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Air flow pattern at courtyards

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Abstract

The relationships, in courtyards, between wind flow pattern and temperature distribution have been studied. Thus, in the first part of this study a dimensionless temperature based on the exchange of heat by convection is defined. Then, using the ratio of depth to width (Aspect Ratio) as the main parameter, we are able to explain the curious behaviour observed. Finally, courtyards are divided into several zones in order to separate the different heat sources in each one, allowing us a stratification study.

INTRODUCTION

Courtyards are typical architectural forms used in private and public spaces.[1] They present a local microclimate different from surrounding sites, based in a low incoming direct radiation and reduced wind velocity. They also may be used to improve the summer conditions in Southern climates for example by the evaporation of water.

Flow pattern in courtyards is decisive when calculating their thermal behaviour and therefore it is an important issue since the objective is to improve microclimate around buildings. Thus, in the last stage, we will be able to calculate the thermal comfort in courtyards.

We are interested in characterise this behaviour by studying the different parameters related with the removal of high temperatures.

THEORETICAL DEVELOPMENT

Results for simulated courtyards must be easily extrapolated to a general form and climatic conditions. It would be worthwhile to obtain a dimensionless temperature with the same form than the dimensionless concentration used by D. Hall in his paper "Dispersion from Courtyards"[2].

The notation and terminology for the courtyards is given in figure 1.

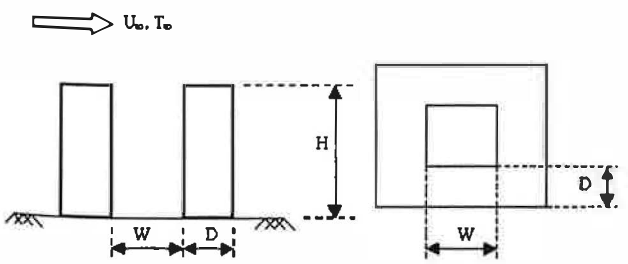

Figure 1. Section and Plan view.

Following David Hall suggestions of looking for an analogy with contaminant dispersion, we propose a dimensionless temperature based on the exchange of heat by convection. Then, if we have a mean flow velocity U_∞, we can define the dimensionless temperature as:

$$\theta = \frac{\rho C_p (T - T_\infty) U_\infty W^2}{Q} \quad (1)$$

where:
- ρ fluid density (kg/m^3)
- C_p specific heat (J/kg K)
- T temperature (°C)
- T_∞ reference temperature (°C)
- U_∞ wind speed at the reference height H_{max} (m/s)
- W side length of the courtyard (m)
- Q heat flow discharged in the courtyard (W)

In the other hand, heat flow can be expressed as:

$$Q = \dot{m}\, C_p (T - T_\infty) \quad (2)$$

where $\dot{m}$ is the flow rate (kg /s)

We can define the air changes per hour as

$ACH = \frac{\dot{m}}{\rho V}$, and using (1,2):

$$\theta = \frac{U_\infty}{H \cdot ACH} \quad (3)$$

Equation (3) is a useful relation between dimensionless temperature and *ACH*. With a fixed dimensionless temperature we get the following relations between *ACH* and U_∞, or *H*:

$$\begin{cases} if \quad U_\infty^{(1)} = U_\infty^{(2)} \quad ACH^{(2)} = ACH^{(1)} \dfrac{H^{(1)}}{H^{(2)}} \\ if \quad H^{(1)} = H^{(2)} \quad ACH^{(2)} = ACH^{(1)} \dfrac{U_\infty^{(2)}}{U_\infty^{(1)}} \end{cases} \quad (4)$$

CHARACTERISATION OF COURTYARDS USING THE ASPECT RATIO

The aspect ratio is defined as the ratio of height to width of the courtyards (*AR=H/W*). In this work we use a range between 0.1 and 5.

Velocity profiles

The most important task in this paper is to relate the temperature distribution with the flow pattern, which we are going to characterise with the Air Changes per Hour (ACH) at intermediate sections and at the top of the courtyard.

The velocity profiles obtained for the different aspect ratios are shown in figure 2.

In all cases U_∞=1m/s.

From this figure it is seen three main and different behaviours.

For low aspect ratio courtyards, (AR=0.1), there is little or no reversed flow.

Intermediate depth courtyards, (AR=0.3, 0.5, 1), show negative velocities near the ground becoming more positive up trough the courtyard.

Deep courtyards, (AR>1.5), show a nearly zero velocity up trough the courtyard, and close to its top the velocity become negative.

Dimensionless temperature profiles

The following graphs show the dimensionless temperature values at the base of the courtyard, and at intermediate sections. Vertical temperature profiles and longitudinal average temperature profiles have been plotted too. We can divided the courtyard into several zones, (for example three zones), and calculate their average temperature. These values can be used in order to obtain a relation between external velocity and temperature inside the courtyard.

Dimensionless temperatures at the base of the courtyard are plotted in figure 3 against aspect ratio.

An example using this graph may be:

Assuming AR=1.5 $\Rightarrow$ θ=6.25

$$if \quad \begin{Bmatrix} U_\infty = 1m/s \\ H = 6m \quad \Rightarrow \quad W = 4m \\ Q = 5000W \end{Bmatrix} \Rightarrow T = T_\infty + 1.5^\circ C$$

For the lowest aspect ratio (0.1 ÷ 0.3), the dimensionless temperature at the base increases with increasing aspect ratio. The reason is that a courtyard with an aspect ratio of 0.1 is more ventilated as we have explained in the previous section. At an aspect ratio of 0.3 the courtyard is more confined and the ingress of external air is less than for a courtyard with AR=0.1

Intermediate courtyards showed a strong recirculating vortex (see figure 2), these courtyards have an almost constant temperature. The minimum value at the base occurs with an aspect ratio of 1, this courtyard presents the strongest recirculating vortex.

Beyond this, the intensity of the recirculating vortex is diminished and is placed at the courtyard top. The dimensionless temperatures at the base of the courtyard rise with the aspect ratio.

Average temperature in each zone

The courtyards are divided into three zones in order to separate the different heat sources in each one: surface temperature, direct and diffuse radiation, inflow air, and volumetric heat sources.

Figure 5 represents a scheme of the courtyard zones.

The average dimensionless temperatures are plotted in figure 6.

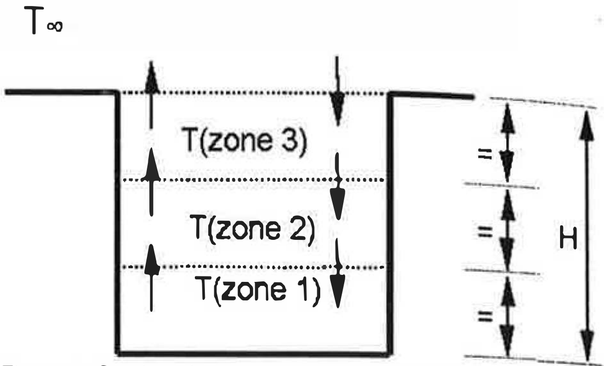

Figure 5. Section view

- Courtyards with a low aspect ratio (shallow courtyards) show a little stratification because there are no recirculating vortex.
- Intermediate courtyards show no stratification because of a strong recirculating vortex.
- Deep courtyards show a big stratification because there is a relatively slight air flow inside of them.

OTHER CONSIDERATIONS

Until this point only isolated courtyards and forced convection flow have been considered. This section treats the influence of an urban environment (see figure 7) and the presence of buoyancy forces (mixed flow) (see figure 8). In these cases a modification of the original graphs may be observed.

Results are very similar for courtyards with an aspect ratio less than 1.5, (at the Base of the Courtyards)

Recirculation vortex in courtyards with a high aspect ratio is more intense when buoyancy forces are considered. Therefore dimensionless temperature is in this case more uniform.

- Urban courtyards present a more intense recirculating vortex than isolated courtyards. In urban courtyards we can expect a more homogenous temperature.
- The flow rate at the top is only slightly different, greater in urban courtyards until an aspect ratio of 2.
- There is no difference in courtyards with a very low aspect ratio (less than 0.1).

CONCLUSIONS

The velocity profiles (see figure 2) have shown that courtyards are quite poorly ventilating spaces. They seem to be very good places in which to try and generate a microclimate, for example by cooling of the local atmosphere using evaporated water.

This paper have related the temperature distribution with the flow pattern, characterised with the Air Changes per Hour (ACH) at intermediate sections and at the top of the courtyard. Thus, the temperature distribution is intimately bound up with the behaviour of the recirculating vortex in the courtyard. We can expect a more uniform temperature in the courtyard space when the intensity of the recirculating vortex has its maximum value. This maximum value occurs with an aspect ratio close to unity.

REFERENCES

1. Alvarez S. et al., *'Architecture and Urban Space'*, PLEA'91. Kluwer Academic Publishers (1991).
2. Hall D. J. et al., *'Dispersion from Courtyards and Other Enclosed Spaces.'* BRE. To be published.

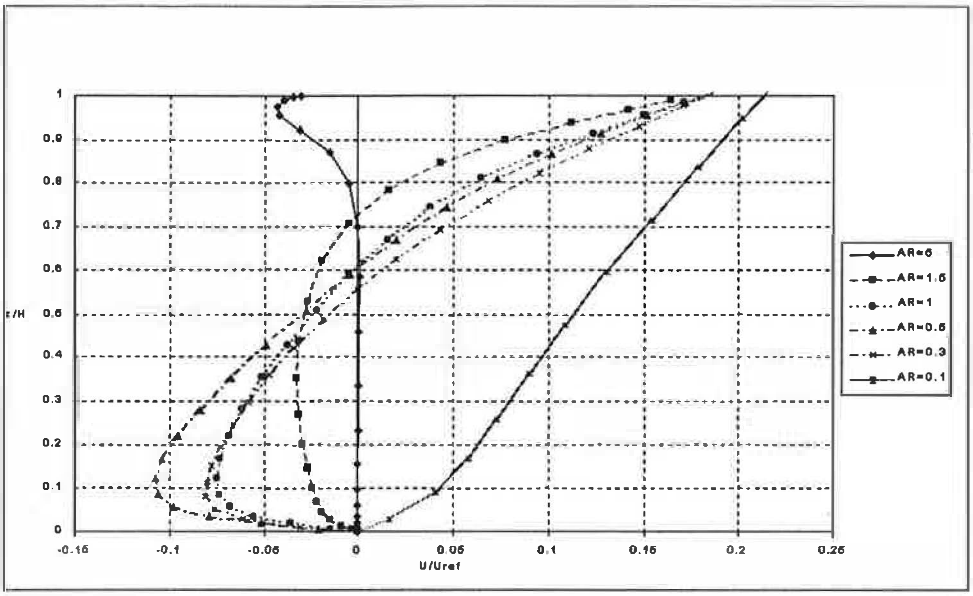

Figure 2. Longitudinal velocity profiles at the central plane.

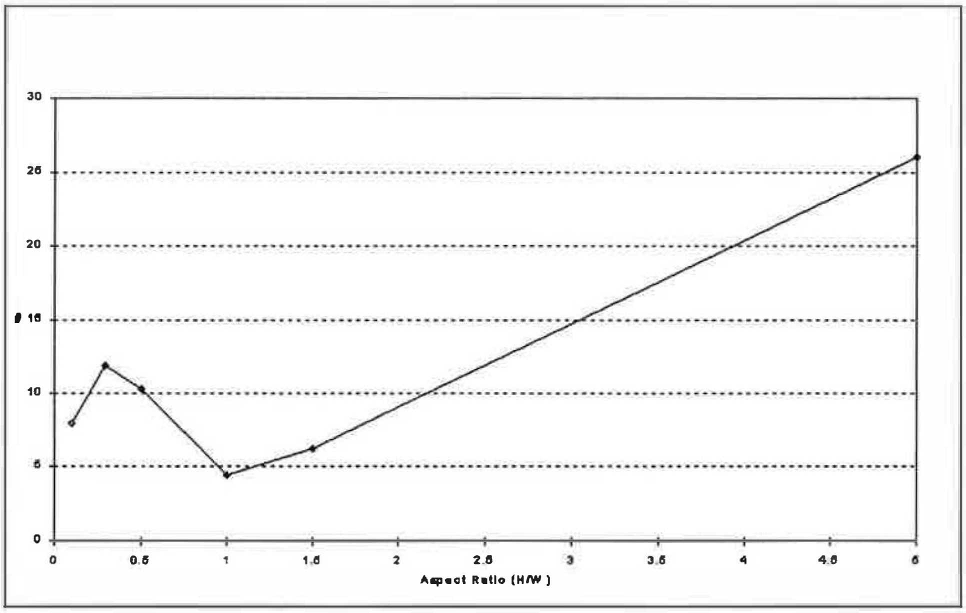

Figure 3. Dimensionless temperature at the base of the courtyard.

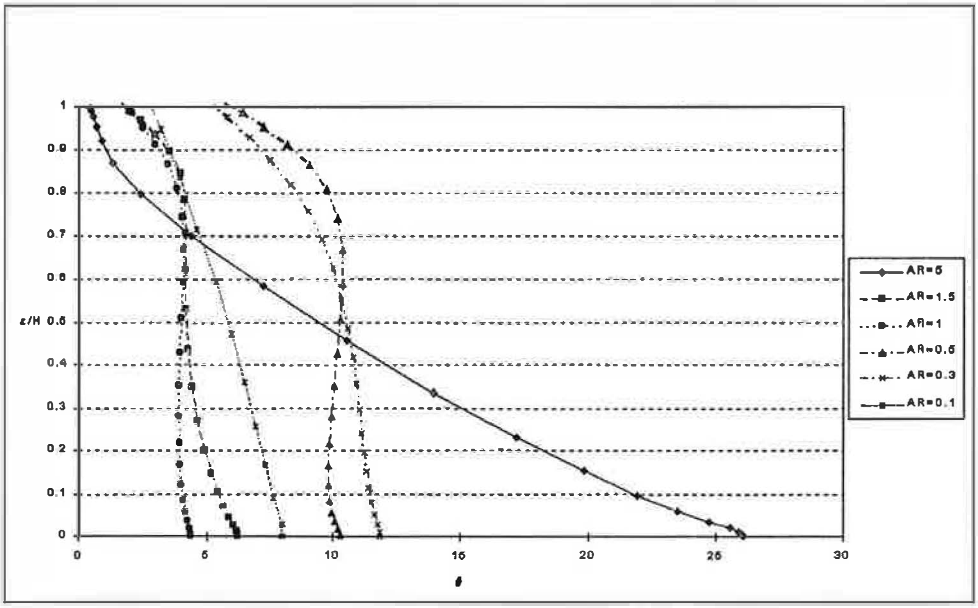

Figure 4. Longitudinal dimensionless temperature profiles at the central plane.

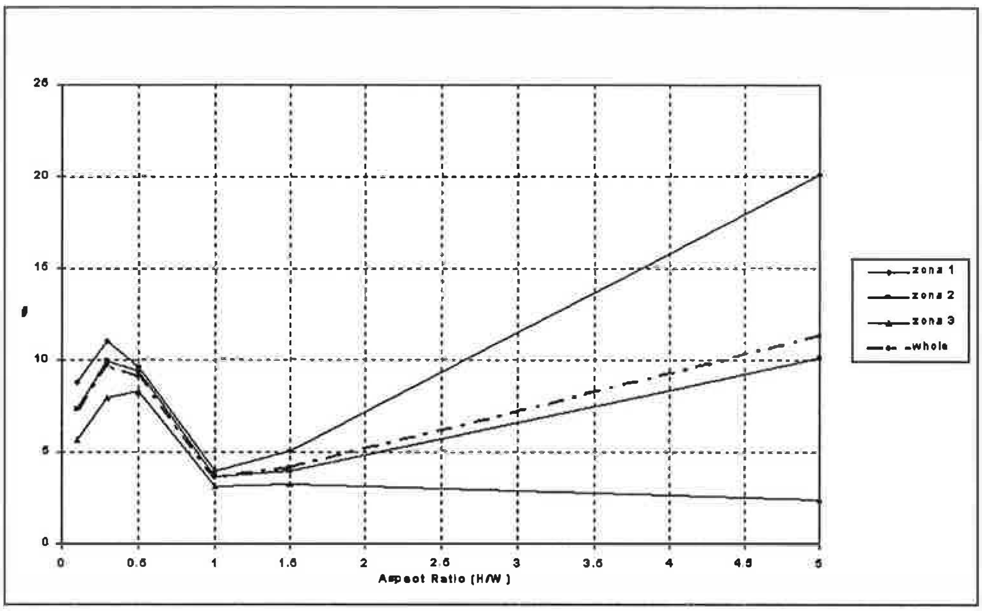

Figure 6. Average dimensionless temperature.

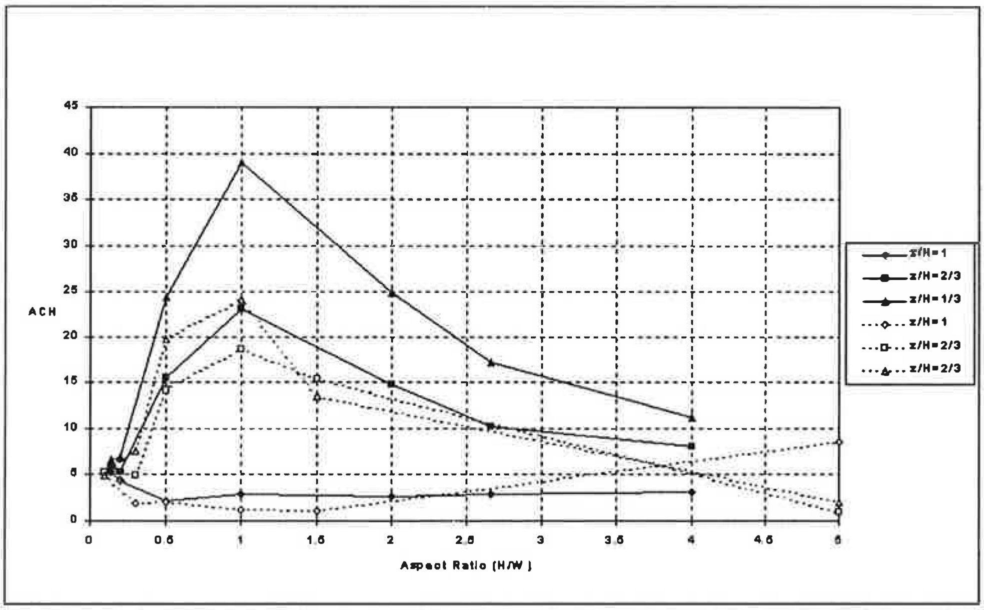

Figure 7. Air Changes per Hour at three sections. Urban courtyard vs. Isolated (Rural) Courtyard.

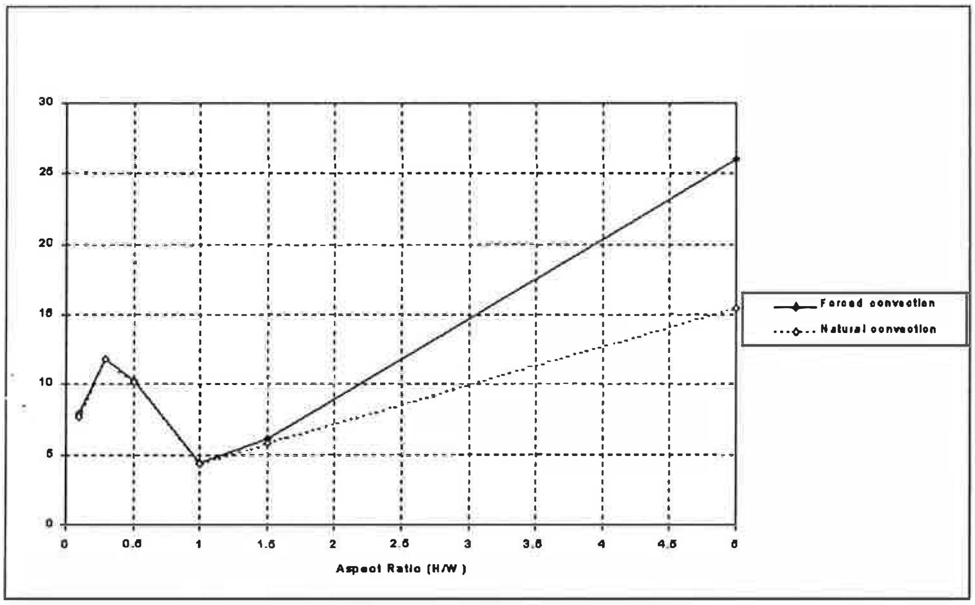

Figure 8. Dimensionless temperature at the base of the courtyard. Natural vs. forced convection.