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Indoor thermal comfort in urban courtyard block dwellings in the Netherlands

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A B S T R A C T

Global warming and elevated temperatures in the Netherlands will increase the energy demand for cooling. Studying passive strategies to cope with the consequences of climate change is inevitable. This paper investigates the thermal performance of courtyard dwellings in the Netherlands. The effects of different orientations and elongations, cool roofs and pavements on indoor thermal comfort are studied through simulations and field measurements. The results show that North-South and East-West orientations provide the least and most comfortable indoor environments. Regarding materials, the use of green on roofs and as courtyard pavement is the most effective heat mitigation strategy. It was observed that the effects of wet cool roofs are much higher than of dry roofs. Cool roofs did not show a specific negative effect (heat loss) as compared to conventional asphalt roofs in winter. Some simulation results were validated through field measurement with a 0.91 °C root mean square deviation.

1. Introduction

Global warming is affecting human thermal comfort [1], and it is estimated that by 2050, the air temperature in the Netherlands could be up to 2.3 °C warmer than in the period from 1981 to 2014 [2]. The built environment can intensify or moderate the environment. The Royal Dutch Meteorological Institute (KNMI) has translated the IPCC variants to four main scenarios in the near future in 2050 [3]. Based on the severest scenario, the expected number of summer days with temperatures exceeding 25 °C would be 41 days in 2050 (the mean temperature in the Netherlands is around +10 °C). For residential buildings, this is important, since these for indoor comfort need to be adjusted to higher outdoor temperatures. Preferably this needs to be done without mechanical interventions, because correction by means of air-conditioning units would increase the consumption of fossil fuels, thereby further aggravating climate change and heating up urban areas locally due to waste heat from the cooling device. One of the most commonly used building archetypes in hot climates is the courtyard form. Courtyards provide shading and consequently a cool microclimate within a building block. It may also ease ventilation through the stack effect. The thermal behaviour of courtyard buildings has extensively been studied in hot and arid climates, but rarely in temperate regions such as West Europe. Courtyards exist in the Netherlands; rarely as single family houses, but mainly as urban blocks. With the warmer future climate estimated for the Netherlands, this study tries to make this archetype climate proof. Therefore, this paper explores the effect of different courtyard geometries and orientations on the thermal comfort of dwellers in the Netherlands. Heat mitigation strategies such as greenery or high albedo materials on roofs and within courtyards are investigated through simulations. An experiment on a scale model of a courtyard with different roofs and courtyard pavements is done to support the results of the simulations. At the end, a one-month field measurement in an actual courtyard house in Delft is done as a validation of the simulation program used in this paper.

1.1. Thermal behaviour of courtyard buildings

Courtyards have been used mostly in harsh climates in order to provide more shading in hot climates, more ventilation in humid climates and more protection against cold winds in temperate and cold climates. In a comparison between different building forms, Okeil [4] generated Residential Solar Blocks (RSB) based on the courtyard form and showed that it is more energy efficient than slabs and pavilions in the hot and humid climate of UAE. In the hot

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and humid climate of Dubai, Thapar and Yannas [5] showed the importance of ventilation in urban squares. They also indicated the importance of the cooling effect of vegetation in providing a comfortable microclimate such as a courtyard.

Ratti et al. [6], based on the six archetypal forms of Martin and March [7], made three “realistic” block layouts for a hot and arid climate. They concluded that the courtyard configuration led to a more favourable micro-climate because of more favourable environmental variables (surface to volume ratio, shadow density, daylight distribution, and sky view factor) as compared to two different pavilion types.

In the temperate climate of the Netherlands, Taleghani et al. [8] compared courtyard buildings with different urban layouts (linear and singular blocks with the same floor area). They showed this typology has the least summer discomfort hours. This was because of the lower surface-to-volume ratio of the courtyard, and it's shading on the surrounding buildings.

To have a better understanding of the thermal performance of courtyard buildings, Wadah [9] describes three main climatic functions that these buildings dealt with;

a) Courtyard buildings can be used as sun collectors and/or sun protectors [6]. The correct orientation and the proper position of the building and its courtyard should be taken into account based on the latitude of the site.
b) Wind has two effects on a courtyard building. First it circulates between exterior spaces and inside the courtyard; second it ventilates the interior building by the courtyard air. In hot areas during the night, warm air rises and leaves the microclimate of courtyard. Then, the cooler air will replace the existing air. Hence, during the hot day, cool air is circulated to the rooms and the courtyard is a source of fresh and cool air [10]. In snow regions there is limited circulation between the courtyard and the building. Moreover, in tropical regions where the temperatures of outside and inside of a courtyard building are close to each other, the courtyard is used for refreshing the interior air.
c) Different natural elements can be utilised in a courtyard to increase the humidity. Humidity is needed in arid areas to achieve comfort by increasing the relative humidity of the air. Plants and water bodies are the major elements used in hot and arid areas. The evaporation and corresponding increase of humidity are a result of sun and wind. Obviously, in other climates in which humidity is not required, fewer natural elements are used.

1.2. Highly reflective materials and cool roofs

Dark surfaces used in urban environments and the lack of vegetation increase the ambient air temperature in cities. This phenomenon is called the urban heat island (UHI) which is more sensible in summer [11,12]. Akbari, Division [13] in a study on American metropolises showed that peak urban electric demand rises by 2–4% for each 1 °C increase in air temperature. This is an indirect effect of dark materials; but, the direct effect is their higher absorption of solar energy. With a low albedo, dark materials reflect less solar radiation increasing their surface temperature and as a result increasing the energy use for the cooling of buildings, especially during the peak periods of energy demand.

There is a large body of literature on highly reflective materials and vegetated (green) surfaces studied in the hot climates of the USA [14–17] and southern Europe [18–20]; and recently in colder climates such as in Moscow (Russia) [21,22], Toronto (Canada) [23,24], and Gothenburg (Sweden) [25]. Vegetation and highly reflective materials are becoming ever more studied and used; however, there are challenges in the use of green roofs. First, the installation and maintenance costs of these roofs are relatively problematic. Sproul, Wan [26] with an economic perspective on 22 case studies with different roof colours showed that relative to black roofs white roofs provide a 50-year positive net savings and green roofs a negative net savings. Second, the behaviour of these roofs (known as cool roofs) is not always beneficial in winter. This could be due to the shading effect of vegetation on the roof but also due to the higher thermal conductivity of water in wet green roofs and the evapotranspiration of vegetation [27]. Liu and Minor [28] showed that with a proper drainage and insulation layer this problem could be solved for a cold climate like Toronto (Canada).

Reviewing the literature, what has been less studied is the effect of cool materials on the microclimate of urban courtyards, and also its effect on the indoor comfort of the dwellers. The other missing (and important) research in the literature is the thermal behaviour of cool materials and green roofs in winter (in dry and wet modes). Therefore, in this paper the effect of highly reflective materials and vegetation on the roof and on the ground of the courtyard is investigated; in summer and winter, and in dry and wet modes. This will be done through simulations and actual experiments.

2. Methodology

2.1. Research phases

This paper consists of three phases. Phase 1 is done through computer simulation. Phase 2 shows the results of a scale model, and phase 3 is a validation of the simulation model using field measurements in an actual courtyard house.

Phase 1 evaluates different criteria in designing a comfortable and energy efficient courtyard building for the temperate climate of the Netherlands. This is a parametric study which is necessarily done with computer simulation (using DesignBuilder). The investigated parameters are the orientations of a courtyard, the effect of different pavements and roofs, differences between different sides and locations in a courtyard building, and etc. To validate the simulations done with DesignBuilder, phase 2 and 3 were done. Phase 2 is a scale model experiment and phase 3 is a field measurement on an actual courtyard house. In phase 2, the effect of different pavements and roofs (that were previously simulated) are checked. In phase 3, the effect of different locations in a courtyard house is checked and validated with the simulations. With these validation phases, it is tried to have the most accurate results. The phases are explained comprehensively here:

2.1.1. Phase 1

In phase 1, eighteen courtyard buildings are studied for their indoor thermal comfort in the hottest summer week in a reference year (between 16th and 23rd of June). The development of the weather data file for the reference year is explained by Taleghani et al. [29].These buildings are modelled in DesignBuilder and the thermal properties of the walls, roofs and windows are described in Table 1. The roofs are conventional bitumen. The facades are brick cavity walls with 10 cm expanded polystyrene standard (EPS) insulation inside the cavity. The type of windows is Double LoE (e2 = .2) Clr 6 mm/6 mm Air. The window to wall ratio is 30%. The

Table 1
The properties used in the simulations.

	U-value W/(m^2K)	Thickness (m)
Roof	0.31	0.210
Wall	0.33	0.350
Glazing	2.55	0.018