MODELLING OF THE HEAT ISLAND GENERATED BY AN URBAN UNIT

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ABSTRACT

This paper presents the theoretical modelling work of an elementary urban units (street), thermal behaviour. The calculation code Codyflow was set up as a way to model the thermal response (structure surface temperature and ambient air temperature) of an urban system to the solicitations of the outside climate. The determination of the air temperature in an urban unit allows the calculation of the ΔT_{u-r} factor representing the difference between the air temperature in the urban system (u) and the air temperature recorded at the closest meteorological station (r), generally situated in the country side. This factor, introduced by OKE, enables the analysis of the heat island generated by an urban system. The simulation results obtained from the Codyflow code, enable the study of the intensity of the ΔT_{u-r} factor in relation to various parameters : physical and geometrical configurations, presence of air flow solicitations...

INTRODUCTION

The presence of an urban site creates perturbations in temperature, humidity and velocity fields of the meso-climatic environment. The urban system can be assimilated to a climate transformer as it generates, from these meso-climatic characters, a specific micro-climate. This micro-climate corresponds to the thermal airflow response of the urban system to the meso-climatic environmental solicitations. It results in internal thermal transfers from conductive and convective origins and in advection and diffusion exchanges in the urban air (fig. 1)

The calculation code, Codyflow [1] was set up as a means to model the micro-climate generated by an elementary urban unit (street, green space, building group). This code is composed of a certain number of modules, each one characterising the thermal comportment of one part of the physical system (fig. 2).

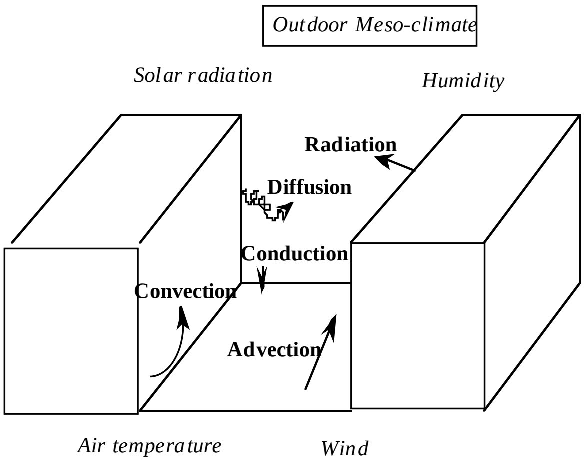


Fig 1. Overall external solicitations and internal heat flows considered in the evaluation of the urban canyon thermal answer.

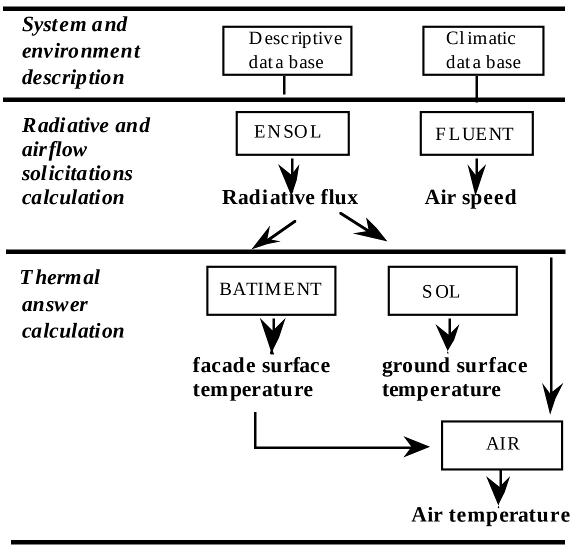


Fig 2. General layout of the Codyflow calculation code.

The objective, in the work presented, is the simulation of the air temperature in an urban canyon, as a way to make evident the heat island phenomena. The air temperature constitutes the major factor, in the study of a heat island, generated by a building group. The urban topology and the construction material used, lead to an ambiant air temperature greater than that representative of the meso-climate environment, due to the heat flows emitted and absorbed by the surfaces. This differnce between urban and rural temperatures, represented by the ΔT_{u-r} factor, enables the quantification of the intensity of the heat island generated. The common hypothesis used regarding its formation is listed in table 1.

Altered energy balance terms leading to positive thermal anomaly	*Features of urbanization underlying energy balance changes*
Increased absorption of short-wave radiation	Canyon geometry - increased surface area and multiple reflection
Increased long-wave radiation from the sky	Air pollution - greater absorption and re-emission
Decreased long-wave radiation loss	Canyon geometry- reduction of sky vie w factor
Anthropogenic heat source	Building and traffic heat losses
Increased sensible heat storage	Construction materials - increased thermal admittance
Decreased evapotranspiration	Construction materials - increased "water-proofing"
Decreased total turbulent heat transport	Canyon geometry - reduction of wind speed

Table 1 : Commonly hypothesised causes of the canopy layer urban heat island (OKE, 1982)

The study will initially describe the equations and physical models used for the determination of the air temperature in an urban unit. Secondly, the results of the simulation, obtained from Codyflow, which enable the study of the intensity of the heat island generated, are presented and analysed.

EQUATIONS AND MODELS

Description of the study configuration

The configuration studied was that of an urban canyon and its meso-climatic environment. The physical system is defined as a variable configuration regarding its geometry (building height, road width, roof overhang) and its physical characteristics (wall composition, ground surface layer, surface state of the facades).

The total of all the information concerning the description of the urban system is held in a descriptive data base, ahead of the mathematical models.

The meso-climatic data (air temperature $T_{amétéo}$, air humidity H_a, wind intensity V and direction γ) is held in a meteorological data base.

Calculation of the air temperature in an urban unit

The calculation of the air temperature in an urban unit requires the consideration of two cases : with or without wind. The wind or airflow solicitation have, in fact, an effect on the thermodynamic behaviour of the ambient air. The presence, or absence of airflow solicitation, induces different physical phenomena (fig. 3).

Thermal behavior of ambiant air		
Solicitation	***With wind***	***without wind***
Phenomenon interesting the ambiant air	Advection	Diffusion
Phenomenom interesting the surperficial exchanges	Forced convection	Natural convection

Fig. 3 Physical phenomena resulting from the type of airflow solicitation

The no wind case

Close to the walls and the ground, the air heats up and creates a turbulence from a convective origin. This accumulated heat, is transferred by turbulent diffusion to the ambient air volume. The evolution of the air temperature is governed by a system of equations, covering the diffusion of the heat in the air and the boundary conditions on the upper and lateral faces of the system (eq.1):

$$\frac{\partial T_{ai}}{\partial t} = \frac{\partial}{\partial x}\left(k_x \frac{\partial T_{ai}}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T_{ai}}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T_{ai}}{\partial z}\right)$$

Boundary condition for the air nodes near the surfaces

$$\rho\ C\ V_i \frac{\partial T_{ai}}{\partial t} = S_i\ h_{ci}\ (T_{si} - T_{ai})$$

Boundary condition for the upper layer air node

$$\rho\ C\ V_i \frac{\partial T_{ai}}{\partial t} = S_i\ k_z\ (T_{ai} - T_{météo})$$

Boundary condition for the lateral layer air node

$$\frac{\partial^2 T_{ai}}{\partial x^2} = 0$$

The turbulent phenomena is covered in the heat equation, through the empirical turbulent coefficients of perceptible sensible heat k_X, k_Y and k_Z, defined in function of the atmospheric stability f by [2]:

$$\begin{cases} k_z = A \cdot f \cdot z \\ k_x = \frac{1}{2} k_z \\ k_y = \frac{1}{2} k_z \end{cases}$$

A is an empirical constant equal to 0.05.

In a no wind situation, the thermal exchanges main direction is vertical. The values taken by k illustrate well the increase in heat exchanges at the moment when the atmospheric instability is at a maximum (12 PM.)

◊ **<u>The superficial temperatures $T_{s\,i}$</u>** are calculated from a thermal balance at the surface. This balance covers the whole of the flow, soliciting the surface or exchanged by it (eq. 2):

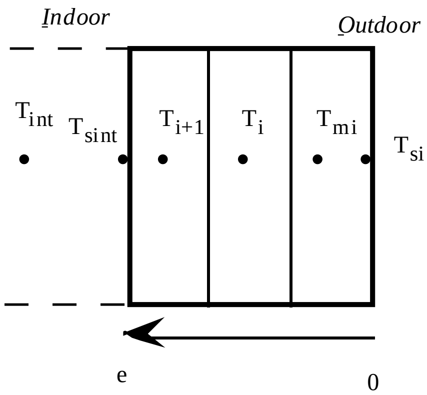
$$\rho\ C \frac{\partial T_{si}}{\partial t} = h_c\left(T_{ai} - T_{si}\right) + \frac{\lambda}{e}\left(T_{mi} - T_{si}\right)$$
$$+ \sum_{j=1}^{n} F_{ij}\ \sigma\left(T_{sj}^4 - T_{si}^4\right) + \phi_{Clo} + \phi_{Atmos}$$
$$- F_{iciel}\ \varepsilon_i\ \sigma\ T_{si}^4$$

where

•$h_c\left(T_{ai} - T_{si}\right)$ represents the heat transfers by convection between the surface and the adjacent air layer. The convective exchange coefficient hc, is a function of the established state of convection. In a no wind situation, the superficial exchanges are governed by a natural convection flow rate. In this case the convective exchange coefficient hc is calculated according to the difference between the surface temperatures and the air. Following to this the correlation established by ASHRAE[3] was retained.

• $\frac{\lambda}{e}\left(T_{mi} - T_{si}\right)$ represents the conductive transfer in the wall or the ground. The conduction is considered unidirectional. The temperature T_{mi} is defined as the temperature in the wall at a distance Δx of the surface; Δx having been set up by the operator. The determination of T_{mi} is obtained by the resolution of a thermokinetic model, composed of the heat equation and the adequate necessary boundary condition , enabling the consideration of the thermal conditions inside the ground and the buildings (fig. 4).

$$\begin{cases} \dfrac{\partial T(x,t)}{\partial t} = a\ \dfrac{\partial^2 T(x,t)}{\partial x^2} \\ \underline{\text{en}\ \ x = 0} \\ T(0,t) = T_{si} \\ \underline{\text{en}\ \ x = e} \\ \rho\ C \dfrac{\partial T_{sint}}{\partial t} = h_g\left(T_{int} - T_{sint}\right. \end{cases}$$



<u>Fig. 4 : The thermokinetic model</u>

•$\sum_{j=1}^{n} F_{ij}\ \sigma\left(T_{sj}^4 - T_{si}^4\right)$ represents the heat exchange by long wave radiations between a surface i and the surrounding surfaces j.

• Φ_{Clo} represents the short wave radiant flow, received by the surface element.

$$\phi_{Clo} = \xi\ \ I\ \ \cos h \cdot \sin \beta \cdot \ \cos(a - \gamma)$$
$$+\ \sin h\ \cos \beta + d_H\ F_{Ciel}$$
$$+ \sum_{j=1}^{n} F_{ij}\ \rho_j\ G_H$$

(eq. 4)

It is made up of the direct solar radiation, of diffused flows from the sky and reflected flows, composed by the overall diffuse reflected radiation by the surrounding surfaces.

The short wavelength flows bring an effect, on the one side, the shade factor ξ,enabling the consideration of the partial or non partial occultation of the surface element ($\xi \in [0\ ,\ 1]$) and on the other, the form factors between the surfaces and between a surface and the sky. These shape factors were determined with the use of the Gouffe method[4].

• Φ_{atmos} represents the diffuse atmospheric flows. It takes into consideration the long wave flows emitted by the atmosphere and received by a surface element:

$$\Phi_{atmos} = F_{i / Ciel} \; La$$

where the term $L_a = \varepsilon_c \, \sigma \, T_c^4$ correspond to the diffuse flow emitted by the atmosphere in its two windows of transparency

• $- F_{iciel} \, \varepsilon_i \, \sigma \, T_{si}^4$ represents the heat flow exchanged by long wave radiation between the surface and the sky.

The surface temperatures of the urban unit are taken as the boundary conditions in the determination of the ambient air temperature.

◊ **The boundary conditions** enable on the one hand the consideration of the vertical heat exchanges between the ambient air and the upper interface of the sky. and on the other, to lay down the no air flow condition throughout lateral interfaces.

Wind case

In the case were airflow solicitations exists, the calculation of the air temperature requests initially, the definition of the air velocity field in the urban unit. This airflow problem is dealt with by the use of the CFD (Computational Fluid Dynamics) Fluent code. From the initial wind conditions and urban unit geometric data, Fluent enables the determination of the air speed vectors in all parts of the system.

The model advocated for the calculation of the air temperature does not deal with the total fluid volume but only the occupation layer. This layer assimilated to a boundary layer, extends to a height of two metres. It enables the consideration of the individual, the pedestrian in the street.

In this layer, the hypothesis is that during a certain lapse of time·Δt, the heating of the air is due only to the convective exchanges between the walls and the ground.

At t+Δt, the ambient air volume stabilises with the exterior area , the thermal charges having been rejected outside the urban area by the advection phenomena.

The temporal development of the air temperature, for the occupation layer, is written as follows:

$$\rho \; C \; V_i \frac{\partial T_{ai}}{\partial t} = S_i \; h_{ci} \; (T_{si} - T_{ai}) \quad \text{(eq 5)}$$

◊ **The superficial temperatures Tsi** are determined by the use of the equation 2, as seen above. In this calculation, the only difference, is the calculation of the convective exchange coefficient hc. In the case of forced convection (existence of airflow solicitations), hc is calculated in function of the air speed close to the wall, using the correlation established by Sturrock[5].

The general physical model

The equations (1) and (5) show the link between the surfaces temperatures and the air. The resolution strategy is based on the iterative method, enabling the determination of the superficial temperature of the air (schema 1), in two successive modules.

Conclusion

The overall physical model presented above enables the fine determination of the air temperature in an urban unit and thus of the ΔT_{u-r} factor, into which the air temperature recorded at the meteorological station, plays an equal part.

The ΔT_{u-r} factor, enables the quantification of the heat island intensity generated by a building group. In the following paragraph, various Codyflow simulation results are presented, which enable the analysis of the influencing factors, on the intensity of the heat island.

RESULTS - DISCUSSION

Configuration of the study

The results presented were established for an urban configuration, of the type urban canyon as described in Fig. 5.

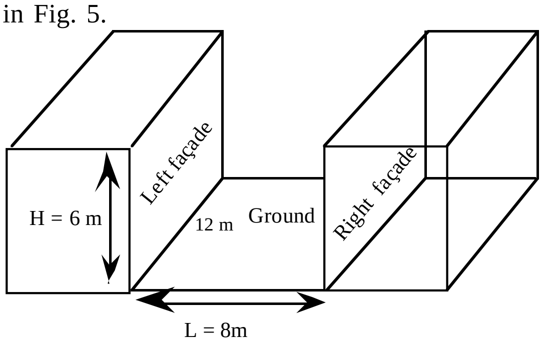


Fig. 5 : Geometric configuration studied

The orientation of the urban canyon, may vary from +90 to -90 in relation to the geographic North.

◊ *The walls* are constituted of a 20 cm layer of heavy concrete, the thermophysical characteristics of which are covered in table 2.

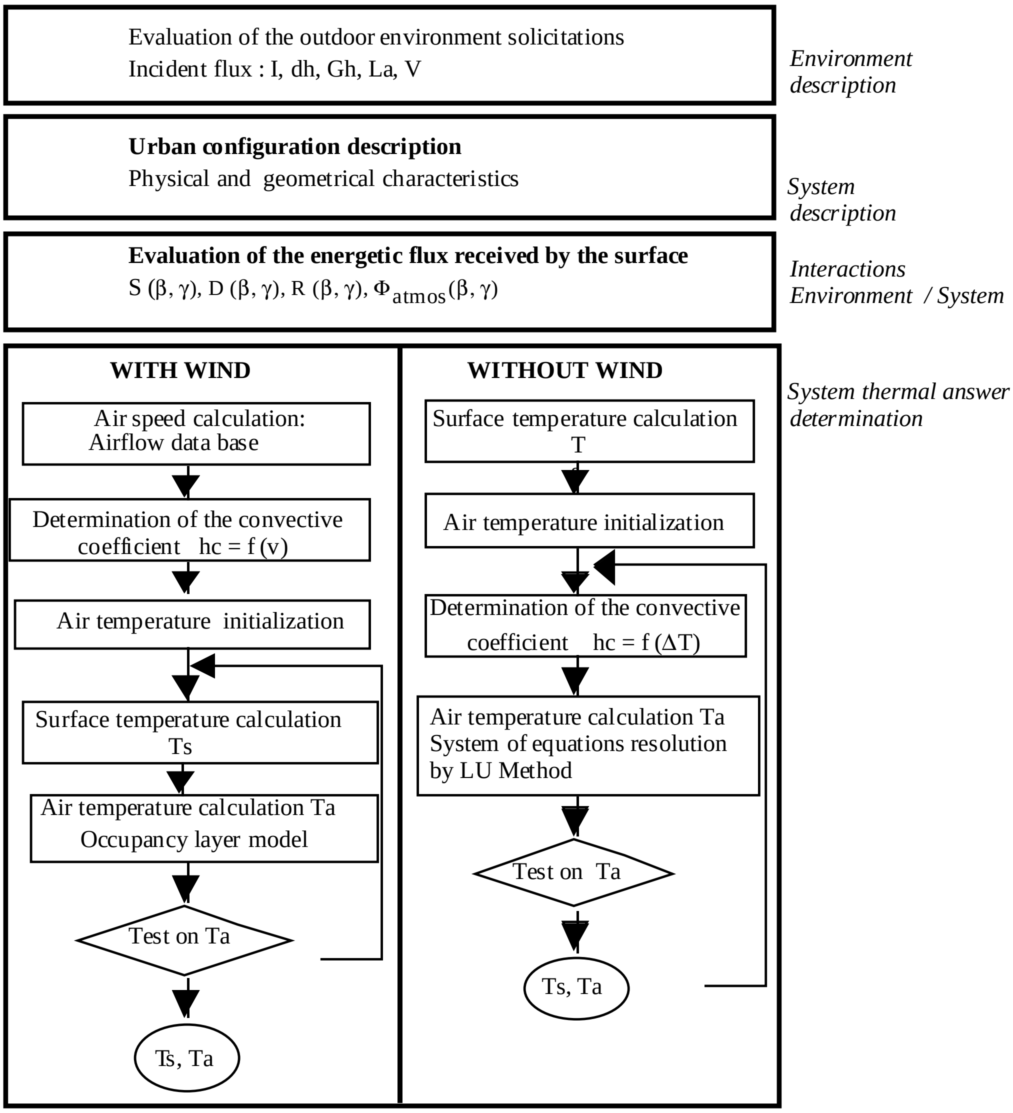


Schéma 1 : The physical model

◊ *The ground* is constituted of a layer of tarmac and a layer of soil, the characteristics of which are shown in table 2. The tarmac layer has, in certain cases been replaced by another material, to evaluate the influence of the different ground compositions, on the thermal results of the urban unit.

Parois	α	ε	λ W.m^{-1}.K^{-1}	ρ kg.m^{-3}	C J.kg^{-1}.K^{-1}
Concrete	0,3	0,8	0,92	2300	0,96
Sol (Asphalte:15 cm; Terre : 1m)	α	ε	λ W.m^{-1}.K^{-1}	ρ kg.m^{-3}	C J.kg^{-1}.K^{-1}
Tarmac *Soil*	0,15	0,95	0,75 0,48	2110 1800	0,87 0,64

Table 2 : Thermophysical characteristics of the materials used

◊ The boundary limits

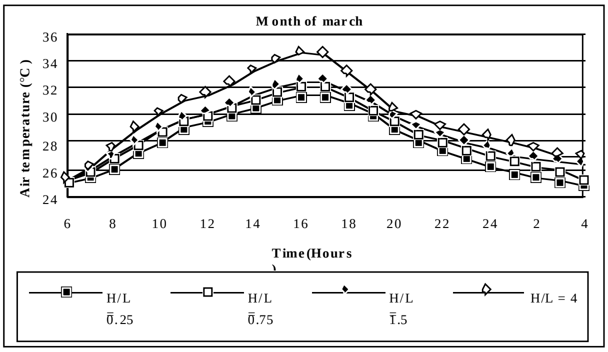
The interior building temperature is taken to be constant at 25°C.
The ground temperature at a depth z_0 = 1.1 metre is taken to be constant at 20°C [6].

Presentation of the results

The influence of the three factors on the air temperature in the urban unit and the intensity of the heat island generated have been studied : the geometric configuration, through the building height, the road width ratio (H/L) ,the materials used and the airflow solicitations.

Influence of the H/L ratio

The geometry of the urban canyon and more specifically the H/L ratio, plays a major role in the intensity of the heat island generated, as is shown in Fig. 6.



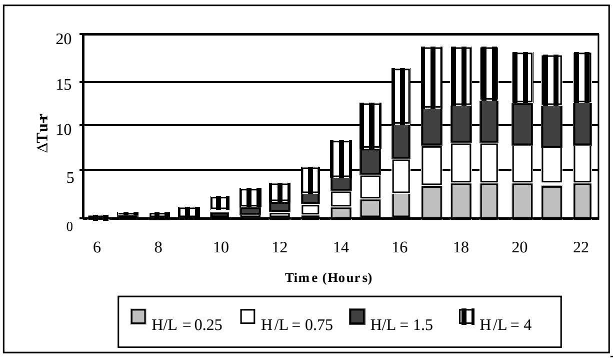


Fig. 6 : Air temperature and $\Delta T_{u\text{-}r}$ variations in function of the H/L ratio.

The variation of the H/L ratio creates variations in the evolution of the air temperature in the urban canyon,when playing on the form factor between the surfaces and the sky.
The narrower is the canyon, the greater the air temperature in the urban system is raised. The temperature difference reaches 6°C between a large canyon (H/L =0.25) and a narrow canyon (H/L = 4) at the least favourable hours of the day. The heat island phenomena is explained by the difference $\Delta T_{u\text{-}r}$. In the case of narrow canyon (H/L = 4) the factor $\Delta T_{u\text{-}r}$ can reach 7°C in comparison to 3.5°C in a large canyon.

Following on site experiments, Oke [7] correlated the maximum $\Delta T_{u\text{-}r(max)}$ value corresponding to the difference between the maximum mesoclimatic and heat island temperature values to the H/L, ratio by the equation :

$$\Delta T_{u\text{ - }r\,(max)} = 7.54 + 3.97 \ln\left(\frac{H}{L}\right)$$

This correlation was validated by Ahmed [8] through an experimental study at Dhaka (Bangladesh). Table 3 shows the comparison between the ΔT values resulting from the empirical correlation given by OKE and those generated by the simulation.

	H/L =0.25	*H/L = 0.75*	*H/L = 1.5*	*H/L = 4*
$\Delta T_{u\text{-}r\ (max)}$ mesured (Oke)	2.03	6.39	9.14	13.04
$\Delta T_{u\text{-}r\ (max)}$ simulated (Codyflow)	3.1	4.2	6	7.5

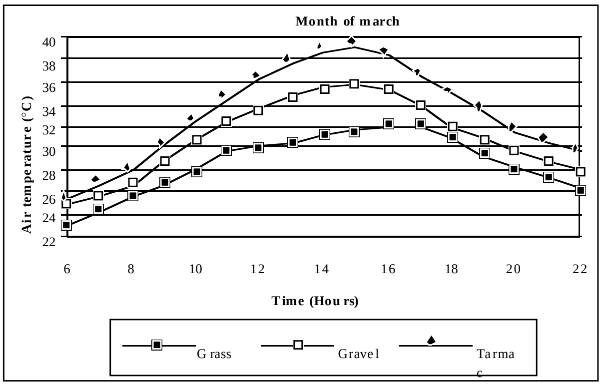
Table 3: Comparison between the $\Delta T_{u\text{-}r}$ (max) values obtained from experiments and calculations

The under estimation of the heat island intensity calculation code is related to various factors :
• The hydric process and the thermal effects due to the humidity were not considered by Codyflow in the evaluation of the air temperature : evapoperspiration phenomena and air heating due to the radiation absorbed by the water vapour.
• The physical effects and more particularly, the thermal effects of the urban environment of the urban unit are not taken into consideration by Codyflow, whereas the measures carried out by OKE were for a road situated in the town centre.

• The physical configuration of the studied system (materials used, surface state, interior wall constitution) is not defined by the experimenter.
The construction materials, have in fact, an influence on the air temperature in the urban unit, which is illustrated in the paragraph below; the air temperatures recorded at 50cm from the ground, in the case where it is made up of gravel, grass and tarmac, are compared.

Effects of the materials

By their thermophysical characteristics, the construction materials, modify the thermal component of the structures and thus the temperature results of the system. This property is illustrated in the graph Fig.7 showing the air temperature at 50cm in the ground for different materials.



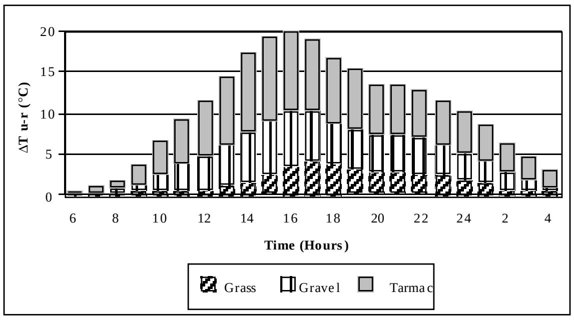


Fig.7 : The effects of different materials on the air temperature near ground level (0.5m)

These results make evident, the effect of a high inertia material (tarmac), on the air temperature, adjacent to the ground. A difference of 8°C between the air temperatures resulting from a tarmac surface and a grassed surface has been recorded.

The influence of airflow solicitations

The graphs in Fig. 8 show the effects of the wind on the average air temperature of the urban unit and on the ΔT_{u-r} factor.

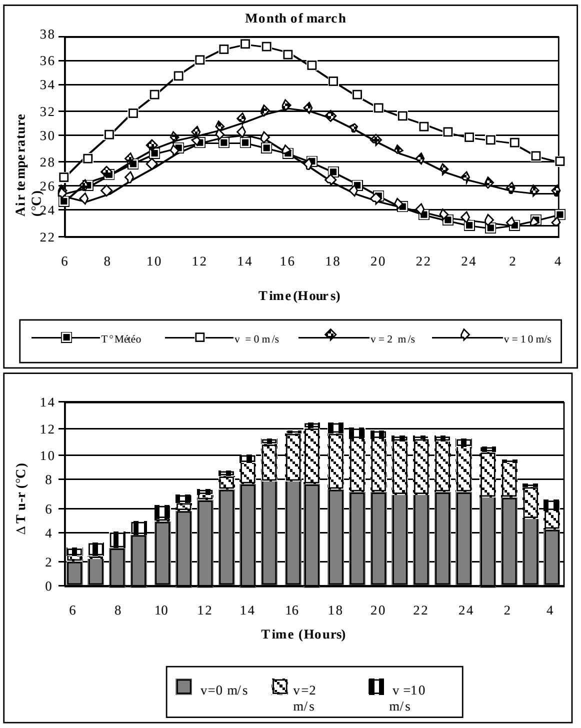


Fig. 8 : Evolution of the air temperature and the difference between the air temperature in the road and the temperature recorded by the meteorological station, for different wind speeds.

This results demonstrate the effect of airflow solicitations on the average air temperature in the urban system. In the case of a strong wind (v = 10 $m.s^{-1}$), the thermal charge is totally rejected outside of the urban unit. The advection transfers powers the air temperature in the urban unit towards those of the weather station ($T_{météo}$).

This effect is illustrated by the ΔT_{u-r} diagram.

CONCLUSIONS

The results presented, obtained from the Codyflow calculation are theoretical and exploratory. However, they enable certain answers to architects and urbanists for the conception phase of an urban project. Codyflow appears as a general simplified code, indispensable for interior use in urban conception. This code follows the directions of thermal works realised on buildings, where simplified codes increase the number of non-specialist users.

The aim of this paper was to illustrate the heat island phenomena , generated by an urban unit. It has shown evidence of the creation of a microclimates in the urban system, characterised by an ambient air temperature greater than that recorded at the local weather station. Evidence shows, important temperature differences between the system and the outside environment.

These different results are to be taken into consideration in the housing modelling codes in urban areas.

The Codyflow code, through its modular structure and multi-model, enables the development of the mathematical models put forward. Complementary research work is never the less necessary, to experimentally validate this calculation code.

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NOMENCLATURE

α absorptivity
e emissivity
I direct solar radiation (W. m^{-2})
dh diffuse radiation (W. m^{-2})
h solar altitude (m)
hc convective heat transfer coefficient (W. m^{-2}. $°C^{-1}$)
l thermal conductivity
R reflected radiation (W. m^{-2})
La atmospheric radiation (W. m^{-2})
Φ_{clo} short wavelength flux (W. m^{-2})
Φ_{atmos} flux exchanged with sky (W. m^{-2})
Φ_{glo} long wavelegnth flux (W. m^{-2})
Φ_{cond} conductive flux (W. m^{-2})
Φ_{conv} convective flux (W. m^{-2})
S_i surface (m^2)
Ts surface temperature (°C)
Ta air temperature (°C)
V_i volume (m^3)