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# A numerical study of interaction of laminar air plumes

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## Abstract

The interaction of two laminar air plumes is modelled numerically in this study. The focus here is on the effects of the intensity ratio and spacing between the two plume sources and the elevation of the plume sources above a plane surface on the inclination of the plumes as a result of the interaction. It is found that the weaker plume is affected by the interaction more than the stronger one, and thus forms a larger inclination angle from the upright position. Both the spacing between the plume sources and the elevation of the sources have a large impact on the interaction of the plumes, depending on the intensity ratio. The present numerical results are compared with previously reported experimental data.

## Introduction

A plume is a movement of fluid in an ambient of different thermo-physical properties. The energy that moves the plume is provided by positive or negative buoyancy force of the plume due to its different physical characteristics from the ambient fluid (e.g. different densities resulting from different temperatures or concentrations). While the plume propagates downstream, its extent grows as a result of entrainment of the ambient fluid. Plumes can be found in many domestic and industrial applications. A typical example of plumes is gaseous fluids expelled from chimneys or stacks, which are often used to discharge exhaust or pollutants. Due to their relevance to domestic and industrial systems, plumes have been the topic of research for many decades (see e.g. Morton et al. 1956; Turner 1962; Schorr & Gebhart 1970; Yang 1992; Moses et al. 1993; and Vatteville et al. 2009).

When two or more plume sources are placed next to each other, the ascending or descending plumes may interact with each other due to the restriction of the supply of entrainment fluid, and the interaction may result in different behaviour of the plumes from that of isolated plumes. In general, if the two heat sources are close enough, merging of two plumes takes place (refer to Pera & Gebhart 1975). The resultant plume may obtain stronger uplifting force as a result of the merging (Bornoff & Mokhtarzadeh-Dehghan 2001). This phenomenon improves the efficiency in terms of the discharge rate or heat exchange rate between the sources and the ambient fluid. A survey of the literature indicates that the interaction of plumes has not received much attention although early studies of this topic dated back to the 1970's (e.g. Pera & Gebhart 1975; Gebhart et al. 1976; Anfossi et al. 1978). The limited investigations of plume interactions are mainly based on experimental observations and measurements, and most of them are concerned with turbulent plumes (e.g. Brahimi & Son 1985).

Pera & Gebhart (1975) carried out a series of experiments to observe and quantify the interaction of two laminar plumes and the interaction between a plume and a plane surface using a Mach-Zehnder interferometer. They reported detailed results regarding the inclination angles of the plumes due to the interaction. To the best of the authors' knowledge of the open literature, there has been no numerical investigation of the interaction of laminar plumes corresponding to the experiment of Pera & Gebhart (1975). The present study will fill the gap. Here, the interaction of two laminar air plumes is modelled numerically. Both two- and three-dimensional simulations are carried out, and the results are compared with the reported experimental data.

## Numerical Details

Figure 1 shows a schematic of the two-dimensional (2D) computational domain adopted in this study, the dimensions of which are chosen to be the same as the physical model used by Pera & Gebhart (1975). The box is 69-cm wide and 84-cm high with all boundaries assumed rigid and adiabatic. The heat sources are square in shape with 1.9-mm sides located at a distance $h$ above the bottom surface. The spacing between the two heat sources is $2s$. Other configurations of the computational domain and plume sources as well as different boundary conditions for the box are currently being tested, and the results will be reported at the conference. The working fluid is air. Initially the air is stationary at a uniform temperature of 20°C. At the start of each numerical experiment, heat fluxes are imposed on the external surfaces of the two source elements and maintained constant throughout each experiment. The maximum heat flux applied in the numerical model is determined according to the maximum heat flux adopted in the experiment of Pera & Gebhart (1975), which was 73 W/m.

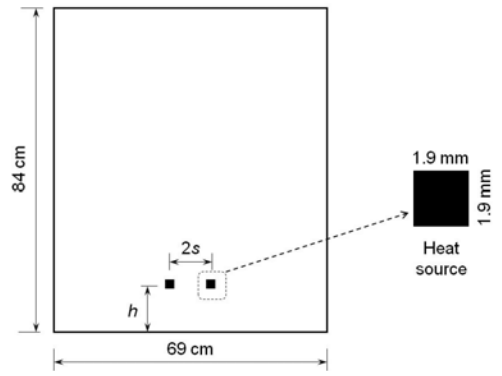



Figure 1. Schematic of the computational domain.

The subsequent development of the thermal flow is governed by the usual continuity, momentum and energy equations. The governing equations are solved implicitly on a non-uniform structured mesh using a finite volume code. All second derivatives and linear first derivatives are approximated using a second-order central difference scheme. The advection terms are discretized using a second order upwind scheme. The time integration is by a first-order implicit scheme, and the pressure-velocity coupling is carried out using the SIMPLE scheme. The discretized equations are iterated with under-relaxation factors.

Mesh and time-step dependence tests are conducted in order to determine the optimum mesh and time-step for the simulations.

For these tests, we consider a case with two heat sources of equal intensities located at 9 cm above the bottom and separated by a distance of 8.52 cm. Three different meshes (coarse, medium and fine meshes) are constructed with a total of 20, 28 and 40 elements respectively evenly distributed over each of the heat sources. The corresponding time-steps are chosen to be 0.02 s, 0.015 s and 0.01 s respectively to ensure the Courant-Freidrich-Lewy (CFL) number remains approximately the same for the three meshes. It is found that the three meshes and time-steps produce very similar results with negligibly small variations. Accordingly, the coarsest mesh with a time-step of 0.02 s is adopted for the calculations with two heat sources of various intensity ratios. The meshes for other configurations with different source spacings and elevations of the plume sources are constructed in a similar way to ensure enough grid resolution in the regions of interest.

## Numerical Results

Starting plumes subject to plume-plume interaction are considered in this study. We focus on the inclination of the plumes at various intensity ratios, source separations and elevations from the bottom. When varying the intensity ratio, the heat flux of one source element is maintained at the maximum intensity and that of the other source element is varied over a range of intensities. The calculated parameters are summarized in Table 1 below.

| **Parameter** | **Calculated values** |
|---|---|
| Source spacing (2*s*) | 2.84 cm, 5.68 cm, 8.52 cm |
| Source elevation (*h*) | 3 cm, 6 cm, 9 cm |
| Source intensity ratio (IR) | 0.04, 0.15, 0.45, 1.0 |

Table 1. List of calculated parameter settings

Previous experiment (Pera & Gebhart 1975) has demonstrated that, when two heat sources of different intensities are placed close to each other, the plume arising from the stronger source is less affected by the presence of the weaker plume, whereas the weaker plume is drawn towards the stronger plume as a result of the interaction between the two plumes. This is confirmed by the present numerical simulation (refer to the example shown in figure 2). In the case shown in figure 2, the intensity ratio is very small (0.04), and the stronger plume is almost unaffected by the presence of the weaker plume, whereas the weaker plume is strongly influenced by the presence of the stronger one. This happens because the entrainment by the stronger plume is much stronger than that by the weaker plume. The inclination angle of the weaker plume measured from the upright position is obtained from the numerical data, as illustrated in figure 2.

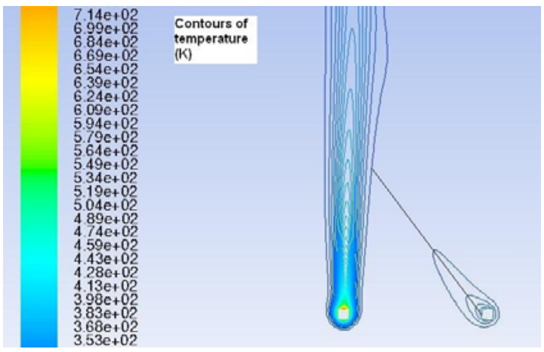



Figure 2. Isotherms showing the interaction of a strong plume with a weaker plume (spacing = 2.84 cm, elevation = 6 cm, intensity ratio = 0.04 and the time is 2 seconds after initiation of heating).

In our simulations, we noticed that the inclination angles of the interacting plumes generally increase with time at the early stage (before they merge). The merging height depends on the spacing between the two plume sources. After merging, the two interacting plumes form into a single plume, and the inclination angle of the weaker plume continues to increase and may oscillate at a later stage (refer to figure 6). Pera & Gebhart (1975) reported that it is not a simple matter to achieve steady plume flows. They further commented that the relatively weak plume flows may be affected by even very small disturbances in the laboratory.

For meaningful comparisons of the inclination angles under different parameter settings, here we consider the inclination angles of the weaker plume at a fixed time of 5 s after the initiation of heating. Figure 3 plots the measured inclination angles of the weaker plume over a range of parameter settings. It is seen in figure 3 that, as the intensity ratio decreases, the inclination angle of the weaker plume increases, confirming that the weaker plume is affected by the plume interaction more than the stronger one. The inclination angle of the plume varies between 10.2° to 12.8° at the intensity ratio of 1 and between 38.3° to 71.1° at the intensity ratio of 0.04, depending on the spacing between the heat sources and the elevation of the sources. In general, the inclination angle increases while the spacing decreases. Furthermore, the closer the plume sources are located from the rigid wall, the larger the inclination angle.

The overall results in figure 3 suggest that the plume interaction is stronger and the inclination angle of the weaker plume is larger when the supply of entrainment fluid is more restricted, which agreed with the observation of Pera & Gebhart (1975).

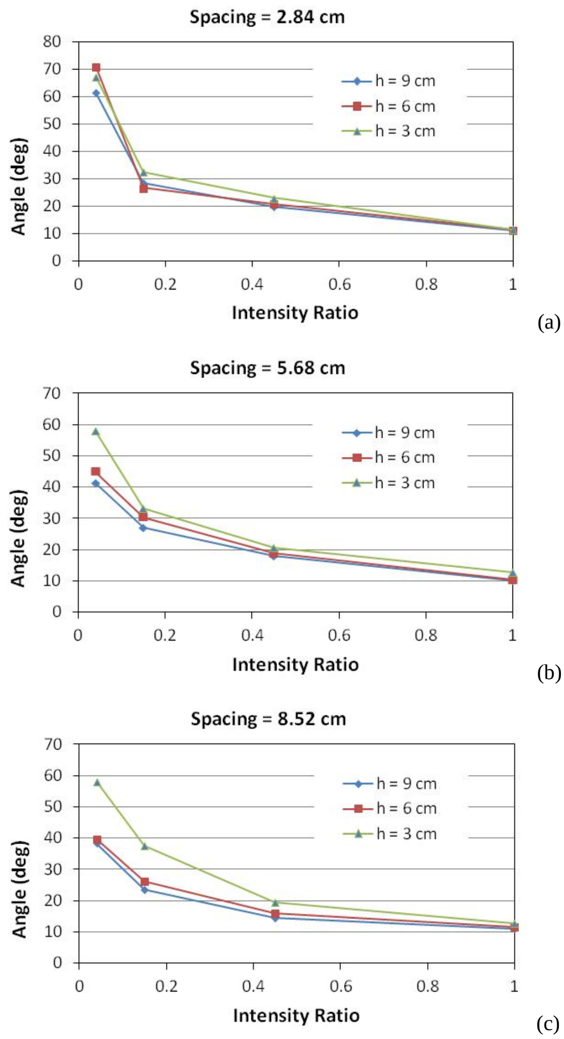



Figure 3. Inclination angle of the weaker plume.

Figure 4 shows the results of the upward mass flux calculated along a horizontal line at a location of 1 cm above two heat sources of equal intensities (both are maintained at the maximum heat flux). It is clear in this figure that, as the source elevation increases and the spacing decreases, the upward mass flux increases. Comparisons between the mass fluxes of the two interacting plumes and those of two single plumes indicate that the upward mass flux is enhanced significantly as a result of the plume interaction.

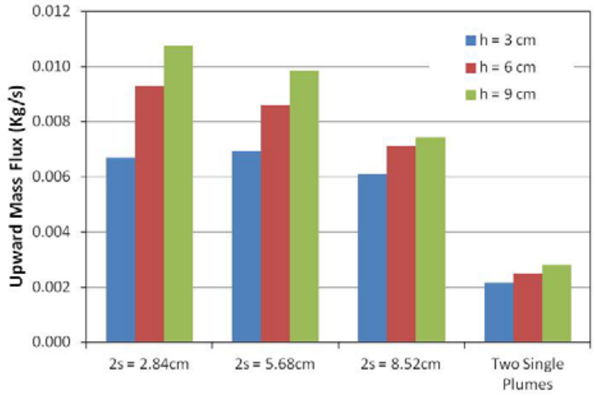
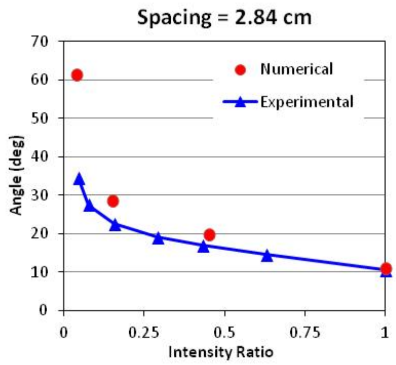
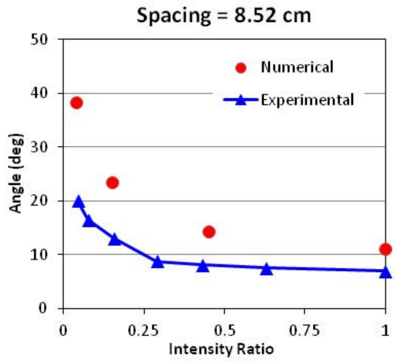



Figure 4. Calculated upward mass flux along a horizontal line at 1 cm above two heat sources of equal intensities.




(a)




(b)

Figure 5. Comparison between experimental and numerical data of the inclination angles at various intensity ratios and two spacings. The experimental data was reproduced from Pera & Gebhart (1975), and the numerical data is obtained with a source elevation $h$ = 9 cm at 5 s from the onset of plumes.

### Comparison between Simulation and Experiment

The present numerical results are compared with the experimental measurement of Pera & Gebhart (1975) in figure 5. It is seen in this figure that, despite that both experimental and numerical results show the same trends of the variation of the inclination angle with the intensity ratio, the discrepancies between the experimental and numerical data are significant. The comparison is even worse at lower intensity ratios. This is partly because at low intensity ratios the weaker plume is very weak and unstable, making it difficult to measure its inclination angle accurately. It is also noticeable in figure 5 that the discrepancies between the experimental and numerical data manifest further at the larger separation (8.52 cm) of the two plumes.

### Discussion

As noted above, the variations between the numerical and experimental data are quite significant, especially at small intensity ratios and large source spacing between the two plumes. These variations may be at least in part attributed to the uncertainties of the experimental data. Since the experimental uncertainties were not properly documented in Pera & Gebhart (1975), here we focus on factors arising from the numerical modelling that may have contributed to the discrepancies between the experimental and numerical data.

#### Numerical Model Uncertainty

Pera & Gebhart (1975) carried out their experimental visualization and measurements of plume interaction 'in a large isolated enclosure'. However, it is unclear whether the enclosure was fully sealed or not. If it was partly open, it is unclear which side was left open. In the present numerical model, we assume the plumes are contained in a fully enclosed box of the same dimensions as the enclosure used in the aforementioned experiment, and all the surfaces of the enclosed box are adiabatic. This configuration will apparently cause the average temperature inside the enclosure to increase continuously over time. As such, all the simulations are run only for a relative short period of time (up to 10 s).

In the experiment of Pera & Gebhart (1975), electrically heated nichrome wires of circular cross-sections were used as the plume sources. The wires were extremely fine with a diameter of only 0.25 mm. The maximum heating capacity of these wires was reported to be 73.0 W/m. Replicating precisely the experimental setup in the numerical model proves to be difficult, especially with regard to meshing near such fine heat sources. In the present numerical model, we adopt heat sources of a square shaped cross-section for easy meshing. The dimensions of the heat sources and the heat flux conditions specified at the surfaces of the heat sources are determined so that the same maximum heating capacity of 73.0 W/m is achieved as per the experiment. It is worth noting that the cross-section of the heat sources adopted here is 1.9 mm×1.9 mm, which is significantly larger than the cross-section of the nichrome wires used in the experiment. Accordingly, the maximum surface heat flux in the numerical model is approximately one order of magnitude smaller than that estimated from the experimental parameter. The impact of these variations between the experimental and numerical models on the comparison of the calculated and measured inclination angles of the plumes is unclear.

#### Unsteadiness

It is observed in the present investigation that the numerically obtained inclination angle of the weaker plume increases with time at the early stage and fluctuates at the later stage. A typical set of results is shown in figure 6 below. It is also worth mentioning that the stronger plume and the single plume forming from the merging plumes also exhibits oscillatory behaviour at the later stage. These oscillations make it difficult to measure the inclination angle of the plumes accurately. The oscillatory behaviour was not reported in the experiment of Pera & Gebhart (1975), and it is unclear at what stage or time their reported inclination angles were measured. Further investigations are currently underway to determine the mechanisms responsible for and the characteristics of the plume oscillations.

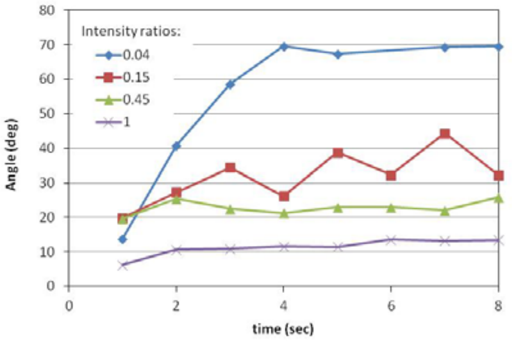



Figure 6. Time variations of the inclination angle of the weaker plume obtained at a source spacing of 2.84 cm and a source elevation of 3 cm.

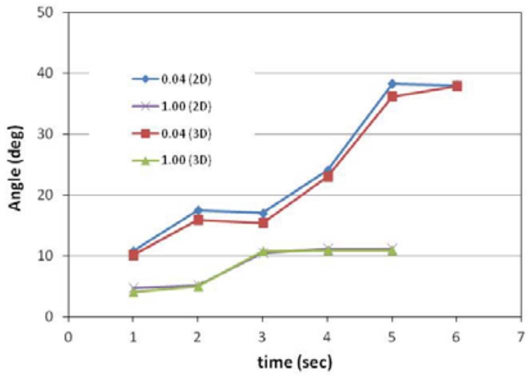



Figure 7. Comparison between the results obtained with two- and three-dimensional models (source spacing 8.52 cm, source elevation 9 cm).

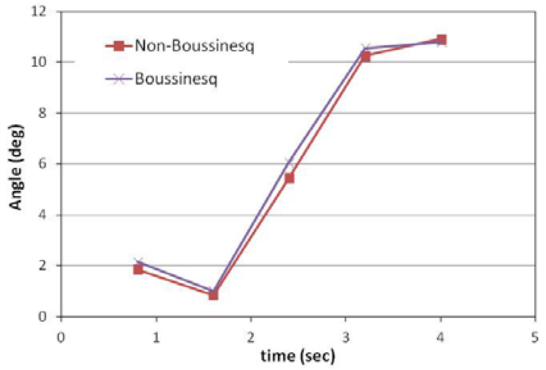



Figure 8. Comparison between the results obtained with and without Boussinesq assumption (source spacing 8.52 cm, source elevation 9 cm and source intensity ratio 1.0).

## Three-Dimensional Effect

The above comparisons between experimental and numerical data are based on two-dimensional simulations. Despite the experimental measurement of the inclination angle assumed two-dimensional structures of the plumes (Pera & Gebhart 1975), the actual physical experiment was three-dimensional. In order to determine the possible effect of three-dimensionality on the inclination angle of the plumes, full three-dimensional simulations are carried out for two cases and the results are compared with the corresponding two-dimensional results in figure 7. In these simulations, rigid no-slip and adiabatic wall conditions are specified on the spanwise end planes. It is seen in figure 7 that the variation between the two- and three-dimensional results is very small, especially at the higher intensity ratio.

## Boussinesq Assumption

All of the numerical results reported above are obtained with Boussinesq assumption in the numerical model. Given that the temperature rise in the system is in fact very large (refer to figure 2), in particular in the region close to the plume sources, it is useful to determine what impact the Boussinesq assumption has on the numerical results. Accordingly, a two-dimensional model without Boussinesq assumption is calculated. In this model, it is assumed that the variation of the air density is governed by the ideal gas law; its viscosity follows the Sutherland Law; and its thermal conductivity is a polynomial function of the absolute temperature. Figure 8 compares the results obtained with and without Boussinesq assumption. Clearly the variation between the two models is negligibly small.

## Conclusions

The interaction of two laminar air plumes is investigated numerically. The effects of the intensity ratio, the spacing between the plume sources and the elevation of the plume sources above a rigid plane surface on the inclination of the weaker plume and the upward mass flux are presented. It is found that the inclination angle increases with the reduction of the intensity ratio, and a smaller spacing between the sources results in a larger inclination angle. The effect of the source elevation on the inclination angle is not significant at large intensity ratios, but becomes more significant at small intensity ratios. As a result of the plume interaction, the upward mass flux is enhanced significantly compared to that for single plumes.

The comparison of the present numerical data with previously reported experimental measurements shows significant variations, particularly at small intensity ratios. Despite various tests have been conducted in order to identify the causes of the discrepancies, the present results are inconclusive. Further investigations are currently underway to clarify the matter.

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