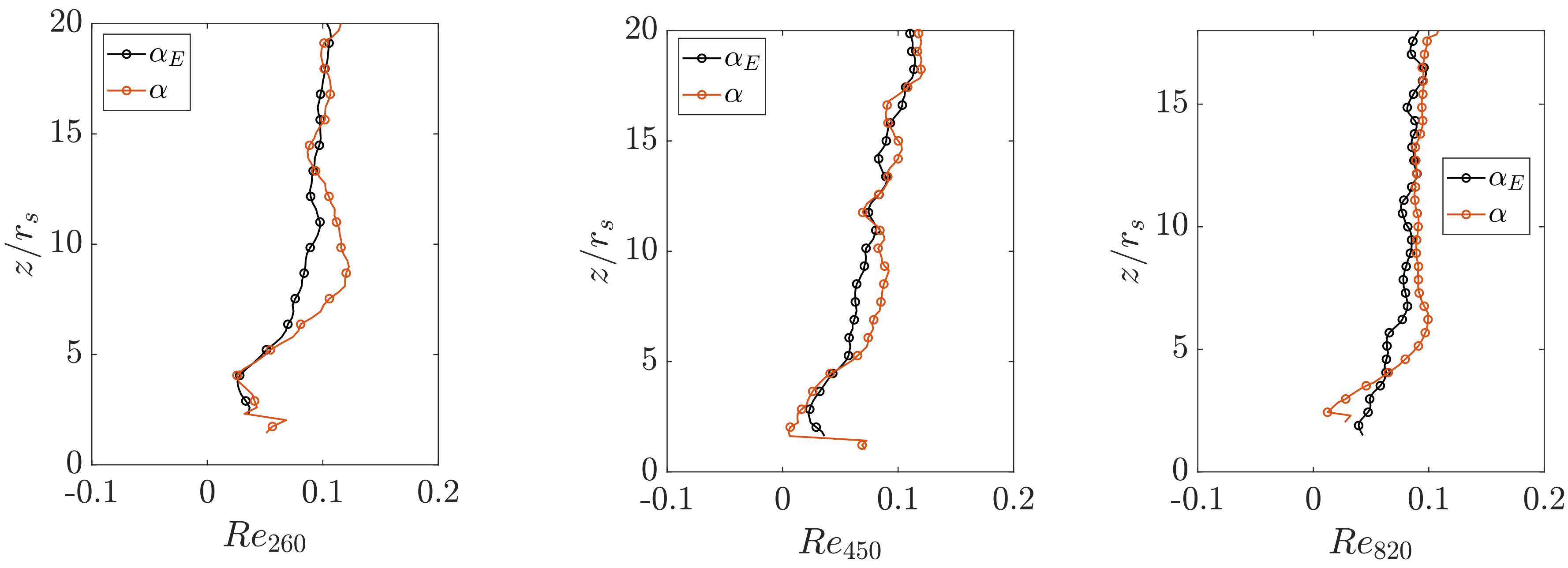
$$\alpha_{Ri} = \left(\frac{1}{\beta_g} - \frac{\theta_m}{\gamma_g}\right) Ri$$

$$\alpha_{shape} = \frac{Q}{2M^{1/2}} \frac{d}{dz}\left(\log\left(\frac{\gamma_g}{\beta_g^2}\right)\right)$$

Ex. Turbulent production terms

$$\delta_g = \delta_m + \delta_f + \delta_p = \frac{4}{w_m^3 r_m} \int_0^\infty \left(\overline{u'w'}\frac{d\overline{w}}{dr} + \overline{w'w'}\frac{d\overline{w}}{dz} + \overline{p}\frac{d\overline{w}}{dz} \right) r dr$$

Entrainment comparison



- Good agreement between α_E and α after $10r_s$
- The major discrepancies are in the near-source region, where density differences are relevant.

Conclusions and Perspectives

- PIV measurements on **highly** buoyant, **pure** plumes with **low** Reynolds numbers were carried out. Experimental analysis of these plumes is not present in the literature.

- The entrainment coefficient α is computed in **two different** ways with good agreement between the two estimations.

- Perspectives: repetition of the experiments with **simultaneous concentration and velocity measurements**. Repetition of the experiments with a fully turbulent condition at the source.

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- PIV measurements on **highly** buoyant, **pure** plumes with **low** Reynolds number were carried out. Experimental analysis of these plumes is not present in the literature.

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THANK YOU FOR THE ATTENTION

Possible fully turbulent condition at the source

Source diameter D[cm]	Exit velocity U[m/s]	Re	Γ	ρ_s/ρ_{amb}	He volume flux[m^3/s]
15	1.69	2300	1	0.2	0.0279

- With laboratory instruments , the maximum helium volume flux at the source is $0.0083[m^3/s]$
- The helium kinematic viscosity is larger than air one: $\frac{\upsilon_{He}}{\upsilon_{air}} = 7.7$
- To have an image field of 10 diameters, an image heigth of 1.5 m is required.

ρ_m reconstruction

- Reconstruction of the characteristic density scale relyng on the entrainment coefficient .

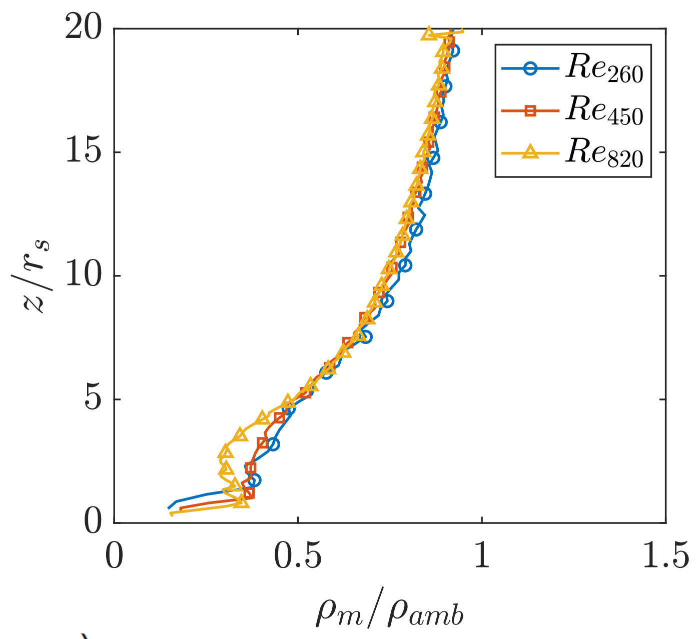
$$\frac{\partial \overline{\rho}}{\partial t} + \frac{\partial}{\partial z}(\overline{\rho w}) + \frac{1}{r}\frac{\partial}{\partial r}(r\overline{\rho u}) = 0$$

$$2\int_0^\infty \overline{\rho w} r\, dr = 2\int_0^\infty \overline{\rho}\, \overline{w} r\, dr + 2\int_0^\infty \overline{\rho' w'} r\, dr = \overline{G} + G'$$

$$(\overline{G(z)} + G'(z)) - (\overline{G(0)} + G'(0)) = \int_0^z 2\alpha \rho_a r_m w_m\, dz$$

$$\overline{G} \;=\; w_m \rho_m r_m^2$$

$$\rho_m(z) = \frac{1}{r_m^2 w_m}\left(\int_0^z 2\alpha\rho_a r_m w_m\, dz + (\overline{G(0)} + G'(0)) - G'(z)\right)$$



Governing equations

Equations for non-Boussinesq plumes

$$\frac{1}{r}\frac{\partial(r\overline{\rho}\widetilde{u})}{\partial r} + \frac{\partial\overline{\rho}\widetilde{w}}{\partial z} = 0$$

$$\frac{1}{r}\frac{\partial}{\partial r}(r(\overline{\rho}\widetilde{u}\widetilde{w} + r\overline{\rho}\widetilde{u''w''}) + \frac{\partial}{\partial z}(\overline{\rho}\widetilde{w}^2 + \overline{\rho}\widetilde{w''^2}) = -\frac{\partial\overline{p}}{\partial z} + \rho_a\overline{b}$$

$$\frac{1}{r}\frac{\partial}{\partial r}(r\widetilde{u}\ \overline{b} + r\widetilde{u''b''}) + \frac{\partial}{\partial z}(\widetilde{w}\ \overline{b} + \widetilde{w''b''}) = 0$$

Equations for Boussinesq plumes

$$\frac{1}{r}\frac{\partial(r\overline{u})}{\partial r} + \frac{\partial\overline{w}}{\partial z} = 0$$

$$\frac{1}{r}\frac{\partial}{\partial r}(r\overline{u}\ \overline{w} + r\overline{u'w'}) + \frac{\partial}{\partial z}(\overline{w}^2 + \overline{w'^2}) = -\frac{\partial\overline{p}}{\partial z} + \overline{b}$$

$$\frac{1}{r}\frac{\partial}{\partial r}(r\overline{u}\ \overline{b} + r\overline{u'b'}) + \frac{\partial}{\partial z}(\overline{w}\ \overline{b} + \overline{w'b'}) = -N^2\overline{w}$$

Governing equations

Profile coefficients with Reynolds statistics

$$\beta_m \equiv \frac{M}{w_m^2 r_m^2} \qquad \beta_f \equiv \frac{2}{w_m^2 r_m^2}\int_0^\infty \overline{w'^2}\, dr \qquad \beta_p \equiv \frac{2}{w_m^2 r_m^2}\int_0^\infty \overline{p} r\, dr$$

$$\gamma_m \equiv \frac{2}{w_m^3 r_m^2}\int_0^\infty \overline{w}^3 r\, dr \qquad \gamma_f \equiv \frac{4}{w_m^3 r_m^2}\int_0^\infty \overline{w}\ \overline{w'^2} r\, dr \qquad \gamma_p \equiv \frac{4}{w_m^3 r_m^2}\int_0^\infty \overline{w}\ \overline{p} r\, dr$$

$$\delta_m \equiv \frac{4}{w_m^3 r_m}\int_0^\infty \overline{w'u'}\frac{d\overline{w}}{dr} r\, dr \qquad \delta_f \equiv \frac{4}{w_m^3 r_m}\int_0^\infty \overline{w'^2}\frac{d\overline{w}}{dz} r\, dr \qquad \delta_p \equiv \frac{4}{w_m^3 r_m}\int_0^\infty \overline{p}\frac{d\overline{w}}{dz} r\, dr$$

$$\theta_m \equiv \frac{F}{w_m b_m r_m^2} \qquad \theta_f \equiv \frac{2}{w_m b_m r_m^2}\int_0^\infty \overline{w'b'} r\, dr$$

Integral equations

$$\frac{dQ}{dz} = 2\alpha M^{\frac{1}{2}}$$

$$\frac{d}{dz}(\beta_g M) = \frac{FQ}{\theta_m M}$$

$$\frac{d}{dz}(\frac{\theta_g}{\theta m} F) = 0$$

Farfield Solutions

	Jet	Plume
Γ	0	1
r_m	$2\alpha_j z$	$\frac{6}{5}\alpha_p z$
w_m	$\frac{M_0^{\frac{1}{2}}}{2\alpha_j} z^{-1}$	$\frac{5}{6\alpha_p}(\frac{9}{10}\frac{\alpha_p}{\theta_m \beta_g}F_0)^{\frac{1}{3}} z^{-\frac{1}{3}}$
b_m	$\frac{F_0}{2\alpha_j \theta_m} M_0^{-\frac{1}{2}} z^{-1}$	$\frac{5F_0}{9\alpha_p \theta_m}(\frac{9}{10}\frac{\alpha_p}{\theta_m \beta_g}F_0)^{\frac{1}{3}} z^{-\frac{5}{3}}$