Computer model and simulation of a traditional passive cooling ventilation system in a modern building in Mazara Del Vallo (Italy)

Beccali M., Finocchiaro P.

DREAM Dipartimento di Ricerche Energetiche ed Ambientali, Università degli Studi di Palermo,Viale delle Scienze edif. 9-90128 Palermo Italy, Tel. +39+091236211;Fax. +39+091484425;

Corrao R., Balsamo V., Giordano D.

DPCE Dipartimento di Progetto e Costruzione Edilizia, Università degli Studi di Palermo,Viale delle Scienze edif. 8-90128 Palermo Italy, Tel. +39+091234144; Fax +39+091488562;

ABSTRACT

Traditional and modern natural ventilation techniques have been integrated in a hybrid system for a retrofitting of a public building in the city of Mazara del Vallo (Italy). The hybrid ventilation and air cooling system integrates a wind tower, an indirect evaporative heat exchanger, a ground cooling pipe network and ventilated façade. The first idea was to design a passive cooling system inspired to the typical wind towers of the Middle East, being the area very well ventilated. On the other hand, air humidity in summer is quite high and therefore the effectiveness of indirect evaporative cooling can be quite low. For this reason, it was adopted a second passive cooling system consisting in a ground heat exchanger which cools down further the air stream. Air exiting form the buried pipes is then drawn into the building. The whole system has been designed in order to achieve the required air-flow rate only by means of wind pressure and stack effect.

From the thermal point of view, the system was designed, modelled and tested by using a dynamic simulation software (TRNSYS). The building has been simulated with a two-zones model coupled with a natural ventilated façade. The climate of the site as well as the influence of the solar radiation on the building were investigated by means of the software ECOTECT. Results are interesting in terms of energy saving for cooling and air circulation and gives useful hints to refine the design process.

1. INTRODUCTION

The aim of the study is the retrofitting of a public building in Mazara del Vallo (Italy) used as a museum. An integrated passive cooling and ventilation system was chosen as alternative to a conventional ventilation system. Both the building and the passive ventilation system as well as the reference system were simulated with the software TRNSYS.

The proposed system is based on traditional architectural concepts typically used in the Mediterranean area but also on some modern building technologies. A wind tower similar to the one used Iran, a cooling system that reminds of the old Scirocco rooms of Palermo, ventilated façade similar to the mashrabiya are the main components of the proposed system.

Thanks to a self orienting capture element set on the top of the wind tower, the required ventilation air stream is drawn into the building. The available pressure comes out from two contributions: the pressure caused by the wind on the aperture of the capture element of the wind tower and the stack effect caused by the indirect evaporative cooling of the outside air stream (Santamourius, Matt, 1998).

After the wind tower, the air stream enters a buried pipe network, where it is further cooled down. At the outlet of the ground heat exchanger, the air stream enters the building and then it is extracted as shown in Figure 1.

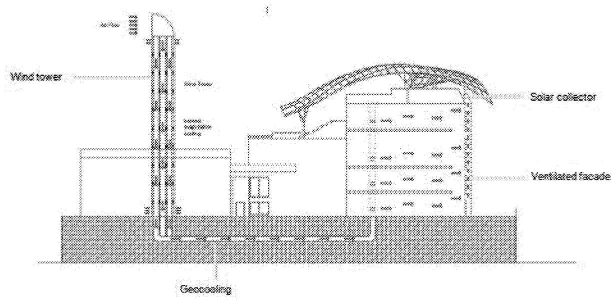

Figure 1. Air flow paths in the building

2. CLIMATIC ANALYSIS

Mazara del Vallo is situated in the south-eastern coast of Sicily, a zone which is characterized by high wind speed but without a prevailing direction. This condition has been verified by means of the software ECOTECT. The results of the analysis are shown in Figure 2. For a certain wind direction, the darker is the colour, the higher is the wind speed, whereas the successive circles indicate the height above the ground.

Thanks to the analysis, a rotating wind capture element able to pick up the wind independently from its direction was designed. The climatic data used in the simulations comes from the database of ECOTECT for the site Trapani-Birgi.

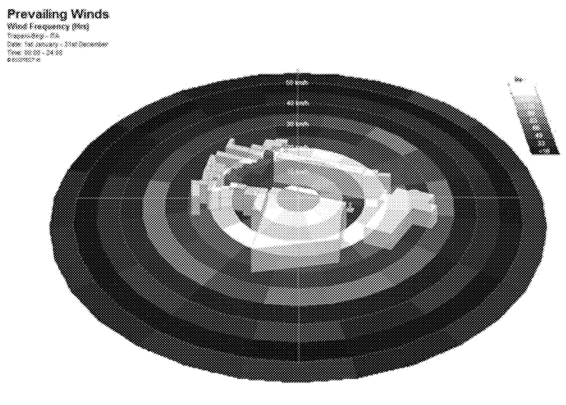

Figure 2. Building orientation and prevailing wind directions

Figure 3 shows in a Mollier diagram temperature and relative humidity of the outside air for the summer months. It can be noted that the maximum temperature for the outside air exceeds 35°C.

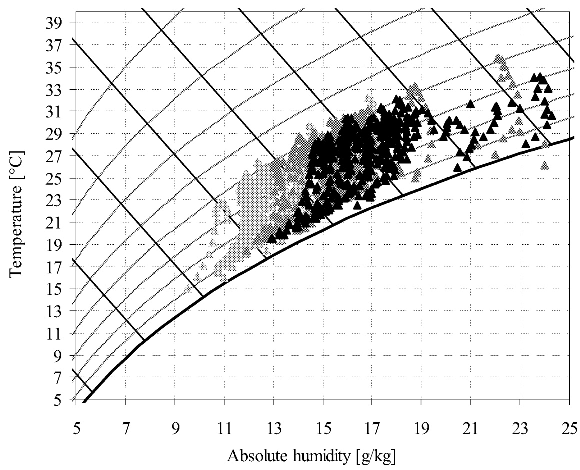

Figure 3. Hourly temperature and absolute humidity values for the considered site in June (light grey), July (dark grey) and August (black)

Thanks to the simulations carried out, it could be possible to characterise the influence of the solar radiation on the main façade of the building to optimize the shading elements as it is shown in Figure 4.

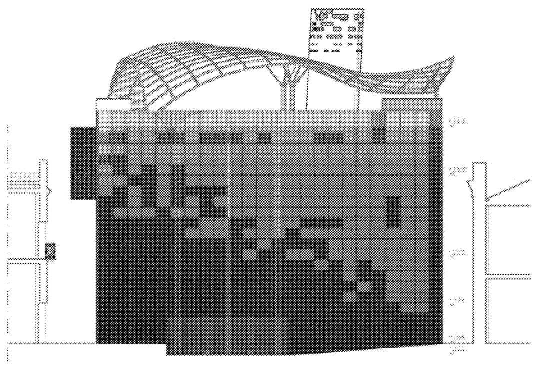

Figure 4. South-east façade of the building with marble shading elements

3. THE BUILDING

The building has been simulated by means of the TRNSYS type 56. The building was divided in two thermal zones as shown in Figure 5. Statistical occupation patterns have been simulated with a maximum value of 350 occupants and 150 as mean value.

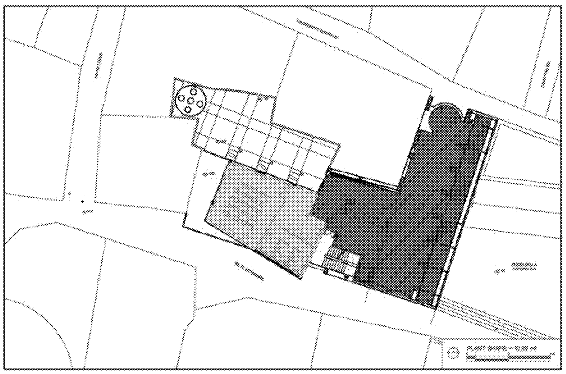

Figure 5. Thermal zones of the building

The overall ventilation air flow rate was set to 7300 m^3/h that means 1,8 1/h air change. Windows are made of aluminium frame and clear double glass with a U-value of 2,95 W/m^2K. External walls and the roof have a overall U-value respectively of 0,45 and 0,37 W/m^2K. The main façade of the building is south-east oriented.

By means of the subroutine Trnbuild the cooling sensible and latent loads of the building were determined, fixed the required indoor temperature and relative humidity respectively to 26°C and 50%. The operation time assumed for the ventilation system was from 8.00 to 20.00.

For the two zones of the building, results of the thermal analysis are shown in Figure 6 in terms of maximum peak loads and cooling energy demand. In the calculation, the mentioned ventilation air change was considered.

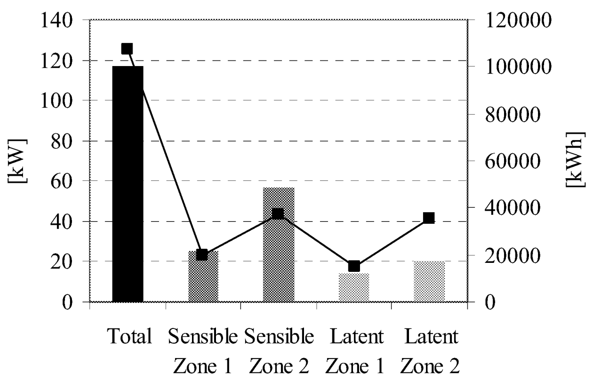

Figure 6. Cooling loads of the building in terms of peak (left) and demand (right)

4. DESCRIPTION OF THE PASSIVE VENTILATION SYSTEM

The wind tower is made of a hollow cylindrical structure with five steel air ducts inside with a diameter of 0,7 m and a overall height of 24 m.

The external duct containing the mentioned five air ducts has a diameter of 3 m. A scheme of the proposed system is reported in Figure 7. For the system modelling a custom TRNSYS type has been created. The system has been modelled as a counterflow air to water heat exchanger where a water film evaporates at the outside surface. The incoming air is cooled by saturated outdoor air.

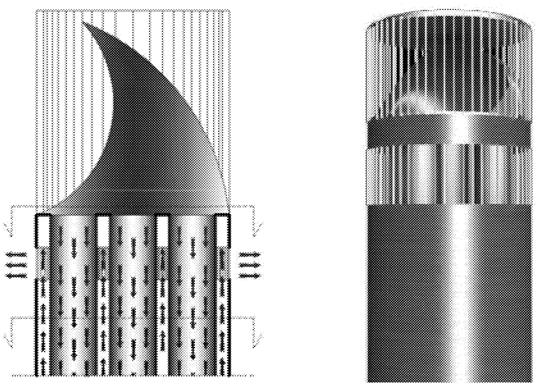

Figure 7. Scheme of the wind tower

Its operation is based on the indirect evaporative cooling process as shown in Figure 8. The proposed system provides the required air change and contributes for the cooling of the building.

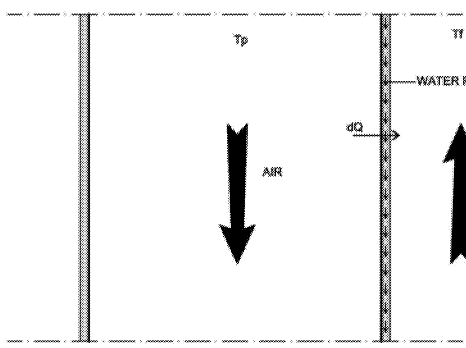

Figure 8. Heat transfer process due to the indirect evaporative cooling process

In order to achieve both a good thermal efficiency in the wind tower system and low pressure drops in the air ducts, the sizing of the wind tower and air ducts needed an iterative calculation process. For a fixed geometry of the air ducts, the produced air flow rate and the thermal efficiency of the wind tower were simulated for the summer season with a time step of 1 hour.

For the calculation of the continuous and localized pressure drops the following expressions were utilized (Kreith, Frank):

$$\Delta P_{cont} = f \cdot \frac{H}{D_{eq}} \cdot \rho \cdot \frac{V^2}{2} \quad (1)$$

$$\Delta P_{loc} = a \cdot \rho \cdot \frac{V^2}{2} \quad (2)$$

where:

f: Friction coefficient between the air flow and the duct

H: Length of the air ducts

D_{eq}: Equivalent diameter of air ducts

ρ: Air density

V: Air velocity in the duct

The overall pressure drop can be determined as the sum of the previous terms (1) and (2).

$$\Delta P_{drop} = \Delta P_{cont} + \Delta P_{loc} \quad (3)$$

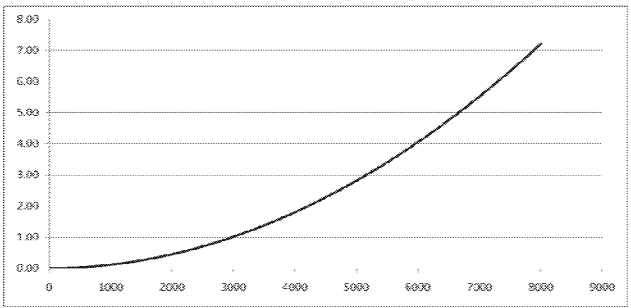

Figure 9. Overall pressure drop in Pa versus air flow rate in m3/h

For the calculation of the pressure head produced by the wind tower, two different contributions were considered: the pressure head caused by the wind speed and the one related to the stack effect.

The pressure difference due to the wind speed may be expressed as:

$$\Delta P_{wind} = \tfrac{1}{2} \cdot \rho \cdot (C_{p,in} + C_{p,out}) \cdot V^2 \quad (4)$$

where $C_{p,i}$ and $C_{p,out}$ are the wind pressure coefficients at the tower head inlet and outlet section of the building. $C_{p,i}$ is positive and $C_{p,out}$ is negative. These coefficients are determined through experimental studies of cool tower models in wind tunnel (Badran, Ali A., 2003). Values of coefficients may be selected as $C_{p,i}$ = 0.85 and $C_{p,out} = -0.17$. Hence, $C_p = C_{p,i} - C_{p,out} \approx 1$.

On the other hand, the pressure difference due to the stack effect may be expressed as:

$$\Delta P_{\rho} = H \cdot g \cdot (\rho_{in} - \rho_{out}) \quad (5)$$

where:

g: Gravity acceleration

ρ_{in}: Air density at inlet of the wind tower

ρ_{out}: Air density at outlet of the wind tower

The overall pressure head can be determined as the sum of the previous terms (4) and (5):

$$\Delta P_{tot} = \Delta P_{wind} + \Delta P_{\rho} \quad (6)$$

As a results, the air flow rate can be calculated setting equal the ΔP_{tot} and the ΔP_{drop}. Figure 10 shows the air flow rate produced by the wind tower and delivered to the building for two selected weeks in August. It can be seen that for the considered time period the system reaches averagely the required air flow rate.

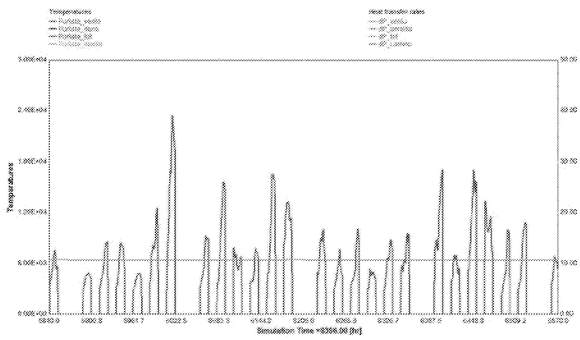

Figure 10. Air flow rate delivered to the building for two weeks in August

The thermal analysis of the system was carried out by means of a natural convection model. In particular, for the specific case the following expressions were used respectively for the calculation of the convection coefficient at the external and internal surface of the ducts (Bonacina, 1989, National Building Code of Jordan):

$$h_w = \frac{Nu_w \cdot \lambda_w}{\left(\frac{v_w^{\ 2}}{g}\right)^{\frac{1}{3}}} \quad (7)$$

$$h_f = \frac{Nu_f \cdot \lambda_f}{D_{eq}} \quad (8)$$

$$Nu_w = 3{,}3 \cdot 10^{-3} \cdot \mathrm{Re}_w^{\ 0.3} \cdot \mathrm{Re}_p^{\ 0{,}15} \cdot \mathrm{Pr}_w^{\ 0{,}61} \quad (9)$$

$$Nu_f = 0{,}023 \cdot \mathrm{Re}_p^{\ 0.8} \cdot \mathrm{Pr}_f^{\ 0{,}3} \quad (10)$$

where:

λ_w: Water thermal conductivity
v_w: Velocity of the water at the external surface of the ducts
λ_f: Thermal conductivity of air at the internal surface of the ducts
D_{eq}: Equivalent diameter of air ducts

From the previous expressions the overall heat transfer coefficient of the system can be calculated as follows:

$$U = \frac{1}{\frac{1}{h_f} + \frac{1}{h_w} + \frac{s}{\lambda}} \quad (11)$$

where:

λ: Thermal conductivity of duct material
s: Thickness of the air ducts

For the calculation of the thermal efficiency of the system, the ε-NTU method was used (Bonacina, 1989).

Therefore the efficiency could be calculated as follows:

$$\varepsilon = \frac{1 - \exp\left[-NTU \cdot (1 - r))\right]}{1 - \left[r \cdot \exp(-NTU \cdot (1 - r))\right]} \quad (12)$$

$$NTU = \frac{U \cdot A}{\dot{C}_{\min}} \quad (13)$$

$$r = \frac{\dot{C}_{\min}}{\dot{C}_{\max}} \quad (14)$$

where:

C_{min}: Minimal heat capacity rate
C_{max}: Maximum heat capacity rate
A: Heat transfer area

For two selected weeks in August Figure 11 shows simulation results of overall thermal efficiency of the system.

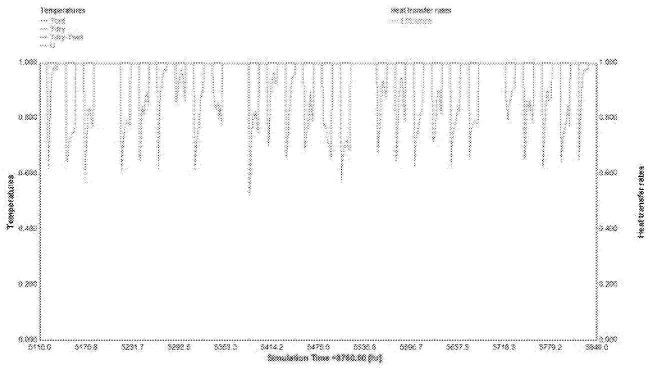

Figure 11. Thermal efficiency of the wind tower for two weeks in August

The heat transfer process causes a temperature decrease of the outside air flow ranging from 5 up to 8°C, with an seasonal mean thermal efficiency of 0,73. The air coming from the tower is then canalized in buried pipes with a length of 28 m at depth of three meters.The TRNSYS models used for buried pipe network and the ground were Type 556 and Type 77. For the most cases considered in the simulations, the ground heat exchanger shows a lower contribution in terms of temperature decrease of the air stream in comparison to the one produced by the wind tower reaching the maximum values of 3-4°C.

5. RESULTS

The results are presented in terms of reduction of cooling energy demand of the building obtained by the proposed passive cooling system in comparison to a conventional reference ventilation system. As a reference cooling system was assumed a typical electric ventilation and cooling system composed by an common air handling unit and cooling devices located in the conditioned area. Figure 12 shows the cooling energy demand reduction for the proposed system.

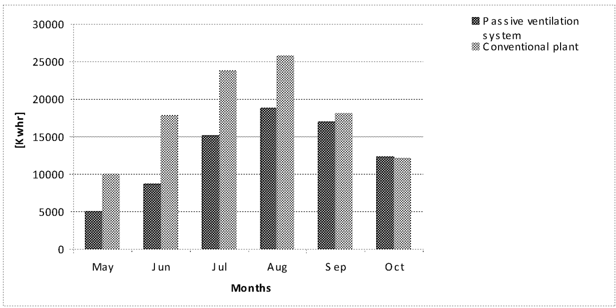

Figure 12. Cooling energy demand of the building coupled with the proposed and reference system

The reduction of the cooling energy demand for the whole summer season amounts to about 30%. The seasonal primary energy consumption for the reference and passive cooling system were calculated as follows:

$$PE = \left(E_{el\_fan} + \frac{Q_{cooling}}{COP} \right) \cdot \frac{1}{\eta_{el}} \qquad (13)$$

where:

E_{el_fan}: Electricity consumption for the air circulation

η_{el}: Average electric system efficiency = 0,4

COP: Coefficient of performance of the electric chiller = 3

The seasonal primary energy consumption of the proposed passive cooling system and the reference one are respectively about 25,5 MWh and 39 MWh, that means a primary energy saving of about 35%. It can be noted that, besides the thermal benefits obtained, the passive cooling system doesn't need any electricity for the air circulation. Figure 13 shows the primary energy consumption monthly diagrammed.

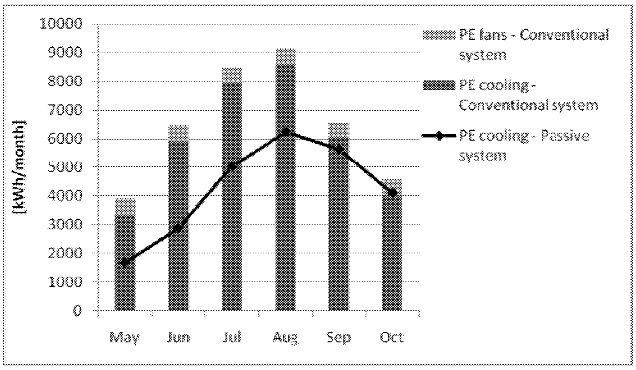

Figure 13. Primary energy consumption for the reference and passive cooling system

6. CONCLUSIONS

The passive cooling and ventilation system presented combines typical elements used in the traditional Mediterranean architecture with modern energy saving concepts and materials.

Contrarily to the expected results, the simulations carried out have shown a lower contribution of the ground heat exchanger in terms of air temperature decrease achieved in comparison to the one produced by the wind tower. Global energy performances obtained are interesting both in terms of energy saving for cooling and air circulation.

The primary energy saving in summer operation amounts to 35% in comparison to the conventional reference system considered .

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