WIND DRIVEN AND THERMAL AIR FLOW PATTERNS COURTYARDS

S.Álvarez, F.Sánchez, F.J.Zambonino, J.F. Coronel, L. Peréz-Lombard

Departamento de Ingeniería Energética y Mecánica de Fluidos, Grupo de Termotecnia,
Escuela Superior de Ingenieros.
Camino de los Descubrimientos s/n
41092 Sevilla (SPAIN)
email: TMT@tmt.us.es

ABSTRACT

Air flow patterns and temperature distribution within courtyard have been studied. Wind and thermally driven flow have been thoroughly analysed as a function of the depth to width ratio (Aspect ratio) as main parameter. CFD results show a quite similar behaviour regarding to velocity profiles for all the cases, though temperature profiles are highly affected by dimensions of the courtyard. The whole study can be extrapolated to urban canyons, where air flow patterns are quite similar as a result of having the same geometry.

KEYWORDS

Courtyards, hot isle, air flow patterns, thermal patterns, wind driven flow, thermally driven flow, heat dissipation, urban canyons, convection in enclosures.

INTRODUCTION

Courtyards are typical architectural forms used in private and public spaces [1]. They all present a local microclimate different from surrounding sites, based in a low incoming direct radiation and reduced wind velocity. They may also be used to improve summer conditions in Southern climates, for example by the evaporation of water. Flow pattern in courtyards is decisive when calculating 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. External and internal conditions will directly influence heat dissipation, causing different situations in which comfort varies dramatically.

WIND DRIVEN FLOW. 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 shown in figure 1.

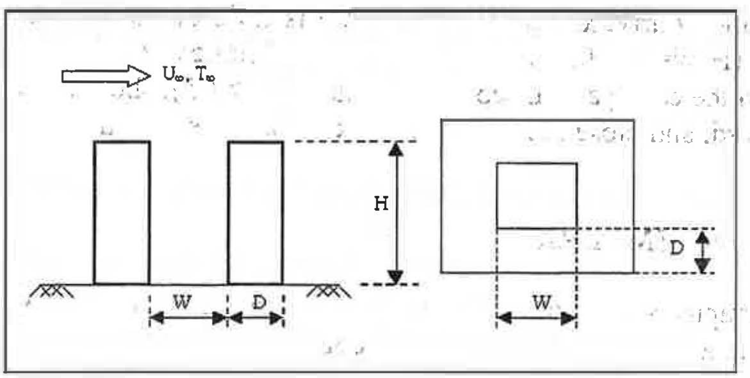

Figure 1. Section and Plan view

Following David Hall suggestions about looking for an analogy with contaminant dispersion, we propose a dimensionless temperature based on the heat exchange by convection. The value of this temperature is related to the heat source within the courtyard, modelled as a heating local point. Then for a mean flow velocity U_∞, we can define the dimensionless temperature in equation (1):

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

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

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.

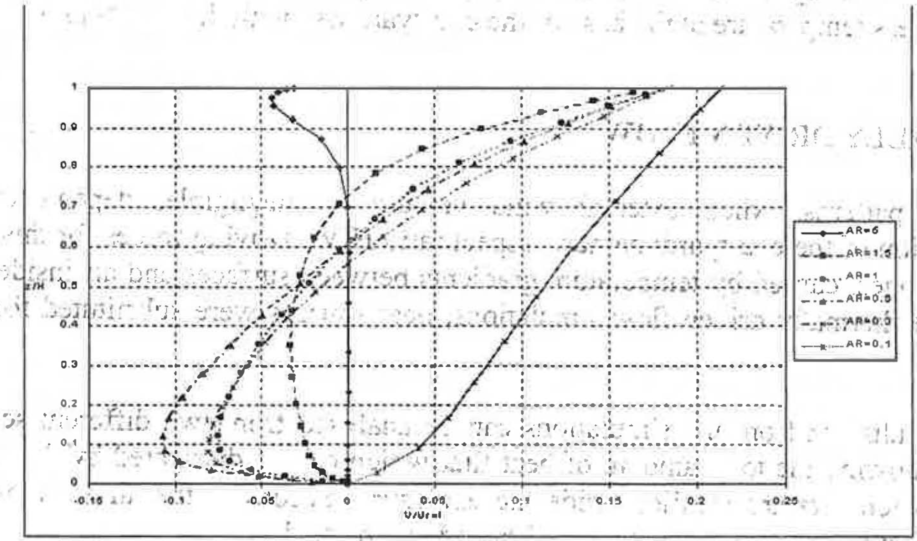

Figure 2. Longitudinal velocity profiles at the central plane

For low aspect ratio courtyards, (H/W=0.1), there is little or no reversed flow. Intermediate depth courtyards, (H/W=0.3, 0.5, 1), show negative velocities near the ground becoming more positive up trough the courtyard. Deep courtyards, (H/W>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 within the courtyard. Dimensionless temperatures at the base of the courtyard are plotted in figure 3 against aspect ratio.

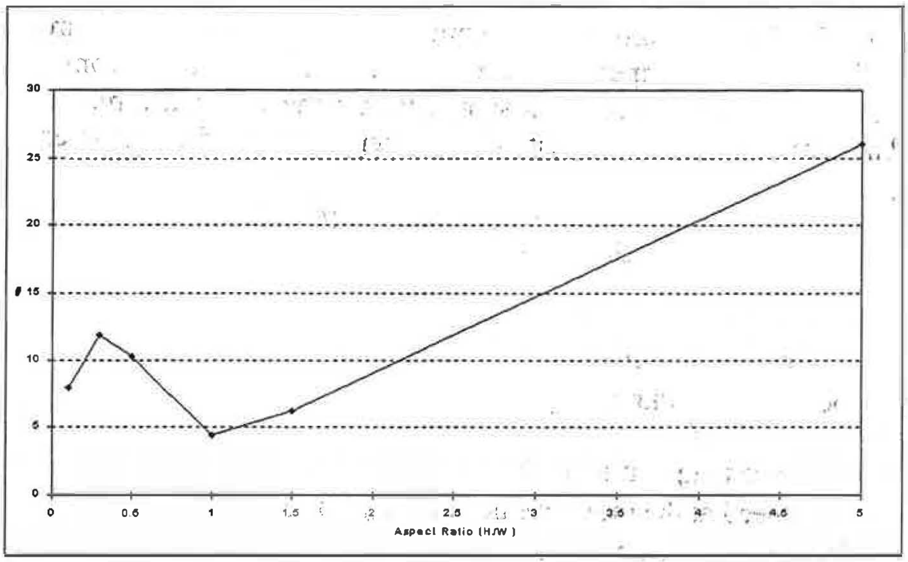

Figure 3. Dimensionless temperature at the courtyard base

For the lowest aspect ratio (0.1 to 0.3), 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 explained previously. When aspect ratio is about 0.3, the courtyard is more confined and incoming external air is less than in a courtyard with H/W=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, since this courtyard shows the strongest recirculating vortex. Beyond this point, the intensity of the recirculating vortex is diminished and is placed at the courtyard top. Thus the dimensionless temperature at the base of the courtyard rise with the aspect ratio.

THERMALLY DRIVEN FLOW

Air flow patterns, when external wind velocity is negligible, depend on geometric configuration of the courtyard; namely, aspect ratio H/W. Driving forces for this situation are buoyancy ones, caused by temperature gradients between surfaces and air inside the volume. For all the thermally driven flow simulations, heat sources were substituted for hot vertical walls.

All the results got from the simulations can be analysed from two different scopes. Firstly, they are showing the total amount of heat flux which can be dissipated by the vertical walls, as well as temperature profiles inside the enclosure. Secondly, the air flow patterns of the fluid moving inside the canyon can be obtained and plotted.

HEAT FLUX DISSIPATION. TEMPERATURE DISTRIBUTION

Heat flux dissipated by vertical walls (q_{0-H}) depends on the temperature gradient between hot walls and external air, but it is also influenced by geometry. Equation (2) shows that for the same temperature gradient, and considering air with constant properties, heat flux given by the wall to the surrounding air varies similarly to average Nusselt number along the wall.

One of the limits of the problem is placed on H/W=0, i.e., courtyards wide enough for the natural convection on the wall to be modelled as natural convection on a vertical plate. Empirical correlations can be found in bibliography for this case. Thus, Bejan[3] reports Churchill and Chun´s correlation of average Nusselt:

$$Nu_{0-H} = \frac{h_{0-H} H}{k} = \left\{ 0.825 + \frac{0.387\,Ra_H^{1/6}}{\left[1+\left(\frac{0.492}{Pr}\right)^{9/16}\right]^{8/27}} \right\}^2 \qquad (2)$$

where: Pr	Prandtl number (dimensionless)
Ra_H	Rayleigh number based on H and ΔT (dimensionless)

Figure 4 plots Nusselt number values obtained with the expression above for H/W=0, together with the rest of values obtained for the set of CFD simulations solved. It must be firstly mentioned that Nusselt number value for H/W=0 is an asymptote. Therefore for any other H/W ratio, Nusselt number value drops because of the couple of hot vertical walls which hinder the natural movement of air produced in the vertical plate case. For all the H/W values, Nusselt number grows when temperature difference does, as many books reporting this topic show.

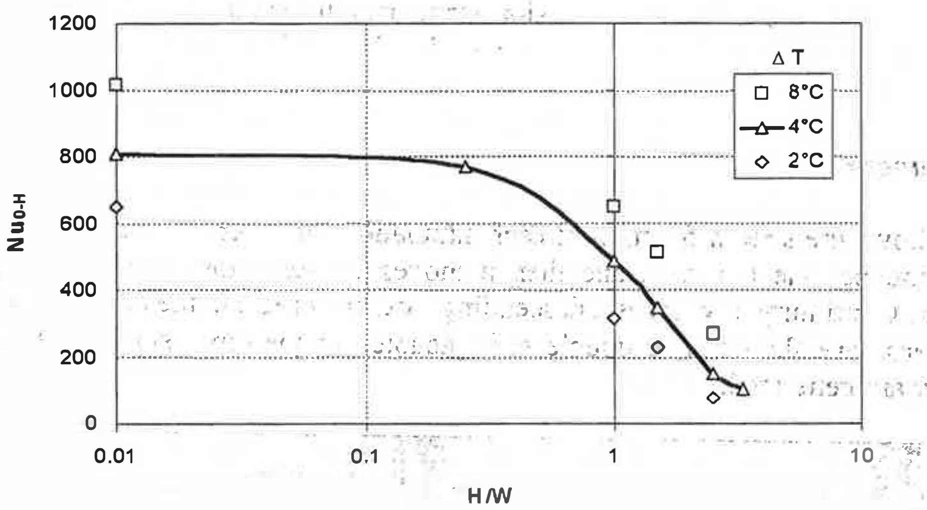

Figure 4. Average Nusselt numbers for different aspect ratios (H/W) and several temperature differences (ΔT)

Temperature distribution

A new definition of dimensionless temperature is necessary for thermally driven flows:

$$\theta = \frac{T - T_{ext}}{T_{sup} - T_{ext}} = \frac{T - T_{ext}}{\Delta T} \tag{3}$$

where: T Temperature at any point of the courtyard (°C)
T_{ext} External air temperature (°C)
T_{sup} Surface temperature of hot walls (°C)

Dimensionless temperatures become larger for smaller temperature gradients (ΔT). Figure 5 plots the average dimensionless temperature for the whole of the courtyard and for different aspect ratios and temperature gradients. When the aspect ratio grows, the dimensionless temperature tends to the asymptotic value of the unity.

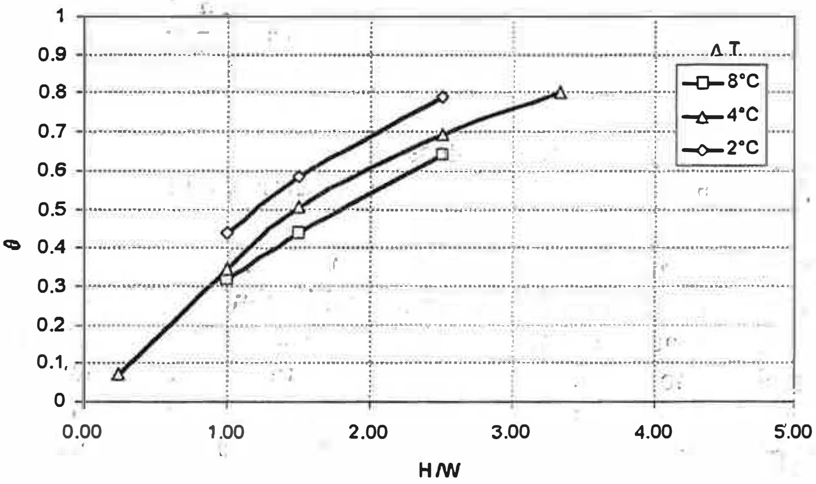

Figure 5. Average dimensionless temperature in the courtyard for several H/W and ΔT

Velocity patterns

Figure 6 shows the stream function of each simulation for several aspect ratios. Air is heated up when touches the hot wall, and then it moves up very close to the surface by natural convection. Continuity law forces a descending external stream in the middle of the courtyard. Flow patterns are shaped as a double swirl adapted to the dimensions of the courtyard in which they are generated.

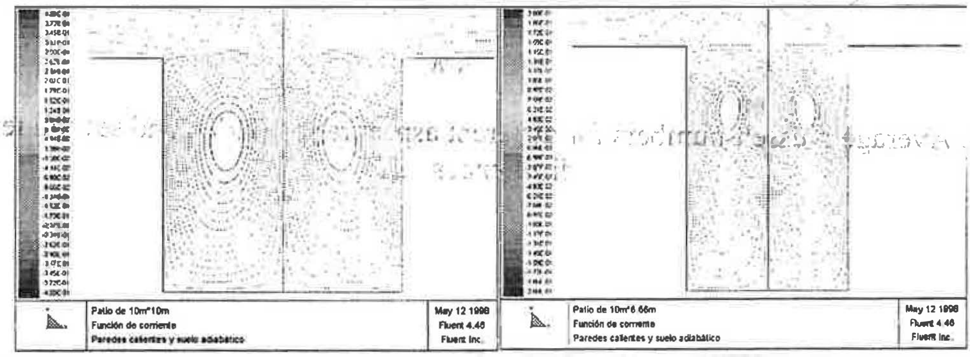

Figure 6. Stream functions for aspect ratios H/W = 1 and H/W = 1.5, with ΔT = 4°C

The amount of air entering by the top of the canyon is approximately the same for all the configurations where H/W is larger than one. However volumetric fluxes developed inside courtyards are totally different depending on the swirl intensity. Figure 7 shows vertical mass fluxes for several courtyards.

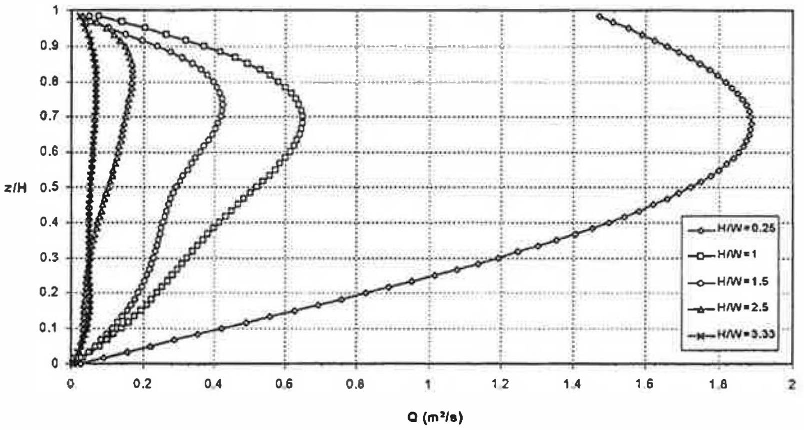

Figure 7:Vertical volumetric flux inside the canyon for several aspect ratios (H/W) and for $\Delta T = 4°C$

CONCLUSIONS

Wider courtyards have an improved capability for exchanging larger heat fluxes, as a result of larger external volumetric fluxes coming into the enclosure. For both wind driven and thermally driven flow, results show that courtyards are poorly ventilated spaces. Hence they seem to be very good places where a microclimate can be generated, as for example by cooling the volume by means of evaporating water. This paper has related temperature distribution with the flow pattern, characterised by Air Changes per Hour (ACH). Thus temperature distribution is closely linked with the behaviour of the recirculating vortex in the courtyard.

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