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Natural ventilation in cities: the implications of fluid mechanics

1. Introduction

The global urban population first exceeded the global rural population in 2007 and is expected to reach 6.3 billion in 2050 (UN, 2014). During this period of rapid urbanisation, change in land use and intensive human activities have led to urban environmental problems, such as the urban heat island, air pollution, and excessive energy consumption with associated greenhouse gas emissions (Grimmond, 2007). Cities are typically warmer than surrounding rural areas (the heat island) due to higher building densities, larger thermal mass of construction materials, less vegetation cover and associated radiative processes, and modified wind flow (Oke, 1973; Wilby, 2003). In addition, extreme temperatures associated with heat waves bring increased health risks to urban populations (Grimmond, 2007; Baniassadi and Sailor, 2018). Urban areas are also major carbon sources, producing approximately 70% of anthropogenic carbon emissions from human respiration and fossil fuel consumption (from industries, transportation, etc.; UN-Habitat, 2011). Global warming and deteriorating outdoor air quality, accompanied by increased expectations for the quality of indoor environments, result in an increasing energy demand in buildings for cooling using air conditioning (Sailor, 2001; Sailor and Pavlova, 2003; Santamouris et al., 2001; Santamouris, Cartalis, Synnefa, and Kolokotsa, 2015). This leads to a vicious cycle of increased urban emissions of heat, pollutants, and greenhouse gases and an associated increase in energy demand. On the other hand, natural ventilation of buildings provides a sustainable way to cool the indoor environment and reduce building energy consumption, but its use is challenging in urban areas due to the heat island, reduced wind speeds, air pollution and noise (Ghiaus, Allards, Santanamouris, Georgakis and Nicol, 2006; Martins and Carrilho da Graça, 2017).

The objective of the MAGIC (Managing Air for Green Inner Cities) project is to break this vicious cycle, by developing an advanced computational system that can be used to predict the airflow and air quality in a city in order to optimise the use of natural ventilation in buildings, thereby reducing energy demand and greenhouse gas emissions. An integrated management and decision-support system is being developed to achieve this, comprising:

(i) a fully resolved air quality model that simulates the air flow and pollutant and temperature distributions in complex city geometries, fully coupled to observations, naturally ventilated buildings, and green and blue spaces;

(ii) fast-running models that allow rapid calculations for real time analysis and emergency response;

(iii) a cost-benefit model to assess the economic, social and environmental viability of planning options and decisions.

The key requirement is that output is of sufficient quality and resolution to support decisions that provide high-quality indoor environments using natural ventilation in place of air conditioning, thus reducing energy demand and emissions from the built environment. Experiments and simulations of selected city stereotypes in different local climate zones (Stewart and Oke, 2012) are planned to support (i) and (ii) above, and here we describe the initial phase of that activity.

To examine the potential of natural ventilation under the challenges of both the urban heat island and air pollution, the MAGIC team conducted experiments and simulations for both the indoor and outdoor environments at a test site. We monitored air quality indoors and outdoors, used wind tunnel experiments and computational fluid dynamics (CFD) to simulate the outdoor environment, with internal modelling to treat the indoor environment and the indoor-outdoor exchange. Accompanying this, we are using water flume experiments to develop ways of improving the indoor modelling. We are developing reduced order modelling (ROM) to enable rapid simulations that can be used in place of the computationally expensive CFD model, but which retain much of the fidelity of the CFD model. Methods are also being developed to assimilate data into the models so they are able to interpolate sensor data and generate good initial and boundary conditions from which simulations can predict into the future. A further use of these methods is to optimise the placement, and type, of sensors in the local environment. A schematic of the links between these activities – the MAGIC circle – is shown in Fig. 1.

The field study consisted of external and internal air quality measurements over a five month period, the latter within a naturally ventilated office room in the Clarence Centre (51°29'54.38"N, 0°6'14.9"W) in the Borough of Southwark, London (Fig. 2). The study area is categorised as a compact, mid-rise, urban local climate zone (Stewart and Oke, 2012), including a modest number of high-rise buildings and affected by air pollution from intensive traffic flow. A naturally ventilated room on the top floor of the three-storey test building was selected for the study (Fig. 3(a)). It is connected to two adjacent naturally ventilated rooms (the four windows to the left in Fig. 3(a)) and has simple window configurations with two windows facing a busy road (London Road), one window facing a quiet courtyard and a skylight in the ceiling. A number of natural ventilation types can therefore be investigated, including single-sided ventilation (SSV, openings on one façade), cross ventilation (CV, openings on opposite façades) and stack ventilation (SV) due to buoyancy (Linden, 1999; Mateus and Carrilho da Graça,2015; Daish, Carrilha da Graça, Linden and Banks, 2016).

Section 2 describes the methodologies employed in the research, and Section 3 the main results, including discussion of the influence of the outdoor urban environment on the natural ventilation potential and the impact of the urban configuration and buildings. Section 4 describes the ROM and data assimilation work, and includes studies under way to understand the level of detail that needs to be included in the modelling. Finally, conclusions and future work in the next phase of MAGIC are given in Section 5.

2. Methodologies

2.1 Full-scale field experiment

To monitor the indoor and outdoor environment, we designed our own monitor units with six sensors, which enabled us to make simultaneous measurements of carbon dioxide (CO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), temperature, relative humidity (RH), and barometric pressure. The CO and NO_2 sensors (Alphasense Ltd, UK) operate on an electrochemical principle. The CO_2 sensor (Senseair AB, Sweden) operates on a non-dispersion infrared method that determines CO_2 concentration based on light absorption (Mead et al., 2013). Each unit is powered by a rechargeable lithium battery with a low-power microcontroller and a power saving routine to minimize power consumption. The sampling outputs were saved in a memory chip with a typical time interval of 30 seconds and downloaded through a USB interface. All units were calibrated before deployment by placing them side-by-side in ambient conditions monitored with reference instruments. Each unit is lightweight (less than 500 g), compact (circuit board dimensions: $10 \times 8.4 \times 2.8$ cm^3) and low-cost (less than £1000), which allowed us to deploy a denser sensor network than more expensive and bulkier units (Fig. 4).

From August 2017 to January 2018, 18 monitors (9 indoors and 9 outdoors) were deployed in and around the case study building. The outdoor network covered most major roads within a radius of 300 m of the test room, denoted by filled red circles in Fig. 2. To characterise the outdoor environmental conditions on the two sides of the test room (i.e. London Road side and courtyard side) (see Fig. 3(a)), three monitors were deployed close to the test room, with Monitors 1 and 2 along polluted London Road and Monitor 3 in the relatively clean courtyard. Another monitor was located approximately 650 m from the test room at the Elephant and Castle air quality monitoring station with a reference NO_2 instrument. In addition, a meteorological station with a weather station package (MetPak, Gill Instruments Limited) and a solar pyranometer (SPN1, Delta-T Devices Ltd) was installed on the rooftop of the nearby eight-storey Building 139 (denoted by a red diamond in Fig. 2), to record local wind speed, wind direction, temperature, relative humidity and barometric pressure (all at 1 Hz), as well as total and diffuse solar radiation every 10 minutes.

Inside the case study building the sensor network was deployed with 7 monitors in the test room and 2 monitors in two adjacent rooms, connected to the test room via open doorways (Fig. 3(b)). The monitors in the test room were arranged to capture spatial variations in locations of particular interest such as the windows/skylight and in the room centre/edge. A floor-to-ceiling vertical array of 8 temperature sensors (PT100 Pico SE017) was also deployed in the test room to measure the vertical temperature stratification. The temperature sensors were calibrated by a co-location test prior to deployment with additional on-site calibration and data collection at 1 Hz by two PT-104 PicoLog data loggers connecting to a laptop. Finally, a 180-degree fisheye camera was mounted on the ceiling to monitor the number of occupants and window opening sizes.

2.2 Wind tunnel experiments of the external flow at 1:200 scale

The flow and pollutant dispersion over the test site was simulated in the EnFlo Meteorological Wind Tunnel (working section of 20 m length and 3.5×1.5 m^2 cross-section), which can be used to simulate a range of atmospheric stability conditions. The neutrally-stable boundary layer approach flow was developed with standard Irwin spires and staggered rows of distributed roughness elements along the initial 12 m fetch of the wind tunnel. The stream-wise mean wind velocity conformed to a standard profile shape for a turbulent boundary layer over suburban terrain (power-law exponent of 0.19 ± 0.01). The free-stream mean velocity was maintained steady, within ± 0.5% of set-point. The 1:200 scale model of the urban site included buildings within approximately 300 m of our test building with prominent peripheral high-rises within 500 m added for westerly (W; Building 149) and south-easterly (SE; Building 12) winds (Fig. 2). The geometry was extracted from a digital map and database (MasterMap; Ordnance Survey 2016). Buildings were simplified to 149 cuboids by extruding their general footprints to the most reliable measured height (ground to base of roof; Ordnance Survey 2014). The first set of experiments used flat-roof buildings; later work examined the importance of roof shape and the impact of individual high-rise buildings. The approaching wind direction was controlled over the full compass range, within ± 0.25°, by automated turntable positioning of the model using an overhead camera and image correlation.

Smoke flow visualisation (Fig. 5) provided an overview of flow conditions and highlighted specific features, such as the wake of the tall Building 45. A two-component laser Doppler anemometer (2D-LDA; Durst, Melling and Whitelaw, 1976; Carpentieri, Hayden and Robins, 2012) provided quantitative measurements of mean and fluctuating air velocity with a typical sampling rate of 50Hz. The instrument was used in two alignments in order to obtain three flow components. Dispersion studies used a passive hydrocarbon tracer, the concentration of which was measured with a Fast Flame Ionisation Detector (FFID) with a frequency response near 200Hz (Fackrell & Robins, 1982; Carpentieri et al., 2012). Turbulent mass fluxes were determined by simultaneous LDA and FFID measurements. The external surface pressure distribution on the model Clarence Centre (Building 147) was measured by 88 pressure taps on the road side, courtyard side and roof of the test site model. Each tap was connected to a pressure transducer by 400mm of 1mm internal diameter plastic tubing. Pressures were measured with transducers (RSCDRRM2.5MDSE3, Honeywell International) at 200Hz, this being about twice the frequency response of the transducer. No interference from Helmholtz resonance in the tubing system was observed.

2.3 CFD simulation, the Fluidity model

CFD simulations were carried out for the study area using Fluidity, an open-source, finite-element, fluid dynamics model (http://fluidityproject.github.io/). A large eddy simulation (LES) approach is used to represent turbulence. The LES equations describing the turbulent flows are based on the filtered incompressible Navier-Stokes (NS) equations (momentum equations and continuity of mass). In addition, a subgrid-scale model based on the anisotropic eddy viscosity is used to close the equations. The dispersion of pollutant is described by the classic advection-diffusion equation with the pollutant concentration treated as a passive scalar. A source term was added to the advection-diffusion equation to mimic a constant release of pollutant. All the equations are solved using second order schemes in time and space. The NS equations are discretised using a continuous Galerkin discretisation, while the advection-diffusion is discretised using a coupled finite-element/control-volume method. The time step is adaptive based on the courant number (CFL number) defined by the user, and the Crank-Nicholson scheme is used for the time discretisation. Details of the equations and their implementation can be found in Ford et al. (2004) and Aristodemou, Bentham, Pain and Robins (2009).

The mesh is unstructured (Fig. 6), anisotropic and adaptive, which can be refined automatically in regions of interest during a simulation (Pain, Umpleby, De Oliveira and Goddard, 2001). The mesh is constrained by three parameters given by the user: the maximum number of nodes, and the minimum and maximum edge length of elements. The mesh adaptivity can be field-specific, so that the mesh refines based on different computed fields. In the simulations presented in this paper, field-specific adapativity options were assigned to the tracer field and the velocity field.

The outlet boundary condition is defined by a zero pressure (no-stress condition); perfect slip boundary conditions are applied at the top and on the sides of the domain and no-slip boundary conditions are applied on the bottom surface of the domain and all building facades. The properties of the fully developed boundary layer measured in the wind tunnel, i.e the mean velocity profile, the Reynolds stresses profiles and the turbulence lengthscale profiles, were used to set up the turbulent inlet boundary conditions using the synthetic eddy method (Pavlidis, Gorman, Gomes, Pain and ApSimon, 2010). The numerical results have been compared with the wind tunnel data to validate the simulations.

2.4 Modelling of internal conditions

The U.S. Department of Energy building simulation tool EnergyPlus (https://energyplus.net) was used to quantify the effect of outdoor urban environmental conditions on internal conditions under natural ventilation. The model integrates building data (construction, materials and internal usage) and outdoor meteorological data (wind speed, wind direction, solar radiation, air temperature, air humidity) to simulate the indoor environment by considering indoor-outdoor exchanges of heat and pollution. The geometrical representation of the test room is shown in Fig. 3(a) and the methodology of EnergyPlus modelling is illustrated by Fig. 7. External wind pressures coefficients on the test building facades were derived from both wind tunnel experiments and Fluidity simulations, both of which included the effects of surrounding building clusters. These wind-pressure coefficients determine the exchange through each window for a given wind speed (Daish et al. 2016) The results showed that the test site was significantly sheltered by its urban surroundings and that for many situations inflow was in the expected ‘lee’ of the test building rather than the side that was naively considered to be the windward based on the prevailing wind direction.

3. Results and discussions

3.1 Evaluation of the EnergyPlus model

One week (25 September to 1 October 2017) when the full set of indoor and outdoor observations was available was chosen to evaluate the EnergyPlus model. The data included air temperature and relative humidity (Fig. 8(a)), CO_2 and CO (Fig. 8(b)), wind and solar radiation (Fig. 8(c)) and the number of occupants and window opening position (Fig. 8(d)). Indoor temperatures (with diurnal variation of 4.9^{o}C) were usually higher than outdoor temperatures (with a larger diurnal variation of 11.9^{o}C) possibly due to the thermal mass and air tightness of the building envelope. The variation of indoor CO_2 was found to be closely related to occupancy levels due to exhaled human breath, while the variations of outdoor CO_2 and CO are influenced by outdoor traffic with two concentration peaks coinciding with morning and afternoon rush hours.

The simulated and measured indoor averaged temperatures agree well with the same trend and root-mean-square-error (RMSE) of 1^{o}C (Fig. 8(a)). A possible cause of this RSME might be the use in EnergyPlus of a single temperature which ignores spatial variations within the space, such as the vertical temperature stratification. Fig. 9 shows an example of the diurnal development of the temperature stratification on 25 September 2017. Temperature stratification started to form at 0900 when occupants first entered the test room with the air near the ceiling approximately 1^{o}C warmer than near the floor. The room temperature increased until the window was opened at 1500, providing single-sided ventilation and producing a reduction in room temperature and enhanced stratification. After the window was closed, the room began to warm up again with increasing stratification until the occupants left at the end of the day, after which it cooled and gradually reached a well-mixed state at night. To characterise the indoor temperature stratification and spatial concentration variations, water flume experiments and indoor Fluidity simulations (section 4.3) will be conducted to assess the limitations of EnergyPlus.

3.2 Evaluation of Fluidity modelling

To examine the capability of Fluidity modelling and promote understanding of wind and dispersion conditions at the site, we selected two areas around the test building (i.e. Building 147 in Fig. 2): the central roundabout (the centre of the study domain, Fig. 10(a)) close to the test building and a street canyon adjacent to the test building (i.e. London Road side, Fig. 10(b)). The wind tunnel experiments revealed the flow to be complex, with recirculation and separation in street canyons, and deep and persistent wakes from the taller buildings. These regions of turbulent flow tested the modelling capability of Fluidity. ~~As an example, Fig. 10~~We compare~~s~~ velocity profiles at these two locations from both the wind tunnel experiments and Fluidity simulations for a wind blowing from the NorthWest (NW). Wind velocity and height above the ground were normalized by the velocity at the top of the approaching boundary layer U_{ref} and the boundary layer depth δ, respectively. The wind tunnel profiles were reproduced by the Fluidity simulation reasonably well at the roundabout (Fig. 10(a)). However, some discrepancies appeared between the roundabout and the street canyon of London Road (Fig. 10(b)). Here, Fluidity under predicted the streamwise component, U_{mean}/U_{ref}, for $z/\delta < 0.15$, though this discrepancy diminished further along the street canyon (Fig.~~ure~~ 11). These discrepancies probably imply a lack of local model resolution and results are expected to improve by refining the simulation resolution.

All the vertical profiles shown in Figs. 10 and Fig. 11 show a canopy layer that is approximately 0.2 – 0.3δ in depth, and characterised by lower wind speeds than expected at the same height in the undisturbed approach flow. The depth of the canopy layer is between 40 and 60m at full scale, chiefly influenced by the tallest upwind buildings; specific effects seen in the wakes of high-rise buildings are discussed in Section 3.4 below. The measured and simulated profiles converge in the upper part of the boundary layer, above about 0.5δ, tending towards the upstream flow conditions. Generally, although mean wind speeds at street level are low, the turbulence levels, when expressed in terms of local wind speeds, are generally larger in the canopy layer than in the upstream flow at the same height.

3.3 Impact of urban form

Wind tunnel dispersion experiments, using passive tracer gas released from a ground-level source at the central roundabout, were carried out to characterise on-site dispersion behaviour, and to provide additional data-sets for use in evaluating Fluidity. A further objective was to compare behaviour with that previously observed in London at the DAPPLE site in Marylebone Road (Arnold et al. 2004; Wood et al. 2009). The two sites have very different characteristics – the street pattern at the DAPPLE site is grid-like and the range of building heights is modest, whereas the MAGIC site has a predominantly radial street arrangement and a greater range of building heights. Dispersion behaviour will of course reflect these differences but, nevertheless, the decay of maximum mean concentration with radial distance from the source was very similar in the two cases, following an inverse square form. This is a useful conclusion, showing the robustness of the empirical correlation developed during the DAPPLE experiments.

Dispersion behaviour in the prevailing wind directions (W and WSW) was simulated with Fluidity to illustrate dispersion conditions in the environment surrounding the test building (Building 147). In the examples shown, pollutant was released from point-sources alongside the test building: one in the street canyon (London Road, L) and one in the courtyard (C). Example instantaneous tracer iso-surfaces and vertical profiles of nondimensional mean pollutant concentration are shown in Fig~~s~~. 12, Fig. 13(a) and Fig. 13(b). Concentrations are made dimensionless using: $C^*=CU_{ref}H^2/Q$, where C is the concentration, H is the average building height and Q is the pollutant emission rate. A strong sensitivity to wind direction and source location is clear. Features of note include dispersion along London Road (Source L, W wind), dispersion into the courtyard (Sources L and C, W wind), dispersion away from the courtyard (Source C, WSW wind), as well as the differences in extent and depth between the W and WSW wind cases. The flow over and in the wake of Building 147 dominates dispersion in the near-field as is clear from Figs. 13(a) and 13(b). Overall, cross-wind dispersion in the street network driven by the urban geometry can be substantial, and can take plume material far from the nominal plume centreline based on the mean wind direction above roof level. This too was a feature of dispersion at the DAPPLE sites, where plumes from road-level sources often spread across a 90° sector.

3.4 Impact of tall buildings

The work of Heist et al. (2009), Brixey et al. (2009) and Aristodemou et al. (2018) illustrate some of the important effects of a single large building on the urban flow field. Broadly speaking, down-flow on the front face of the building leads to outward flow in the streets upwind and often an intensification of the vortex in the street canyon immediately upwind, whereas up-flow on the back face leads to inward flows in the streets downwind. A wake region of reduced wind speed and enhanced turbulence levels persists over several building diameters downwind.

To illustrate the impact of tall buildings at the MAGIC site, we selected a prominent building (Building 45, Fig. 2) as an example. The effect of the building wake is clearly observed experimentally and well predicted numerically. In the wind tunnel experiment, lateral profiles of velocity downwind revealed an extended wake region of mean velocity deficit and increased turbulence intensity. Comparison of the wind tunnel experiment and the Fluidity simulation of the lateral profiles of the normalized mean velocity components at half-building height in the wake of Building 45 are shown in Fig. 14. Two main zones can be identified: a deficit region downstream of the building and two disturbed regions to the sides. The behaviour of the three components suggests vertical recirculation at this height.

The wake behind an isolated tall building was clearly detectable at a downwind fetch of four building heights – that is approximately 400-500m for the buildings affecting the MAGIC site. The wake is characterised by a velocity deficit and enhanced turbulence. As can be seen in Fig. 14, wakes become quite wide downwind and continue to spread as they decay. It is therefore likely that wakes from just a few tall, upwind buildings may combine to create an extensive region of velocity deficit, so that not only will the flow over the downstream region be reduced but it will be far from being a classical boundary layer, making its specification in standard operational dispersion models particularly difficult.

3.5 Some outstanding modelling issues

The question of what level of detail to include when modelling flow and dispersion in an urban area is unanswered. It is, of course, quite clear that dispersion at the microscale is dependent on features such as building and street geometry but details of roof geometry are often ignored with buildings modelled with flat roofs, as is the case in our basic model of the test site. Further, traffic induced flow and turbulence may be important, particularly in low wind speed conditions (e.g. Brown, Lawson, De Croix and Lee, 2000; Yassin, 2011; Badas, Ferrari, Garau and Querzoli, 2017).

The effect of roof geometry on flow and dispersion over the MAGIC site is being investigated as part of the wind tunnel work. Here, though, we concentrate on results from Fluidity simulations for the simple case of turbulent flow over two parallel canyons. As in the main body of Fluidity work, the Synthetic Eddy Method (Pavlidis et al., 2010) was used to develop turbulent inlet boundary conditions that matched the fully developed boundary layer flow in the wind tunnel. A 3.5 x 4 x $2m^3$ domain representative of a wind tunnel was used and simulations run with street canyons aligned at 90^o and 100^o to the wind direction (i.e. normal and slightly off-normal to the mean flow). The geometry of the first building was fixed as a flat roof in all simulations and building-height-to-canyon-width ratio was H/W=1. The geometries of the second and third building were varied in order to investigate the effect on the flow within the second canyon. Three geometries were used; (a) pitched roof, H/W=1.5, (b) flat roof, H/W=1 and (c) flat roof, H/W=1.5 (Fig. 15).

A passive tracer was released near ground level at the centre of the second canyon. Fig. 16 shows the time-averaged normalized tracer concentration when a quasi-steady state had been reached. We see that in cases (a) and (b), the orientation of the street canyon has little effect on tracer dispersion. However, in case (c), tracer is dispersed much further along the canyon. In (a) and (b) tracer is more readily mixed into the flow above rooftop, limiting along-canyon dispersion. Upwind dispersion of the tracer into the adjacent canyon is seen in case (b). There were significant differences between the pitched and flat roof cases for both orientations.

During DAPPLE, experiments in the region around Marylebone Road (Arnold et al., 2004; Wood et al., 2009), concentrations of a released tracer were observed at locations well upwind of its source, the likely dispersion process being transport of the tracer by traffic-induced flow. Vehicle motion and emissions can be simulated by the traffic model in Fluidity (Garcia et al., 2011). Vehicles are modelled as a highly-viscous slug (effectively a solid) and Fluidity adapts the mesh to capture the interface between moving vehicles and the air. As the vehicle velocities are predefined, the Navier-Stokes equations are solved only for air, with additional momentum source and absorption terms for the force applied by a vehicle on the surrounding air. A traffic simulation was run using Fluidity to demonstrate the effect on dispersion, in which a bus travelled upwind along a street canyon at $10ms^{-1}$ (Fig. 17). The wind speed was constant at $3ms^{-1}$. Tracer released at the centre of the canyon, formed a cloud through which the bus passed. The figure shows a tracer iso-surface, corresponding to a normalized concentration of 0.1, 10s after the bus passed through the cloud, clearly demonstrating pronounced upwind transport.

4. Modelling enhancements

4.1 Reduced-order CFD simulation

Resolving much of the detailed air flows and associated transport of pollution within cities is extremely computationally intensive. It is currently impossible to model the system sufficiently quickly to be able to predict behaviour in real-time or assess risks adequately. An aim of this work is to demonstrate a key step towards the use of a reduced order model (ROM) for operational purposes, with the tantalizing possibility of it being used in place of Gaussian plume or related models for practical applications. This could provide greatly improved model fidelity and confidence for air flow and pollution modelling in urban environments.

There are three aspects in producing an operational model: 1) an ability to predict the full-model results using a non-intrusive reduced order model (NIROM); 2) an ability to have a model with similar dynamics which can be run as long as one likes and has similar dynamics to the full model and can predict from different initial conditions; 3) a model that is parameterised and takes varying forcing from boundary conditions, physics like temperature variation, etc. The NIROM is based on deep-learning methods and proper orthogonal decomposition (POD). The key idea is that deep learning is used to construct a set of hypersurfaces, representing the reduced system (including linear and nonlinear processes). The novelty of the method rests in how the ROM is generated; i.e. how the hypersurfaces are calculated using a long short-term memory network (LSTM) (Wang et al., 2018). Previous research (Xiao et al., 2014, Xiao, Fang, Pain and Navon, 2017) has shown that the predictive accuracy of a ROM is maintained while CPU costs are reduced by several orders of magnitude. Fig. 19 shows the flow around the test site, using the full Fluidity simulation (left) and the ROM (right). The ROM was constructed from the first 27.5 minutes of the Fluidity simulation. It used 48 POD basis functions and ran in 31s on a laptop (excluding time spent on input and output), compared with the 215 hours that the Fluidity simulation took to run on 10 cores. Fig. 18 shows the ROM is in excellent agreement with the full simulation. Future work will focus on developing a domain decomposition ROM which will form the basis functions within subdomains, thereby identifying the POD functions more efficiently. This method will also allow a ROM to be generated region by region without solving the full model across the whole domain.

4.2 Data assimilation

Pollutant concentrations and wind conditions monitored in urban areas are used to characterise environmental conditions and to examine dispersion model performance. Direct interaction between observations and predictions, aimed at improving the latter, is an emerging and potentially very powerful use of this data. The formal process is termed data assimilation.

A data assimilation technique, illustrated schematically in Fig. 19, is being integrated with the Fluidity model (in the full or ROM form). This is an uncertainty quantification technique used to incorporate observed data into a predictive model in order to improve numerical forecasts (Kalnay 2003). The approach implemented is variational data assimilation (Andersson et al. 1998; Baker, Huang, Guo, Bourgeois and Xiao 2004), first developed for weather forecasting, and based on the minimization of a cost function that estimates the discrepancy between numerical results and observations, assuming that both forecasts and observations contain errors that can be adequately described by error covariance matrices (Kalnay 2003). The greatest challenge in developing the framework of data assimilation is the ill-conditioned nature of the background covariance matrix. To reduce noise in the prediction generated by data assimilation, the empirical orthogonal functions (EOF) method (Lorenz 1956) is used. EOFs strongly reduce the dimension of the problem, alleviating computational cost, but a consequence is that important information can be missed (Cacuci, Navon and Ionescu-Bujor 2013). We have shown, using pressure and velocity fields from Fluidity simulations, that by selecting the mean value of the maximum and minimum singular values of the background error covariance matrix as the regularization parameter, the computational cost can be minimised without significant loss in solution accuracy.

4.3 Water flume experiment (Laboratory-scale indoor experiment)

Water flume experiments with a simplified, scaled geometry will be used to help build simple theoretical models of ventilation processes. Using water provides compelling flow visualisation of the indoor-outdoor exchange that is not available by other methods (Linden 1999), and allows appropriate modelling of buoyancy forcing but with Reynolds numbers necessarily smaller than at full-scale. Fluidity simulations were performed to identify whether the reduction in Reynolds number had any serious impact on flow conditions. Full-scale simulations represented a cross-ventilated room (5.4m wide, 7.4m long, 2.7m high) in a large domain (21.6 by 35 by 5.4 m^3), with air as the working fluid and an inlet velocity of 1 m s^{-1}. Computational simulations at the 1:10 laboratory-scale, used water as the working fluid and an inlet velocity of 2 cm s^{-1}; the Reynolds number was approximately 50 times smaller than in the air simulation.

In these simulations, the indoor and outdoor temperatures were equal. The room was initially filled with a passive tracer that was then flushed out by cross-ventilation. The simulations used an adaptive mesh, with a 5-cm minimum edge length (5-mm in the water simulation), chosen such that the evolution of the mean pollutant concentration in the room converged. An appropriate dimensionless time is $\tau = tU/L$, where L is the room length and U the inlet velocity. Comparison of a vertical slice through the two simulations at $\tau = 100$ shows the two simulations to produce very similar pollutant distributions (Fig. 20), and time decay of mean concentrations are in even better agreement (Fig. 21). These simulations suggest that the dynamics that control the overall ventilation rates are not significantly affected by the reduction in Reynolds number.

Water flume experiments will examine the effect of temperature variations on a cross-ventilated room. The results of these experiments will be used to build simple theoretical descriptions that can be integrated into EnergyPlus, improving the modelling of internal flows and indoor-outdoor exchange.

5. Conclusions and future work

This paper reports research from the MAGIC project that aims to provide the tools to enable increased uptake of natural ventilation of buildings in cities, thereby reducing the urban heat island, building energy usage and greenhouse gas emissions. We have successfully carried out a field experiment and developed wind tunnel and Fluidity site models for flow and dispersion. Using these results, we are able to make connections between internal conditions within the naturally ventilated building and the external environment. The connection between external and internal conditions is achieved by an interdisciplinary approach that uses wind-tunnel-derived pressure coefficients and velocity data to test Fluidity predictions, and to provide input for building energy modelling such as EnergyPlus. We have also shown that Fluidity can model interior flows and verified that small-scale water tank modelling can be used to obtain quantitative information even at reduced Reynolds numbers. The importance of roof shape has been demonstrated by both Fluidity and wind tunnel simulations and some of the effects of traffic movement by Fluidity modelling. Precise control of air and surface temperatures in the wind tunnel will facilitate simulation of urban thermal phenomena such as dispersion under stable or unstable atmospheric conditions, effects of differential solar irradiation, and the urban heat island.

We are developing reduced order models and data assimilation to provide an optimised fast model for real-time operational use and to inform on optimal location and operation of sensors. The capabilities of Fluidity will be improved through data assimilation and by including additional physical processes such as the effects of green and blue spaces. The accuracy of the representation of the outdoor environmental conditions (such as wind pressure coefficients) will be increased with further cross-validation of wind tunnel and Fluidity models, such that the indoor-outdoor exchanges can be sufficiently resolved to assess natural ventilation potential. This will also involve improved representation of indoor conditions (temperature and CO_2 variations in space and time) and improved modelling of the indoor-outdoor exchange.

Our next step is to integrate these components into a comprehensive tool to provide accurate predictions for a set of scenarios of interest to urban planners and architects. In the next phase of the MAGIC project, we will examine more scenarios with naturally ventilated buildings within different local climate zones (different land use cover and pollution levels). Future scenarios will help us to identify the benefits of pedestrianising a street (accounting for the displaced traffic), to understand how this process would be improved by the introduction of green or blue infrastructure (e.g. trees, fountains), and to identify beneficial changes to building design and operation with relevance to occupant well-being and sustainability of urban communities.

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