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Evaluation of the effects of courtyard building shapes on solar heat gains and energy efficiency according to different climatic regions

Enes Yaşa [a,*], Vildan Ok [b]

[a] N.E.U. Faculty of Architecture, Deparment of Architecture, Meram, Konya 42090, Turkey
[b] Üresin apt. Gülden sok., No:3,Selamiçeşme, Kadıköy, İstanbul 34437, Turkey

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A B S T R A C T

The courtyard buildings, which we face either as a regulator of inter-building microclimate or as a climatic regulator at urban scale especially in hot climate regions, and which constitute one of the fundamental characteristic building styles of such climatic regions, should be applied in a form compatible with the features of the climatic region it is used. There is the need for a study that allows formation of a model toward determination of the optimum courtyard form and meeting the conditions of comfort by establishing an optimization model taking into consideration the climatic, meteorological differences for each climatic region the specific climatic region requires. The purpose of this study is to examine the energy efficiencies of the courtyard buildings used either as a micro climatic regulator in hot-dry climatic regions, or as a climatic regulator at urban scale, and to determine inter-building and courtyard comfort statuses, besides, to manifest different thermal behaviors of such buildings by estimating the same fully and accurately using real meteorological data under different design and climatic conditions with computer energy simulation on different courtyard form options put forth for different climatic regions, and thus to provide new information to designers at the process of putting forward the optimum courtyard form according to the characteristics and data of the specific climate for different climatic regions. By using the CFD program, this study has analyzed the thermal comfort statuses and energy performances of 7 different courtyard shapes in inter-courtyard and building volumes that are discussed in hot-dry, hot-humid and cold climatic regions as well as the effect of the sunbeams received by the building surface and the daily solar movement on the thermal performance on the building. As a result of the entire analysis made for all building shapes, the obtained values were interpreted and the total energy performances were evaluated for each climatic region. In this study, the courtyard buildings will be assessed in terms of their thermal performances.

1. Introduction

When we look at the courtyard buildings in general, we see that recently, frequent studies are conducted for examining inter-courtyard thermal performance. Such studies can be examined as inter-courtyard air movements, courtyard-building-sun-shadow relation and building-courtyard option and inter-courtyard air movement relation as well as thermal performances of courtyards in different climatic regions. In other study conducted for evaluating the effect of courtyard option on the total energy performance; Clark and Aldawoud [1] examined the energy performance of the central atrium whereby the energy performance of a courtyard building with the same geometry and ratio has been comparatively examined [2]. In another study, which examined the effects of building shape and form on climatic performance in different climatic regions and which assessed the courtyard option in environmental terms, Ratti et al. [3] conducted numerical analysis studies on the shape and form of courtyard building, the relevant building form and its climatic performance in environmental terms. In a different study that examined the thermal performance of courtyard building, Mohsen [4,5] assessed the solar radiation effects of the geometric and physical parameters of the courtyard on the courtyard building façade. The variability of the radiation, which was obtained by changing the courtyard parameters, was examined [4,5]. Muhaisen and Gadi [6] on the other hand, conducted many studies on the courtyard shape and courtyard buildings. These especially focus on the effect of courtyard shape on solar radiation gain-loss, and also on the sun-shadow effect. The purpose of the study conducted by this couple in 2006 is to provide enough radiation in order to obtain the heat required by the building during winter and to reduce the required

* Corresponding author. Tel.: +90 532 505 1705.
E-mail addresses: enesyasa@yahoo.com, eyasa@konya.edu.tr (E. Yaşa), okv@itu.edu.tr (V. Ok).

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Nomenclature

A_o	amplitude of periodic temperature variation (°C)
c	specific heat (J/kg K)
F_o	Fourier number = $\Delta H_t/(H_x)^2$
h	heat-transfer coefficient (W/m^2 K)
I_s	solar radiation lux (W/m^2)
k	thermal conductivity (W/m K)
L	layer thickness (m)
N	number of layers
q	heat flux (W/m^2)
R_e	effective resistance (m^2 K/W)
R_n	nominal resistance (m^2 K/W)
t	time (s)
T	temperature (°C or K)
T_f	*i*, indoor air temperature (°C)
T_f	*o*, outdoor air temperature (°C)
T_f	*o*, mean outdoor air temperature (°C)
T_{sky}	sky temperature (K)
υ	wind speed (m/s)
x	coordinate direction (m)

Greek letters

α	thermal diffusivity (m^2/s)
Δx	internodal distance (m)
Δt	time step (s)
ε	surface emissivity
λ	solar absorptivity density (kg/m^3)
σ	Stefan–Boltzmann constant (W/m^2 K^4)
Φ	phase shift angle (rad)
Ω	frequency (rad/s)

Subscripts

c	convection
$con\upsilon_i$	inside convection
$con\upsilon_o$	outside convection
i	inside surface or nodal point
o	outside surface
r	radiation exchange
s	solar radiation

energy for the cooling requirement during summer; or for providing sufficient shadow area, to proportion the courtyard's inner envelope or to conduct a courtyard shape study [6]. In another study they conducted, they examined the effect of inter-courtyard sun-shadow performance; and developed a mathematic model for calculating the shadowed and sunny areas of courtyard buildings in circular geometry. This model so developed examines, during any period within the year, the interactions between the sun and the courtyard buildings in circular geometry, the latter located on ground in any ratio or dimension [7]. In another study that touched upon the courtyard shape and option, Muhaisen and Gadi [6] examined the shadowing performances of many angled courtyard shapes such as pentagon, hexagon, heptagon and octagon. Recently, the literature hosts studies that especially examine the thermal performances of CFD and courtyard option [8,9]. Among these, Rajapaksha et al. [10] examined in CFD the passive cooling potential of courtyard buildings, which have single storey and intense massive envelope and located in hot humid climate regions, and manifested the results obtained from this calculated analysis (CFD) and thus asserted that as far as buildings with single storey and highly dense masses are concerned, courtyard buildings located in hot humid climatic regions are suitable for passive cooling. Another study conducted by the Rajapaksha et al. [11], examined the passive cooling potential of the courtyard in a building with single storey and highly dense mass under a hot-humid climate. They tested the presence of inter-courtyard in building design, and its potential to increase and optimize the natural ventilation for minimizing the extremely hot conditions in internal volumes.

Recent years especially witness an increase in numerical simulation studies. Experimental studies are lesser in comparison. An example of studies conducted in this direction is the study of Safarzadeh and Bahadori named: "Airflow in Buildings with Courtyards" [12]. In order to forecast the inter-courtyard airflow ratios by taking into consideration, within the courtyard, the air speeds and air flow directions of courtyard buildings located in the Hot-Dry climatic regions of Iran such as the cities of Ahwaz, Kerman, Mashad, Shiraz, Tabriz and Tehran, comparisons have been made both experimentally in a wind tunnel and through numerical simulations, and findings have thus been reached. It was consequently seen that owing to the wind shadowing effects by the courtyard wall and the trees in the courtyard, the wind pressure coefficients on the walls of the windward buildings have decreased as compared to buildings without courtyard [11]. Another study conducted by Muhaisen and Gadi, emphasizes the effects of the courtyard building shapes with different ratios, and especially of their sun related gains, on total energy. The study aims at observing the ratio at which the heating and cooling requirements of a courtyard building located in a particular climatic region are effected by the variability of the radiation that is obtained as a result of the increase in the surface area of the courtyard shape [6]. All these studies suggest that the number of advanced studies apart from some acknowledgements and certain methods is quite few. Additionally, studies and examinations on the subject show that concerning the courtyard buildings in question, we are far from a comprehensive strategy and research on what kind of direct effects they have in terms of either energy efficiency or climatic comfort, as well as how they act. For this reason, the purpose of the below study is the formation of a model toward the determination of the optimum courtyard form and meeting the conditions of comfort by establishing an optimization model while taking into consideration the climatic, meteorological differences for each climatic region that is required by the specific climatic region and accordingly, to evaluate the energy performances of all courtyard options examined.

2. Limitations and assumptions in the case study

This study is limited to comparative analyses between seven different yard building options considered for application in plot centers of "Hot-Dry Climate", "Hot-Moist Climate" and "Cold Climate" with different characteristics dominant in Turkey.

The width of the courtyard being increased at east–west direction in proportion with the building height, a total of 24 h of analyses for each option have been made separately on hourly basis. For each configuration, 7th month and 21st day, in other words, July 21st constituting the example of the hottest period has been elected as the average of the long-term meteorological data for summer months or cooling period instead of all months and days of a year; and 1st month and 21st day, in other words, January 21st, the example of the coldest period, has been elected as the average of the longest period meteorological data average for the winter months or heating period. The reason why these days are discussed is that data where average values are frequently encountered have been found out for the heating and cooling periods having examined the long term meteorological data. The limitation of the courtyard building transparent surface rates, however, the transparent surface ratio of the courtyard option in non-building facades is 20%,