

A Review of Urban Heat Island Effect and the Role of Convective Heat Transfer Coefficient

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Abstract. The urban heat island (UHI) effect represents a significant environmental challenge associated with rapid urbanization worldwide. This comprehensive review examines the intricate relationship between urban underlying surface properties and the UHI phenomenon, with particular emphasis on the pivotal role of the convective heat transfer coefficient (h_c). The paper systematically analyses how various urban surface materials, including asphalt, concrete, bricks, and vegetation, differentially influence local thermal environments through variations in their thermal properties and surface characteristics. The discussion focuses on the mechanisms through which these materials alter surface-atmosphere energy exchange processes, ultimately contributing to spatial heterogeneity in UHI intensity. Furthermore, this review explores the development of rapid assessment frameworks based on empirical relationships between material properties, surface roughness, wind speed, and convective heat transfer efficiency. These analytical frameworks facilitate rapid assessment of urban heat island (UHI) effects and furnish practical decision-support tools for urban planners and designers to select thermally optimal materials in urban development and renewal initiatives. The interdisciplinary implications spanning urban climatology, environmental physics, and urban planning are examined, along with future research directions for enhancing urban thermal environments and promoting sustainable urban development strategies.

Keywords: Urban Heat Island (UHI), Convective Heat Transfer Coefficient, Urban Surface Materials, Surface–Atmosphere Energy Exchange

1. Introduction

The urban heat island effect has emerged as one of the most pronounced environmental manifestations of rapid urbanization worldwide. This phenomenon refers to the characteristic elevation of temperatures in urban areas compared to their rural surroundings, creating distinctive "islands" of heat within urban landscapes. First documented by Luke Howard in the early 19th century through observations of London's climate, the urban heat island (UHI) effect has since been recognized as a ubiquitous feature of urban environments across diverse geographical and climatic contexts [1].

This phenomenon has profound implications for energy consumption, environmental quality, and public health. The elevated temperatures characteristic of UHI effect directly increase cooling

energy demands during warm periods, exacerbating peak electricity loads and contributing to higher greenhouse gas emissions [2]. Additionally, the thermal stress associated with UHI effect can significantly impact human health and comfort, particularly during heatwave events when urban temperatures may reach dangerous levels. Furthermore, the UHI effect influences air quality by modifying chemical reaction rates and facilitating the formation of secondary pollutants such as ozone.

This review aims to synthesize current understanding of the UHI phenomenon with particular emphasis on the role of convective heat transfer processes at the urban surface-atmosphere interface. Traditional research has predominantly focused on factors such as urban geometry, population density, and land use patterns when explaining UHI formation. However, recent investigations have increasingly highlighted the crucial role of turbulent exchange processes and particularly the convective heat transfer coefficient (h_c) in modulating UHI intensity across different urban morphologies.

2. Formation mechanisms and influencing factors

The emergence of urban heat islands (UHI) originates from substantial modifications to the surface energy balance, induced by the substitution of natural landscapes with built environments. The energy balance equation for urban surfaces can be conceptually represented as the interplay between net radiation, sensible heat flux, latent heat flux, and heat storage in the urban fabric. Natural landscapes, characterized by vegetation and permeable soils, facilitate substantial latent heat flux through evapotranspiration, which effectively dissipates incoming solar radiation [3]. In contrast, urban surfaces—predominantly composed of impervious materials such as asphalt, concrete, and brick—possess distinctly different thermal characteristics that promote the conversion of solar radiation into sensible heat, consequently elevating the temperature of the overlying air layers.

The thermal properties of urban materials play a crucial role in this energy partitioning process [4]. Artificial materials typically possess low albedo (particularly dark surfaces like asphalt), high thermal capacity, and high thermal conductivity, causing them to absorb more solar radiation, heat up quickly, and retain heat for extended periods. This thermal inertia results in elevated nighttime temperatures, which represents a characteristic feature of the UHI phenomenon. Additionally, the complex three-dimensional structure of urban areas creates urban canyons that trap radiant heat and reduce sky view factor, further inhibiting nocturnal cooling processes.

Several key factors contribute to the development and intensity of the UHI effect. Urban underlying surface properties represent perhaps the most fundamental factor, as the transformation of natural surfaces to artificial materials (concrete, asphalt, masonry) radically alters surface-atmosphere interactions [5]. The composition and morphology of urban surfaces influence their radiative properties, thermal characteristics, and aerodynamic properties, all of which modulate heat exchange processes.

Anthropogenic heat sources constitute another significant contributor to UHI intensification [6]. Human activities in urban areas—including industrial processes, transportation, and building operations—continuously release waste heat that directly adds to the urban thermal load. The magnitude of anthropogenic heat emission varies spatially and temporally, with particularly pronounced contributions during winter in northern cities where heating systems may sometimes exceed solar net radiation as the dominant heat source.

Air pollution further exacerbates the UHI effect through multiple mechanisms [7]. Urban atmospheres contain elevated concentrations of aerosols and greenhouse gases that absorb terrestrial longwave radiation, contributing to a localized greenhouse effect. Additionally, pollutants affect the

radiation balance and consequently influence UHI intensity in complex ways that may exhibit diurnal asymmetry—with potential cooling effects during daytime due to reduced solar radiation and warming effects at night through inhibition of surface heat loss.

The regional climate background also exerts considerable influence on UHI magnitude and characteristics. Research indicates that humid climate cities tend to experience more pronounced UHI effects because suburban natural vegetation exhibits higher convective cooling efficiency, while urban surfaces experience reduced convective efficiency [8]. This climate sensitivity highlights the necessity of formulating context-specific UHI mitigation measures that incorporate regional climatic disparities.

3. The central role of convective heat transfer coefficient

The convective heat transfer coefficient (h_c) has emerged as a critical parameter in understanding the spatial variability of urban heat island intensity. Physically, h_c represents the efficiency of sensible heat exchange between urban surfaces and the adjacent atmosphere, quantified as the rate of heat transfer per unit area per unit temperature difference. In the surface energy balance equation, h_c directly determines the magnitude of sensible heat flux, which, alongside latent heat flux, constitutes the primary components of surface energy partitioning.

The significance of h_c in the UHI context stems from its role in modulating the cooling potential of urban surfaces [9]. Surfaces characterized by higher h_c values more efficiently dissipate heat from the surface to the atmosphere, thereby mitigating increases in surface temperature. Conversely, surfaces with lower h_c values exhibit reduced heat dissipation capacity, leading to greater surface temperature increases under identical insolation conditions. This differential heat transfer efficiency explains why otherwise similar urban areas can exhibit substantially different thermal behaviours.

The value of h_c depends on several factors, with surface roughness and wind speed representing the primary determinants. Surface roughness influences h_c through its effect on aerodynamic resistance and turbulence generation. Natural vegetated surfaces with high roughness promote mechanical turbulence development, enhancing convective heat transfer; urban smooth surfaces suppress turbulence, reducing heat exchange efficiency. Wind speed represents another crucial driver, as increased advection enhances convective heat transfer rates. The relationship between h_c and wind speed typically follows an empirical power law, with the exact parameters depending on surface characteristics.

The thermal properties of surface materials also indirectly influence h_c through their effect on surface temperature, which establishes the temperature gradient driving convective heat transfer. Materials with low albedo and high thermal conductivity attain higher surface temperatures under solar radiation, creating stronger temperature gradients that potentially enhance convective heat transfer. However, this effect may be offset by other material characteristics that influence the aerodynamic properties of the surface-atmosphere interface.

The complex interplay between these factors results in substantial spatial heterogeneity in h_c across urban landscapes. This heterogeneity contributes significantly to the observed spatial variability in UHI intensity, as surfaces with low h_c values (e.g., smooth asphalt pavements) contribute more substantially to the UHI effect than surfaces with high h_c values (e.g., vegetated areas). Understanding and quantifying these relationships provides valuable insights for urban planning and design aimed at mitigating undesirable thermal effects.

Measurement of h_c presents considerable methodological challenges due to the complexity of urban environments and the dynamic nature of surface-atmosphere interactions. Approaches include direct measurement using micrometeorological techniques such as eddy covariance systems, which

quantify turbulent fluxes directly, and indirect inference through thermal imaging and modelling techniques. Recent developments have enabled more refined characterisation of h_c across a wide range of urban surfaces, thereby enhancing the parameterisation of urban surface processes in climate models.

4. Assessment frameworks and methodological innovations

The development of practical frameworks for assessing UHI effects based on convective heat transfer principles represents an important innovation in urban climate research. These assessment approaches typically build upon established relationships between surface characteristics, meteorological parameters, and convective heat transfer efficiency to enable predictive capability regarding UHI intensity.

Central to these frameworks are empirical relationships derived from extensive observational data that correlate surface material properties, roughness characteristics, and wind speed with resulting h_c values. These relationships often take the form of "material + roughness-wind speed- h_c " curves that establish quantitative associations enabling prediction of h_c from relatively easily measurable parameters. Such empirical curves demonstrate that: (1) for identical wind speeds, higher surface roughness yields greater h_c values; (2) h_c increases with wind speed, but the rate of increase depends on surface roughness; and (3) differences in h_c between materials are more pronounced at lower wind speeds.

Based on these empirical relationships, researchers have developed classification matrices that categorise h_c values into ranges corresponding to specific UHI intensity levels. These matrices enable rapid assessment of UHI effects based on h_c values alone, providing an intuitive tool for preliminary evaluation of urban surface thermal performance. The matrices typically reveal that surfaces with low h_c values (e.g., asphalt, concrete) contribute most significantly to the UHI effect, while surfaces with high h_c values (vegetated surfaces) substantially mitigate the UHI intensity.

These technical developments have been translated into field-deployable methodologies that enable practical assessment of UHI effects in urban environments. The typical procedure involves: (1) identification of surface material type through image recognition or field records; (2) estimation of surface roughness based on material type and surface condition; (3) measurement or estimation of local wind speed conditions; (4) determination of h_c using empirical relationships; and (5) assessment of UHI intensity level through consultation of classification matrices. This approach enables relatively rapid evaluation of how different urban surfaces contribute to the UHI effect, providing valuable insights for material selection during urban development projects.

The integration of these assessment frameworks with thermal comfort indices such as Physiological Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI) represents a further methodological advancement. By combining information about surface thermal behaviour with human thermal comfort models, these integrated approaches provide a more comprehensive understanding of how material choices affect not only ambient temperatures but also human thermal sensation, enabling more people-centred urban design.

5. Applications and future directions

The comprehension of convective heat transfer mechanisms in urban settings, coupled with the formulation of assessment frameworks grounded in this knowledge, offers extensive practical applications in urban planning, design, and governance. These applications span multiple scales

from individual building design to city-wide climate adaptation strategies, reflecting the pervasive influence of surface-atmosphere interactions on urban thermal environments.

At the urban planning level, knowledge of h_c and its relationship to UHI intensity informs material selection for urban infrastructure projects. Planners can use this information to prioritise thermally optimal materials for pavements, roofs, and other surfaces, thereby reducing the thermal load on urban areas. Specifically, surfaces with higher h_c values (typically associated with greater roughness) may be preferred in areas where heat mitigation is a priority, while surfaces with lower h_c values might be strategically employed in cooler climates where winter heat retention is desirable [5].

The integration of h_c considerations into urban design guidelines represents another important application. By establishing performance standards based on thermal criteria, municipalities can encourage or require development practices that mitigate undesirable UHI effects. These guidelines might address aspects such as minimum vegetation coverage, maximum impervious surface ratios, or required thermal properties for building materials, all informed by an understanding of how these factors influence convective heat transfer and ultimately urban temperatures.

At the building scale, architects and engineers can incorporate h_c principles into building design to improve thermal performance and reduce cooling energy demands. Building envelope design, exterior material selection, and site planning can all be optimised to enhance convective cooling during warm periods, particularly when combined with other passive cooling strategies such as shading and ventilation. These approaches contribute to improved indoor thermal comfort and reduced mechanical cooling requirements.

The application of h -based assessment frameworks extends to climate change adaptation planning as cities prepare for projected temperature increases and more frequent heatwaves. By identifying areas particularly vulnerable to heat stress based on their surface characteristics, cities can prioritise intervention strategies and target resources toward communities at greatest risk. These adaptive approaches become increasingly important as climate change exacerbates existing UHI effects through rising baseline temperatures.

Looking forward, several promising research directions emerge that could further advance our understanding and management of UHI effects. These include: (1) improved characterization of h_c across a broader range of urban surfaces and climatic conditions; (2) enhanced integration of remote sensing and in situ monitoring for more comprehensive spatial assessment; (3) development of more sophisticated modeling approaches that better represent the complex interactions between urban surfaces, atmosphere, and human systems; and (4) exploration of synergistic effects between multiple mitigation strategies to identify optimal combinations for specific urban contexts.

The ongoing development and refinement of high-resolution modelling systems specifically designed for urban applications represents a particularly promising avenue. These modelling systems, capable of simulating urban climate processes at kilometre-scale resolution, offer unprecedented ability to predict how different urban configurations and adaptation strategies might perform under various climate scenarios. When combined with emerging artificial intelligence techniques, these tools may enable more proactive and targeted urban heat management strategies.

Additionally, there remains a need for more interdisciplinary research that bridges the physical science of urban climates with social science perspectives on vulnerability, adaptation, and governance. Such integrated approaches would facilitate more equitable and effective heat mitigation strategies that address not only the biophysical aspects of UHI effect but also the social dimensions of heat vulnerability and adaptive capacity.

6. Conclusion

This review has examined the complex interplay between urban surface characteristics, convective heat transfer processes, and the urban heat island phenomenon. The compiled evidence reveals that the convective heat transfer coefficient (h_c) acts as a key determinant of the emergence and magnitude of urban heat island (UHI) phenomena by virtue of its influence on surface-atmosphere heat exchange dynamics. Variations in h_c across different urban surfaces, driven primarily by differences in surface roughness and wind conditions, contribute significantly to the spatial heterogeneity observed in urban thermal environments.

The development of assessment frameworks based on empirical relationships between surface properties, meteorological parameters, and h_c values represents an important advancement in urban climate research. These frameworks enable relatively rapid evaluation of UHI effects and provide practical tools for urban planners and designers seeking to mitigate undesirable thermal consequences of urban development. By facilitating evidence-based material selection and urban design decisions, these approaches contribute to more thermally sustainable urban futures.

In conclusion, the convective heat transfer coefficient represents a crucial parameter in understanding and addressing the urban heat island effect. By elucidating the mechanisms through which urban surfaces influence local thermal environments through convective processes, this research provides valuable insights and tools for creating more sustainable and livable cities in the face of ongoing urbanisation and climate change.

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