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SIZING OF VENTILATION OPENINGS IN BUILDINGS WITH PASSIVE DOWNDRAUGHT EVAPORATIVE COOLING

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ABSTRACT

This paper describes preliminary results of an investigation to size ventilation openings in buildings which employ Passive Downdraught Evaporative Cooling (PDEC) such that uniform flow rates exist on all storeys of the building. This enables more control to be exercised over ventilation and cooling. The paper describes a *Sizing Equation* which provides the ratio of the opening sizes on one storey to those on another necessary to achieve equal flow rates. The equation has been applied to a PDEC building design and the opening size predictions tested using a computational fluid dynamics model. Results are very encouraging, although further work is needed to investigate remaining imbalances in flow rates.

KEYWORDS

Ventilation, Modelling, Sizing, Passive, Cooling, Evaporative, Downdraught

INTRODUCTION

The application of Passive Downdraught Evaporative Cooling (PDEC) to non-domestic buildings has recently been the subject of a three year EU funded research project (Bowman et al. (2000)). PDEC is a low-energy technique of ventilating and cooling buildings in hot, dry climates. The technique works by injecting a fine mist of water particles into warm, dry ambient air using micronisers at the head of an atrium-type space. This space may take various forms ranging from a narrow tower to a large courtyard (investigated in this work). The particles evaporate in the dry air thereby reducing its temperature and raising its relative humidity. This denser-than ambient air then falls into an area, referred to in this paper as a *capture zone,* from where it can flow into occupied spaces. As the air is heated by internal gains, it rises and flows out through openings at the perimeter of the building. Under this flow regime, a column of cool, dense air is established in the capture zone. This produces a stack pressure which drives the air into the occupied spaces. However, the driving force varies depending on the depth of the cool air column acting at that level. That is, openings on lower storeys will experience larger stack pressures than those on higher storeys. If openings between the capture zone and the occupied zone are sized identically on all storeys, this will yield larger flow rates on the lower storeys (assuming the opening configurations are similar on all storeys). In many situations this is likely to be undesirable.

This paper describes preliminary results of an investigation for sizing ventilation openings within PDEC buildings such that uniform flow rates can be maintained on all storeys. This is useful when internal heat gains are identical on each floor. The predicted ventilation opening sizes are tested using a Computational Fluid Dynamics (CFD) model. The paper begins with a description of the building geometry for which ventilation opening sizes have been predicted.

BUILDING DESCRIPTION

The building geometry chosen for investigation in this work is based on a design developed by architects Ford and Associates during the course of the EU project.

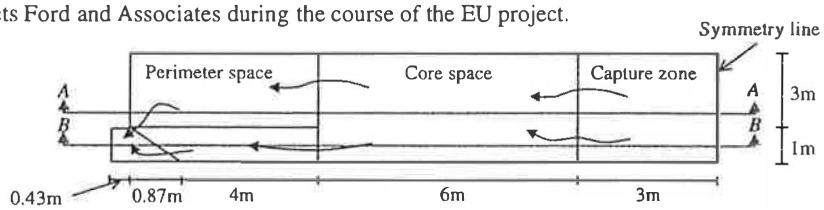

Figure 1. Typical floor plan of PDEC building showing possible airflow paths

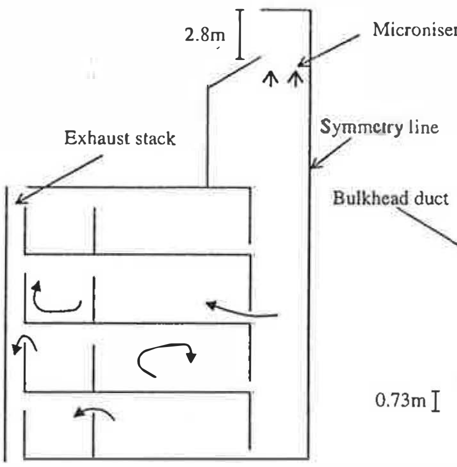

Figure 2. Section AA of PDEC building

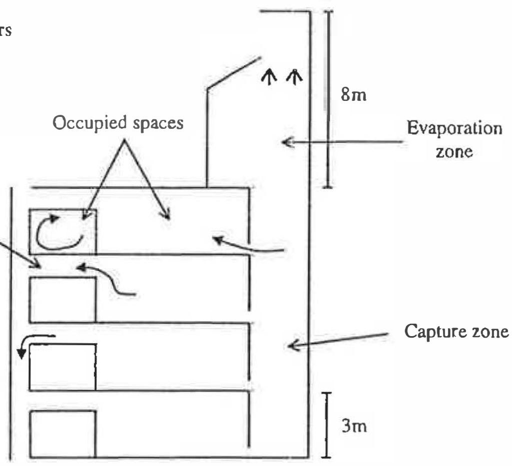

Figure 3. Section BB of PDEC building

The hypothetical four storey office building is located in Seville, southern Spain. The occupied spaces are divided into core and perimeter spaces (Figure 1) and stale air is exhausted via a perimeter stack (Figures 2 and 3). Cool air from the capture zone passes into the core space from where it flows either into the perimeter space and into the stack, or into the bulkhead duct and into the stack. Due to the high ambient temperatures experienced in Seville during summer occupancy hours (often exceeding 35°C), in most cases the air exhausted from the building into the stacks will be cooler than ambient air and will therefore tend to flow downwards.

SIZING OF VENTILATION OPENINGS

The techniques used in this section are based on previous work carried out by researchers at the University of Cambridge, in particular, Hunt and Holford (1998).

The task was to derive a set of opening sizes between the capture zone and core space which encouraged uniform airflow rates on each storey. This was done by fixing all opening sizes (except those between the capture zone and the core space), and considering the pressure drop across each opening along each flow path and on each storey. A ratio was then derived which relates the effective opening area of the flow path on the ith storey (i = 1,2,3,4) with that for the nth (uppermost) storey, as follows. This will be referred to as the *Sizing Equation*:

$$\frac{\dfrac{1}{A_{in(i)}^2}+\dfrac{1}{A_{out(i)}^2}+\delta}{\dfrac{1}{A_{in(n)}^2}+\dfrac{1}{A_{out(n)}^2}+\delta}=\frac{[M-(i-1)H]+\lambda(i-1)H}{[M-(n-1)H]+\lambda(n-1)H} \tag{1}$$

where δ represents the effective opening area of the inlet opening at the top of the capture zone and the outlet from the exhaust stack,

$$\lambda = \frac{T_{occ}-T_{amb}}{T_{PDEC}-T_{amb}} \tag{2}$$

where T_{occ} is the temperature in the occupied space
T_{PDEC} is the temperature in the capture zone
T_{amb} is the ambient temperature,

$A_{in(i)}$ is the effective inlet opening area into the ith storey from the capture zone,

$A_{out(i)}$ is the effective opening area of the outlet from the ith storey (includes perimeter space and bulkhead duct),

M is height of the PDEC capture zone and

H is height of each storey.

There is no scope here to include the detailed derivation of the Sizing Equation (Eqn. 1) or the full expressions for δ, $A_{in(i)}$ and $A_{out(i)}$. This will be reserved for a later publication. However, the main assumptions made are noted here:

- identical heat gains exist on each storey yielding similar temperatures on all floors,
- the PDEC air in the capture zone is well mixed and at a constant temperature,
- air in the exhaust stack is at a constant temperature equal to that in the occupied spaces,
- all storeys are of the same height, H,
- for simplicity the top of the exhaust stack is closed to the exterior,
- pressures within the space are hydrostatic and temperature differences are small compared with ambient temperature.

When specifying λ, values for T_{PDEC} and T_{occ} were set based on simulation results for which the core space was fully open to the capture zone. From this simulation, a good estimate of the likely value of T_{PDEC} was made. Using the induced volume flow rate through the capture zone that this simulation predicted and the internal gains in each of the occupied spaces, a value for T_{occ} could be determined.

In Eqn. 1, $A_{out(i)}$ was fixed according to the architectural design of the building. $A_{in(i)}$ (i = 1,2,3) were then deduced as a function of $A_{in(4)}$. A value of 0.6m^2 was assigned to $a_{in(4)}$ ($A_{in(4)} = 0.535\text{m}^2$). This area was set such that it was smaller than the combined effective area of all other openings along the storey (4) flow path. This yielded the following set of opening areas:

$$a_{in(1)} = 0.525\text{m}^2,\ a_{in(2)} = 0.548\text{m}^2,\ a_{in(3)} = 0.571\text{m}^2 \text{ and, } a_{in(4)} = 0.600\text{m}^2.$$

CFD MODELLING

CFD Modelling Technique

This section gives a brief summary of how the injection of water particles and their effect on the surrounding air were modelled. Full details of the CFD techniques used are given in Cook et al (2000).

Each microniser was represented using five particle trajectories, one directed downwards and the others evenly spaced on the surface of a cone whose angle to the downwards trajectory is 45°. Each trajectory releases particles of size 60µm at a speed of 30m/s with a temperature of 30°C. The total flow rate of all five trajectories is 6 l/h. The motion and behaviour of the particles was modelled by solving equations for particle momentum, heat transfer with the surrounding air, and mass transfer to the surrounding air (evaporation). By solving these particle transport equations, the CFD code is able to predict the individual particle trajectories. This is useful for attaining an indication of the likelihood of water ingress into occupied spaces.

The resulting effect on the surrounding air, i.e. induced downdraught and temperature depression, is represented through a coupling within the iteration process. This works by first solving the continuum (air) phase equations with no particles present and then injecting particles and solving their governing equations subject to the calculated continuum field. The presence of the particle trajectories are then accounted for in a further iteration of the continuum equations. The procedure continues until satisfactory convergence is attained.

CFD Results

For each simulation, ambient conditions of 35°C and 34%RH were assumed and heat gains of 32Wm^{-2} (core space) and 50Wm^{-2} (perimeter space) were specified to represent occupants, lighting, equipment and solar gain. Nine micronisers were used (total flow rate, 54 l/h), based on the desired target temperature in the capture zone.

An initial simulation (Simulation 1) was conducted in which no control was exercised over airflow rate between the capture zone and the core space. This serves, firstly, to illustrate the problems associated with imposing no control and, secondly, provides an indication of the temperature generated in the PDEC capture zone and the induced airflow rate, both of which are required for determining λ (Eqn. 2). The results for Simulation 1 are shown in Figures 4 and 5 and Table 1. The simulation predicts the downdraught from the micronisers into the capture zone as expected. However, most (66%) of the air that enters the capture zone exits through the lower storey leaving spaces higher up with the risks of inadequate ventilation and over-heating (Figure 5). The steady flow field (Figure 4) predicts a 'counter-PDEC' flow whereby (stale) air from the occupied spaces flows *back* into the capture zone at ceiling level, thus opposing the desired flow direction from the centre to the perimeter of the building. This illustrates another potential problem of imposing no flow constraints. It is also important to note that air in the exhaust stack flows in both directions, exiting either via the top or bottom of the stack.

This is thought to be due to the air entering the stack from lower storeys inhibiting the downwards motion of air from storeys higher up which is therefore forced out of the top of the stack.

TABLE 1
PREDICTED STEADY AIRFLOW RATES

	Flow in top of capture zone (m^3/s)	Flow into 1st storey (m^3/s)	Flow into 2nd storey (m^3/s)	Flow into 3rd storey (m^3/s)	Flow into 4th storey (m^3/s)
Simulation 1	3.00	1.98 (66%)	0.51 (17%)	0.16 (5%)	0.36 (12%)
Simulation 2	2.64	0.94 (36%)	0.66 (25%)	0.54 (20%)	0.51 (19%)

The percentage values indicate the proportion of the total flow through the capture zone.

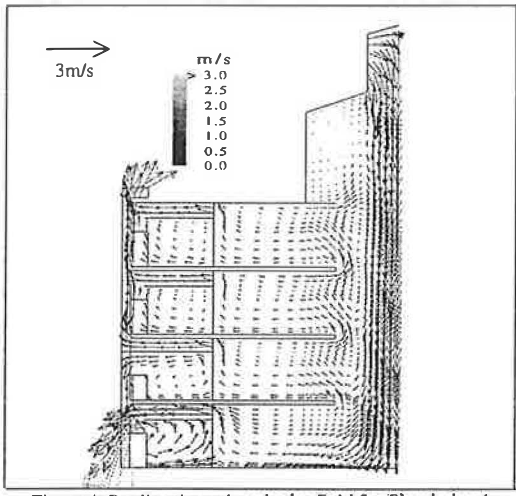

Figure 4: Predicted steady velocity field for Simulation 1

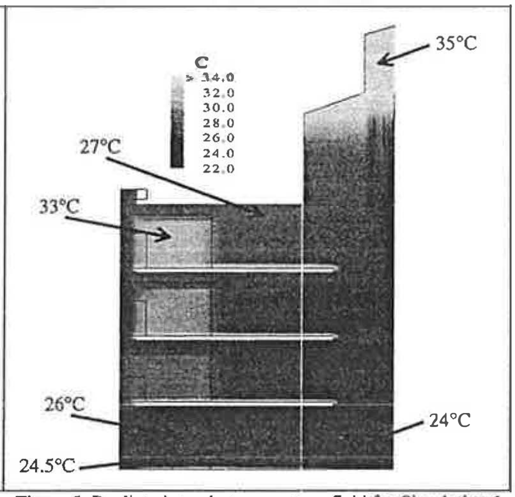

Figure 5: Predicted steady temperature field for Simulation 1

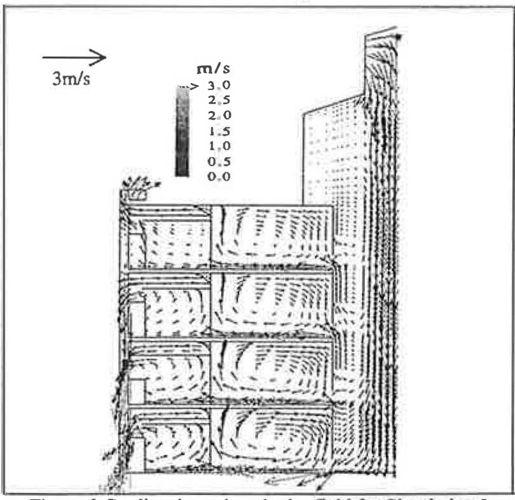

Figure 6: Predicted steady velocity field for Simulation 2

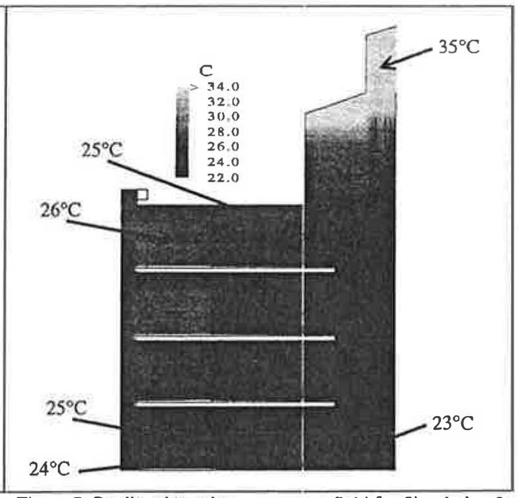

Figure 7: Predicted steady temperature field for Simulation 2

The relationship between the ventilation airflow rate and the number of the storey is complex, e.g. there is a reduction in flow rate between levels 1 and 3 and an increase between levels 3 and 4. This is believed to be a feature of the position of the neutral pressure level in the exhaust stack.

In simulation 2, opening sizes between the capture zone and the core space were specified according to the areas calculated in section 3. The temperature predicted in the capture zone by Simulation 1 and the anticipated temperature rise in the occupied spaces (based on the desired airflow rate through the space) lead to a value of $\lambda = 0.936$. The predicted flow field (Figure 6) shows a far more controlled delivery of air into the occupied spaces without risk of backflow into the capture zone. The variation in flow rates between storeys is less pronounced than in Simulation 1 (Table 1) resulting in a more uniform temperature distribution over the height of the building (Figure 7). A lower temperature is generated in the capture zone caused by the increased resistance to flow through the building which yields a lower total flow rate. This has implications for the resulting value of λ (Eqn. 2) which need to be investigated further. Although there is still an upward flow of air in the exhaust stack, this effect is now reduced following the reduction in airflow rate through the lower storeys.

SUMMARY AND CONCLUSIONS

The work has shown the potential of PDEC for ventilating and cooling an office building in a hot, dry climate. The usefulness and power of CFD for predicting these flows has been illustrated.

The CFD simulations demonstrated the likely problems of imposing no control over the passage of cooled air into the occupied spaces. Namely, the column of cool air drives a larger ventilation flow through the lower storey thereby leaving spaces higher up with risks of poor ventilation and over-heating. This arrangement also allows the possibility of stale air to flow *back* into the PDEC capture zone.

These problems have been tackled by deriving a simplified *Sizing Equation* for the openings between the capture zone and the occupied spaces, based on the resistances to flow along each flow path. The Sizing Equation is developed for a building whose upper exhaust stack opening is closed. As expected, the equation yields smaller openings on lower storeys, where the driving force is higher, and larger openings higher up the building. A simulation based on these opening sizes lead to a significant improvement in the uniformity between storeys of ventilation rate and thus air temperature.

For the particular building considered in the CFD simulations, the flows are still not perfectly balanced. The Sizing Equation is expected to provide a good approximation to the ventilation opening sizes required to achieve equal flow rates on these storeys only when there is zero, or very weak flow through the top of the exhaust stack. Thus the flow imbalance is believed to be due to the flow of air out of the top of the exhaust stack. It is possible that this occurs because the exhaust stack is under-sized for the spaces it serves resulting in air exhausted from the lower storeys inhibiting the downwards flow of air from storeys higher up. There also exist difficulties in determining λ *prior* to simulation, although this value can be refined with relative ease within a few simulations. It is possible that, due to radiation effects which were not considered in the CFD simulations, air temperature in the stack may be higher than that in the occupied spaces which is likely to affect the Sizing Equation. These issues are currently under investigation.

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