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Computational simulation of the residence of air pollutants in the wake of a 3-dimensional cubical building. The effect of atmospheric stability

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HIGHLIGHTS

► Gas residence in the wake of an isolated cube was investigated using a CFD model.
► Residence times were compared with field results for different stability conditions.
► For the cube normal to the flow the model underestimated residence times.
► Non-dimensional residence times are in general independent of atmospheric stability.
► A power law dependence was observed between residence times and wind speed.

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ABSTRACT

This paper presents a computational investigation of the residence of atmospheric contaminants in the wake of an isolated cubical building under different stability conditions, using the computational fluid dynamics code ADREA-HF. Characteristic concentration decay times describing the detrainment behaviour of gas in the near-wake are assessed for different atmospheric stability conditions and the results are compared with experiments conducted in the field (Mavroidis et al., 1999). The flow and concentration fields are also investigated computationally. Two building orientations are examined, with the mean wind direction normal to or at 45° to the leading face of the cubical building. Characteristic decay time patterns calculated by the model agree in general with the experimental ones, while there is a tendency for the model to overestimate dilution rates for the wind direction normal to the face of the building. The residence time (T_d), defined as the time it takes for gas concentration to decay to $1/e$ of its original value, depends on atmospheric stability, with higher values observed in general under stable conditions; T_d is especially influenced by the prevailing wind speeds, with a tendency for higher values under lower wind speeds. On the other hand, the non-dimensional residence time ($\tau = UT_d/H$) is to a large extent independent of the atmospheric stability conditions, as also indicated by the experimental measurements. Residence times are in general larger when the cube is oriented at 45° to the wind than when it is normal to the wind. Finally, the spatial variability of the calculated residence time T_d is also presented and discussed.

1. Introduction

The examination of flow and dispersion around an isolated obstacle aims to identify the effect of a building or any other obstruction on the behaviour of plumes released in their vicinity. Although in real situations there is often a complex interaction between pollutant plumes and groups of buildings, the study of flow and dispersion around isolated simple structures is very useful for detecting the fundamental characteristics of building influenced dispersion. Such studies have important applications in predicting air pollution from stacks located close to buildings, infiltration of toxic releases inside buildings from openings or ventilation systems and the spatial and temporal behaviour of dangerous plumes following accidental transient toxic gas releases (Isaacson and Sandri, 1990; Mavroidis et al., 2007). Such releases very often occur in the vicinity of industrial installations or in built-up areas. Following the scientific and practical importance of the topic, there

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is a considerable amount of work in the literature dealing with atmospheric flow and dispersion near buildings. The broad characteristics of flow and dispersion around an isolated rectangular building in neutral atmospheric conditions have been initially examined in the wind tunnel but also in the field. Britter and Hanna (2003) provided a review of the research on flow and dispersion in urban areas, while the main characteristics of flow and dispersion around a simple rectangular obstacle, which are most relevant to this study, are summarised by Mavroidis et al. (2003). Recent advances in computational fluid dynamics (CFD) and in computer capabilities have lead to an increased body of work on numerical simulation of flow and dispersion around single buildings. Most recently, Tominaga and Stathopoulos (2009) compared the results of various $k-\varepsilon$ CFD models with wind tunnel data around an isolated cubical building and their results suggested that the concentrations predicted by all the models were less diffusive than those of the experiments. They then compared Reynolds Averaged Navier–Stokes (RANS) predictions with results of Large-Eddy Simulations (LES) and their results suggested that LES gives better results than the RANS models for concentration predictions; however, the CPU time required is approximately 25 times longer for LES (Tominaga and Stathopoulos, 2010). Gousseau et al. (2011, 2012) showed that a close agreement is found between LES predictions and wind-tunnel measurements around a cubical building and that when the source is located outside of recirculation regions both RANS and LES models can provide accurate results.

The effect of atmospheric stability on air flow and pollutant dispersion has been the subject of numerous investigations, while there is less work on the effects of atmospheric stability on dispersion in building wakes. Kothari et al. (1985) considered gas dispersion in the wake of a model building immersed in a stably stratified flow field. Snyder (1994) examined the influence of stratification on diffusion in building wakes, while Robins (1994) examined building-influenced dispersion in light wind conditions. He suggested that under unstable conditions similar approaches to those used for neutral conditions may be applied in the near-wake, while in very stable conditions the flow is controlled by the obstacle Froude number. Higson et al. (1995) and Mavroidis et al. (1999) examined the dispersion and residence of a tracer gas in the wake of a rectangular model building under different stability conditions in the field. A numerical and physical modelling study of the stably stratified flow around an isolated model building is described by Zhang et al. (1996), while Olvera and Choudhuri (2006) investigate numerically hydrogen dispersion in the vicinity of a building in stably stratified atmospheres. Santos et al. (2005, 2009a) reported the results of field experiments on building-influenced dispersion under different stability conditions and Santos et al. (2009b) investigated numerically the effect of atmospheric stratification on flow and dispersion around an isolated cubical building. The effects of thermal stratification on flow and dispersion have also been examined in urban street canyons, using wind tunnel (e.g. Uehara et al., 2000) or numerical simulations (e.g. Sini et al., 1996), and, more recently, within urban environments (e.g. Dimitrova et al., 2009). Limited wind tunnel and numerical studies are available on the atmospheric flow and dispersion around obstacles under unstable atmospheric conditions. Wind tunnel facilities have extended their capabilities only recently to enable simulation of unstable flows, while numerical simulation of turbulence under unstable conditions is still an intricate topic for computational fluid dynamics.

The residence of gas in the near-wakes of buildings is one aspect of building-influenced dispersion that requires special attention. When the entrainment of gas in the wake region of a building or other construction ceases, for example due to a puff release, a sudden shut-off of a continuous source or a shift in the mean wind direction, then the near-wake region behaves as a secondary wake-source. This secondary source decays gradually as gas is detrained from the wake. The decay follows an exponential trend and is characterised by a decay time, which is called the residence, retention or detention time (T_d). T_d is defined as the time it takes for gas concentration to decay to $1/e$ of its original value. A more detailed description of the detrainment behaviour in the recirculation region of rectangular obstacles is presented by Mavroidis et al. (1999). The residence behaviour of gaseous releases in the near wake of isolated obstacles has been mainly examined in the wind tunnel (Humphries and Vincent, 1976, 1977; Vincent, 1977, 1978; Fackrell, 1984; Hunt and Castro, 1984; Isaacson and Sandri, 1990; Gomes et al., 1997, 1999), while limited field investigations also exist (Drivas and Shair, 1974; Higson et al., 1995; Mavroidis et al., 1999). Although several numerical studies have examined steady state dispersion in the wake of buildings and other obstacles, there is very little work on transient dispersion in wake flows. Some authors have recently investigated the residence of pollutants within more complex urban settings (e.g. Gomes et al., 2007; Doran et al., 2007; Zhou and Hanna, 2007; Yim et al., 2009; Richmond-Bryant et al., 2011) and introduced concepts such as the city breathability (Buccolieri et al., 2010). Such investigations, although they do not always have a similar focus as the present work, are mainly based on the mechanism of detrainment of gaseous concentrations from the wakes of obstacles and take benefit from the study of residence and detrainment of contaminants in the wake of isolated buildings.

As noted above, there is a lack in the literature of numerical studies examining the residence behaviour of gases in the wakes of obstacles and isolated buildings. The present work aims to calculate, using the CFD code ADREA-HF, characteristic concentration decay times in the near wake of an isolated cubical building and to compare them with detailed results from field experiments. A novel aspect of this work is the numerical examination of the influence of meteorological conditions – and especially of the effect of atmospheric stability – on the residence time of a gas in the wake of a building. The main purpose of this study is to provide a detailed analysis of the residence behaviour of gas in the wake region when the gas source is cut-off, after initially validating ADREA-HF on the prediction of the transient behaviour of concentration decay in an obstacle-obstructed flow. Further than the examination of the detrainment behaviour of a gas plume in the near wake of the obstacle under different stability conditions, including under very low wind speeds, the spatial variability of the residence time within the near-wake of the obstacle is also analysed.

2. Methodology

2.1. Field experiments

The field experiments simulated here were conducted in the USA, at a desert site southwest of Salt Lake City, and are described in detail by Mavroidis et al. (1999). The surrounding terrain was generally flat and the roughness length of the site, calculated from velocity profile measurements, was approximately 16 mm. A 2 m plywood cube was used for the experiments, which could be readily rotated to the required orientation. Two orientations of the cube were investigated, such that the mean wind direction was approximately normal to or at 45° to the leading face of the cube. Propylene was used as a tracer gas. The gas source was located 2.5H upwind of the cube and at the building height (H). The release conditions were such that the gas behaved essentially as a passive tracer. The tracer gas was released at a steady rate for a minimum period of 30 s to fill the near-wake region with contaminant. Then