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Fire plume in a two-layer stratified environment

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Highlights

- ▶ Numerical simulations of fire plumes impinging a two-layer stratified environment
- ▶ Theoretical model for trapping/escaping fire plume
- ▶ Simplified engineering correlation to evaluate the trapping height

Context and objectives

- ▶ In buildings, atria or large rooms, the inner environment is often stratified (e.g. approximated by two layers of air of different temperature)
- ▶ In case of fire, following the density of the plume at the interface, two possible situations :
 - if the plume density is larger than the upper layer density, the plume is trapped in the upper layer and behaves as a turbulent fountain (negatively buoyant plume) rising to a finite height \leadsto **trapping case**
 - otherwise, the plume rises indefinitely \leadsto **escaping case**
- ▶ To determine which of the two possible behaviours arises, it is necessary to determine a **separation criterion** for the plume trapping/escaping cases
- ▶ Configuration
 - Fire source : diameter D and heat release rate Q
 - Stratified environment :
 - ◊ lower layer depth H_l
 - ◊ densities ρ_l and ρ_u of the lower and upper layers (corresponding to temperatures T_l and T_u)
- ▶ When the fire plume is trapped, H_f represents the fire plume height above the interface.

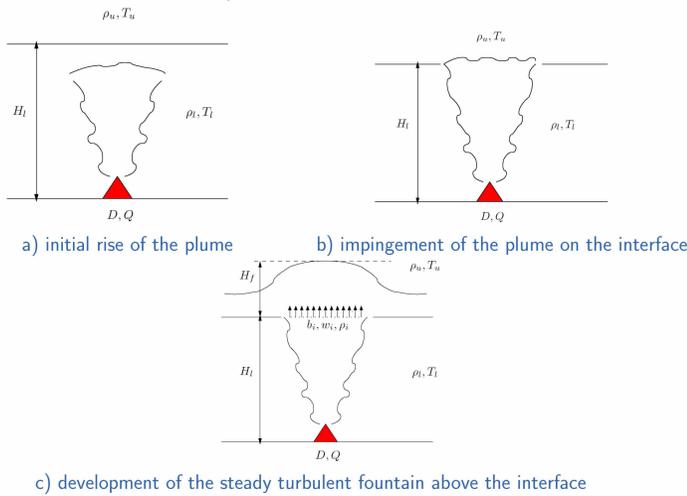


Figure 1 : Schematic of a fire plume developing in a two-layer stratified fluid showing three different stages

Theoretical model

Determination of the trapping/escaping criterion

- ▶ In the lower layer, following Morton (1965) [1], the fire plume variables, namely the radius b , the bulk velocity w and the bulk temperature can be written as follows:

$$b = C_1 \left(\frac{\rho_l}{\rho} \right)^{1/2} z, \quad (1)$$

$$w = C_2 F^{1/3} z^{-1/3}, \quad (2)$$

$$\eta = C_3 F^{2/3} z^{-5/3}, \quad (3)$$

where z is the vertical coordinate, $\eta = (\rho_l - \rho(z))/\rho(z) = (T(z) - T_l)/T_l$ is the density (or temperature) deficit, $\rho(z)$ is the *top-hat* plume density, $T(z)$ is the *top-hat* temperature, and F is the source buoyancy flux of the plume. The buoyancy flux F can be related to the convective heat flux Q_c of the fire source as :

$$F = \frac{g}{\rho_l T_l c_p} Q_c, \quad (4)$$

and the constants C_n are functions of the entrainment coefficient α

$$C_1 = \frac{6\alpha}{5}, \quad C_2 = \left(\frac{3}{4} \right)^{1/3} \left(\frac{6\alpha}{5} \right)^{-2/3} \left(\frac{1}{\pi} \right)^{1/3}, \quad C_3 = \frac{1}{g} \left(\frac{3}{4} \right)^{-1/3} \left(\frac{6\alpha}{5} \right)^{-4/3} \left(\frac{1}{\pi} \right)^{2/3} \quad (5)$$

- ▶ To observe a **trapped plume** above the interface, the density of the plume fluid must be greater than the upper layer density, i.e. $\rho(H_l) = \rho_i > \rho_u$. This simple condition leads us to :

$$\frac{\rho_l - \rho_u}{\rho_l - \rho_i} > 1, \quad (6)$$

and replacing ρ_i by its expression deduced from equation (3), one arrives at the following relations :

$$\begin{cases} \text{trapping case : } \Lambda > C_3 \\ \text{escaping case : } \Lambda < C_3 \end{cases} \quad \text{where} \quad \Lambda = \frac{\epsilon H_l^{5/3}}{1 - \epsilon F^{2/3}} \quad \text{and} \quad \epsilon = \frac{\rho_l - \rho_u}{\rho_l} \quad (7)$$

Theoretical model (continuation)

Determination of the plume height

- ▶ In case of **trapping**, in order estimate the height of the fire plume, we use some fundamental results on turbulent fountains, namely that the dimensionless fountain height (divided by the radius of its source) is governed by the source Froude number Fr
- ▶ In the present case, the fountain source is located at the interface with radius b_i , velocity w_i and density difference $(\rho_i - \rho_u)/\rho_u$:

$$Fr = \frac{w_i}{\left(\frac{g(\rho_i - \rho_u)}{\rho_u} b_i \right)^{1/2}}, \quad (8)$$

- ▶ Using the definition of the parameter Λ and the values of the primary variables b_i , w_i and η_i , the interfacial Froude number can be expressed as follows

$$Fr = \frac{C_2 C_3^{1/4}}{(g C_1)^{1/2}} \left[\frac{\epsilon}{\Lambda(1-\epsilon)} + \frac{1}{C_3} \right]^{1/4} [\Lambda - C_3]^{-1/2}. \quad (9)$$

- ▶ In the case of **forced fountains**, corresponding to $Fr > 3$, the fountain height scales as $H_f/b_i \propto (\rho_i/\rho_u)^{3/4} Fr$ (see [2]) and as $H_f/b_i \propto Fr^2$ for weak fountains (i.e. for $1 < Fr < 3$, see [3]).
- ▶ Replacing b_i and Fr by their respective expressions, we can obtain the fountain height as follows:

$$\frac{H_f}{H_l} \propto \frac{C_2 C_1^{1/2}}{g^{1/2}} (1-\epsilon)^{-3/4} (\Lambda - C_3)^{-1/2} \quad \text{for } Fr > 3, \quad (10)$$

$$\frac{H_f}{H_l} \propto \frac{C_2^2 C_3}{g} \left[\frac{\epsilon}{\Lambda(1-\epsilon)} + \frac{1}{C_3} \right] [\Lambda - C_3]^{-1} \quad \text{for } Fr < 3. \quad (11)$$

- ▶ In the case where the environment is slightly stratified, (i.e. $\epsilon \ll 1$), the leading orders of equations (10) and (11) can be expressed as follows

$$\frac{H_f}{H_l} \propto \frac{C_2 C_1^{1/2}}{g^{1/2}} (\Lambda - C_3)^{-1/2} + O(\epsilon) \quad \text{for } Fr > 3 \quad (12)$$

$$\frac{H_f}{H_l} \propto \frac{C_2^2}{g} [\Lambda - C_3]^{-1} + O(\epsilon) \quad \text{for } Fr < 3 \quad (13)$$

Numerical simulations and Results

- ▶ Twenty-eight simulations using CALIF³S-ISIS software
- ▶ Favre-averaged Navier-Stokes equations (mass and momentum balance) along with the heat transport equation are solved
- ▶ The fire has been modelled as a **volumetric source of heat** without a dedicated combustion model
- ▶ Space discretization : staggered grid with a cell-centred piecewise constant representation of the scalar variables and with a marker and cell (MAC) type finite volume approximation for the velocity
- ▶ Time discretization : a fractional step algorithm is used decoupling balance equations for the transport of energy and Navier-Stokes equations which are solved by a pressure correction technique
- ▶ Validation and suitability of the CALIF³S-ISIS software to properly evaluate the heights of non-Boussinesq turbulent fountains assessed on previous experimental/numerical works [4], [2]
- ▶ We clearly observe that the results of the simulations follow a **power-law** of the type:

$$H_f/H_l = 0.5(\Lambda - C_3)^{-1/2} \quad (14)$$

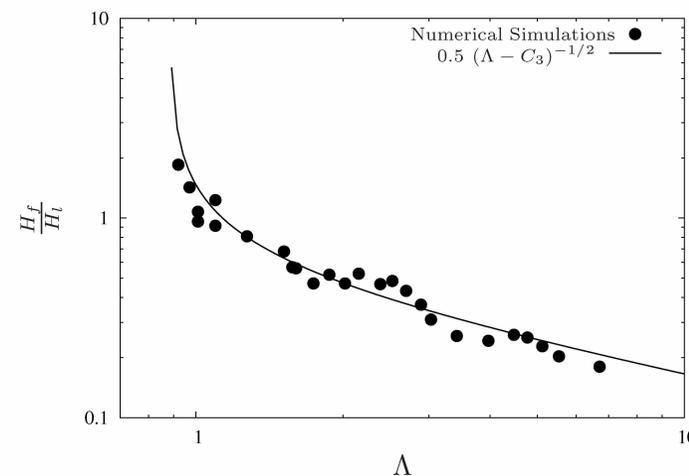


Figure 2 : Comparison between the present model and the numerical simulations made by CALIF³S-ISIS code

Numerical simulations and Results (continuation)

- ▶ For **practical fire safety engineering applications**, equation (14) can be remodelled, considering the heat capacity c_p as a constant, namely $c_p = 1000 \text{ J/(kg.K)}$, and the product $(\rho_l T_l)$ also as a constant (using the ideal gas law):

$$H_f/H_l = 0.5 \left(1090 \frac{T_u - T_l}{T_l} \frac{H_l^{5/3}}{Q_c^{2/3}} - 0.88 \right)^{-1/2} \quad (15)$$

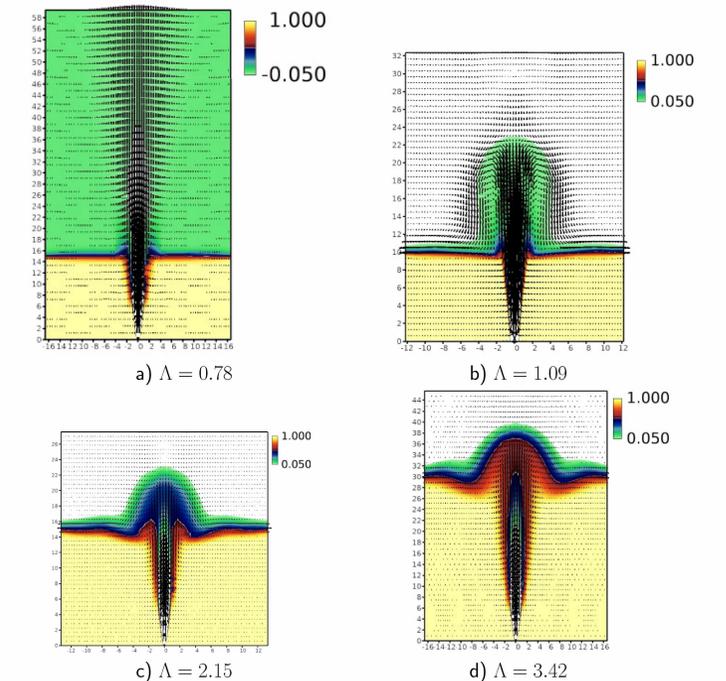


Figure 3: Visualization of the flow in the vertical median plane for four simulations corresponding respectively to increasing values of the stratification parameter Λ . The colour bar is scaled by the maximum level of the variable $\phi = (T_u - T)/(T_u - T_l)$ and the minimum level is set to $\phi = 0.05$ (which gives the approximate localization of the emerging fountain) for the trapping cases and $\phi = -0.05$ for the escaping case

Conclusions

- ▶ Excellent agreement between the theoretical estimate and the numerical data
- ▶ For practical purposes, we also propose a **simplified correlation** to estimate the height of the trapped plume as a function of the interface height, the temperatures of the layers and the fire heat release rate
- ▶ In large buildings, fire detectors located on ceilings cannot identify these situations and great care must be taken to fire detection in these configurations
- ▶ In the situation where the transition between the lower and upper layers may follow a different behaviour (e.g. smoother,...) \leadsto future work

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