Chimney plumes simulation in the boundary layer wind tunnel

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Abstract

In the BLWT operated by Aeronautical Research and Test Institute/Czech Technical University a set of experiments with plume diffusion within near field has been carried out in a simulated atmospheric wind above a terrain of mild roughness at neutral thermal conditions. Mean concentration fields behind ground and elevated point sources were investigated as preparing for later case studies. Centrelines of four chimney plumes with different values of buoyancy and momentum ratio, as well as peak concentrations drop follow the power laws. Lateral and vertical spread of the plumes also approaches the atmospheric data. Finally, a response of concentration field to boundary layer Re-number was tested.

1 Introduction

In general, a wind tunnel of proper design with long working section is to be capable of giving a good experimental solution of any transfer process coming true in atmospheric surface layer. Gas pollutants diffusion is perhaps an ambitious but certainly not a doubtful or recent BLWT application. Realization and precision of the experiments depend on: 1. Simulation of wind structure with respect to terrain type and model scaling, 2. Instrumentation with traced gas source and detection of samples, 3. Model of terrain and/or objects manufactured with high precision, and 4. Compliance with relevant similarity conditions. Introduced experiments were to verify capability of the gas dispersion modelling under the simplest boundary conditions, in the phase.
2 Wind tunnel and the boundary layer simulation

Boundary layer wind tunnel ARTI/CTU operates with air returning from a hall of volume about $10^4$ m$^3$. The working part is of $1.5 \times 1.8$ m cross-section and of 15.6 m in length with adjustable ceiling and pressure monitoring. 55 kW DC motor powers the fan situated behind. There are 40 m$^2$ dust filter; vane straightener, contraction and screen with 0.3 mm mesh in entry part. Step controlled probe traversing and turntable are found in a section for model testing creating 2 m long end of the working part.

During the wind loading tests the simulation hardware was developed step by step yielding an equilibrium boundary layer with wind properties above three terrain types of different roughness. Its velocity profiles and turbulent characteristics approach those of atmospheric surface layer at good planar homogeneity. A roughness parameter with integral length scale as they are indicated on model determine a scaling factor provided that the integral length follows the Counihan distribution in atmosphere, used in ENV 1991 code [1].

Flow simulation above suburb terrain was applied at the plumes modelling. It was generated by 12.5 m fetch of roughness field (folio with 7 mm high conical protrusions) and 0.12 m trip board positioned in front of it. The flow had been closely tested before with scope on low velocity range [2]. The roughness parameter $z_0=0.42$ mm and $L_{u,x}=0.393$ m both indicated at reduced free stream velocity $U_\infty=1$ m/s (index $\alpha=0.16$ at power law fit) yield the scaling of 1:462. Profiles of mean velocity $U$, turbulence intensity $I_u$ and integral length scale $L_{u,x}$ in centre of the test section are shown on Fig.1.

![Diagram showing mean velocity, turbulence intensity, and integral length scale distribution in the boundary layer.](image)
3 Instrumentation

A hydrocarbon tracing and detection system has been designed and purchased. Mass controllers (Alicat products) supply the emission source by air, helium and ethane mixture holding constant mass rate of the components. A gas chromatograph is used for detection of mean concentration on contaminated samples after their accumulation in volume of about 500 cm$^3$ each. The chromatograph integrates voltage on its flame ionisation detector recorded in time when the sample is coming through. The integral (dimension of mV.s) is proportional to tracer content in injected volume (1 cm$^3$ currently). A calibration has been carried out within the working range. Accuracy of the own analysis has an order of 1 ppm. A background concentration of ambient air, increasing during experiment is checked and eliminated. Mean value repeatability is so better than 10 ppm provided that the lasting of sample suction (averaging time) is long enough and wash out process for pipes, bags and hypo is carefully accomplished.

4 Similarity conditions

It should be reminded that the momentum and buoyancy effluent forces are dominating within near diffusion behind source but the outer turbulent flow effect is of growing influence. A jet mixing occurs in close environments of a stack orifice, important for plumes of high momentum. More authors have treated similarity problematic of the plume physical modelling, e.g. [3, 4, 5]. Besides geometric and boundary layer similarity, ratio of stack velocity to ambient flow velocity and/or ratio of stack- to ambient air momentum are of importance ($U_\infty$ local mean flow velocity on chimney height, $W_s$ efflux velocity, $\rho$ density of effluent, $\rho_a$ ambient air density):

$$W_s/U, \quad \rho_s W_s^2/\rho U^2$$  \hspace{1cm} (1), (2)
Both conditions are met at a time as far as the effluent- and ambient air densities ($\rho_e$ and $\rho$ respectively) are the same in model as in a prototype. This ideal state is scarcely attained at large scaling factors and low Froude numbers. Then the density ratio $\Delta \rho/\rho = (\rho - \rho_e)/\rho$ has to be increased to satisfy (4) and (5) requests. In such case the condition (2) prior to (1) is adhered. It is recommended further [5] to have

$$W_s/U \geq 1.5$$  

(3)

to prevent an unrealistic wake effects behind the model stack. A minimum stack Reynolds number $W_sD/v$ suggested by the authors is 2000 for momentum jet and 600 for buoyant plume. However, the conclusions have been based on experiments carried out in uniform cross flow and a question arises whether high level of turbulence in a surface layer doesn’t reduce the critical values.

In case of buoyant plume, a ratio of momentum and lift forces in efflux is of basic importance, expressed by Froude number

$$Fr = \frac{W_s}{\sqrt{g(\rho - \rho_e)/\rho h}}.$$  

(4)

Its prototype values (not far above 1 at low wind velocities and current values of $W_s/U$) constrain researcher to reduce boundary layer velocity as low as possible. But there is a limit of fully rough turbulent flow occurring in earth surface layer expressed through Reynolds number ($\nu_e$ is a friction velocity, $v_e$ cinematic viscosity)

$$Re^* = \frac{u_e z_0}{\nu_e} \geq (Re^*)_{crit}.$$  

(5)

Critical value $Re^*$ of 2 was introduced by Robin [6], while Plate [4] proposed the value of 5 consistent with our wind-tunnel test [3]. Nevertheless even value as low as 1 is to be acceptable according to recent authors [7], extending space for the buoyancy plume modelling.

5 Diffusion from ground and elevated sources

Since design of the wind tunnel excluded strong thermal fluxes, prototype situations have been confined to neutral equilibrium state in the atmosphere. The modelling of plumes was realized above plane surface covered with the homogenous roughness. Stack model was shaped as a pipe of diameter 10/8 mm and it was applied only at $h=0$ (ground source) and as elevated source with height of $h=100$ mm. Resulting concentrations were observed over model space with plan of 1550 x 650 mm, representing about 715 x 300 meters in a prototype.
5.1 Ground level source

Ground level concentrations behind the ground source were followed in the initial study. Adjustments and operating parameters were optimised in the first case. So effluent of zero buoyancy i.e. air at \( \frac{W_o}{U_{z=100 \text{ mm}}} = 1.5 \) (in rate of 6.35 l/min, traced with 1.6% of \( \text{C}_2\text{H}_6 \)) at boundary layer velocity of \( U_o = 2 \text{ m/s} \) with \( u^*z_{e}/v = 3.12 \) were applied. Total pumping time 3 min for volume about 500 cm\(^3\) was set, consistent with velocity field sampling. Suction velocity in tapping orifices was kept proportional to flow velocity being 0.16 \( U_{z=100 \text{mm}} \) so as in all following experiments. Vertical concentration profiles were measured at 10 distances from the source, showing Gaussian distribution. Fig. 3 presents the field of \( \text{ch}^4U/Q \) using isopleths (c...volume concentration, h...reference height, \( U_\), local velocity at reference height, Q...volume rate of emission. Scaling of 1:320 has been applied here. The peak is displaced downwind the source because of jet lift).

![Figure 3: Ground non-buoyant source, ground level concentrations (full scale)](image)

5.2 Elevated source

Concept of the experiments adopted chimney height as constant (h=100 mm) assuming that it has a secondary influence on plume rise and spread. The buoyancy plumes were modelled at free stream velocity of \( U_o = 1 \text{ m/s} \) corresponding to \( \text{Re}^* = 1.68 \). To suppress viscous effects on chimney wake the flow was tripped by surface mount wire and rough arranging of stack surface. Vertical profiles of concentrations were measured using rake probe (Fig. 2) at the source modifications according to Table 1. The lowest value of \( \text{Fr} = 1.16 \) was related to an effluent composed of pure He traced with 6.25% of \( \text{C}_2\text{H}_6 \), otherwise traced mixture of 50% He with air creates the buoyant effluent.

<table>
<thead>
<tr>
<th>Source</th>
<th>( U_o ) m/s</th>
<th>He %</th>
<th>( \Delta \rho/\rho )</th>
<th>( W_o/U )</th>
<th>( p_oW_o^2/\rho U^2 )</th>
<th>Fr</th>
<th>( \text{Re}_D )</th>
</tr>
</thead>
<tbody>
<tr>
<td>N1</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>1.5</td>
<td>2.25</td>
<td>( \infty )</td>
<td>2440</td>
</tr>
<tr>
<td>B2</td>
<td>1</td>
<td>93.75</td>
<td>0.803</td>
<td>1.5</td>
<td>0.424</td>
<td>1.16</td>
<td>74</td>
</tr>
<tr>
<td>B3</td>
<td>1</td>
<td>50</td>
<td>0.428</td>
<td>3.5</td>
<td>7.127</td>
<td>3.81</td>
<td>300</td>
</tr>
<tr>
<td>B4</td>
<td>1</td>
<td>50</td>
<td>0.428</td>
<td>1.5</td>
<td>1.314</td>
<td>1.64</td>
<td>129</td>
</tr>
</tbody>
</table>
The request of minimal $Re_0$ could not be adhered for buoyant effluent as a consequence of low stack velocity and high cinematic viscosity of He portion. However any plume deforming was not observed in the stack vicinity at the visualisation.

There are considerable differences in the resulting plume rise over testing space. Centrelines obtained from the peak concentration heights are shown in Fig. 4 (any shift of origin was not applied). Whereas the plum B2 of maximal buoyancy and minimal $pW_s^2$ is rising nearly over all testing space following 2/3 power consistent with Briggs relation [5], B4 plume of lower buoyancy does so unless it reaches a dilution state where effects of lift force and momentum drop down to zero, finishing plume rise. The plume without buoyancy measured at overcritical speed $U_c=4$ m/s reaches the final height on $x=200$ mm distance. On the contrary, the plume B3 with high momentum follows the pertinent 1/3 power curve over all the testing space. As to the B4 effluent, it was applied at plume impact on buildings in a following work.
Figure 6: Concentration field of the B3 plume

Its buoyancy ratio exceeded an effluent prototype by 9.5% if burning products of methane are considered with 100% air surplus having $\Delta p/p \approx 0.391$ at 190°C. When dimensionless peak values $c^* = \chi^2 U/Q$ are plotted against the source distance, almost all plumes follow common dependency on $-1.5$ power, with a departure of B3 plume (Fig. 5). The correlation could be explained partially by the same boundary layer and chimney height. However, the independence on Fr number was observed in results of [8] also yielding close power index of $-1.47$. Plume B3 differs from the others having lower slope (of index $-1.25$) and less peak concentration in the nearest profile measured behind the source ($x_i=130$ mm). They could be caused by jet mixing just behind the chimney exit and lower impact of outer turbulence on the mighty plume along its following path. The concentration distribution in plane of symmetry is shown in Fig. 6.

Vertical and lateral spread of B3 and B4 plumes were then evaluated. Standard deviations of coordinate z brought over full scale are compared with data [9] for

Figure 7: Vertical spread of the plumes (full scale)
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Figure 8: Lateral spread of the plumes (full scale)

ground source on Fig. 7. Horizontal profiles were measured on centreline heights in plumes B3 and B4 with the aim. Their lateral standard deviations are compared with the Sutton and Briggs formulae [10] in Fig. 8.

5.3 Re-number effect

The effect of low boundary layer velocity on diffusion was inspected too using effluent without buoyancy. Concentrations were measured along the windward line behind the ground source as well as on peak portion of vertical plume profile in the middle distance, each at $U_0 = 1, 2$ and $4$ m/s and at $W_s/U_{100} = 1.5$. The results are presented in Fig. 9 and Fig. 10 suggesting weak velocity effect at elevated source, but stronger one in case of ground distribution behind a ground source. Cause could be found in a flow structure which may be more affected by

Figure 9: Re-number effect. Non-buoyant source $h=0$, concentration on line $(y=0, z=0)$
viscosity effects in vicinity of surface than in a higher part of boundary layer. Consequently it would be difficult to meet the request (5) for scaled diffusion model of a buoyant effluent release in ground level.

6 Conclusion

It could be summarized that resulting shape of centrelines, peak concentration drop as well as plume spread are in qualitative accordance or approaching the properties of real plumes as they are described in literature. Presented plume modelling in the flow simulation argue that given facility and methodology would serve with a good estimation of realistic plume behaviour at case studies within about 1 km in windward direction. Moreover it is expected that dispersion at complex boundary geometry, especially with presence of buildings producing major turbulent effects will have a decreased perceptiveness of oncoming flow structure. Otherwise the conservative departure of diffusion models (stated in wind tunnels with similar magnitude of cross section) could be corrected in principle after wide-ranging comparison study. Farther critical sight should be focused to dispersion from sources situated in surface level, which seems to be more responsive to low Reynolds numbers.

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References


