

Building heat transfer in a changing climate

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Abstract—Buildings are being retrofitted to adapt to the changing climate and reduce energy usage and fuel poverty. UK retrofit guidance refers to steady-state heat transfer through the building envelope. This simplification greatly reduces computational complexity but neglects the thermal inertia of the building envelope, i.e., its ability to store and delay transmission of thermal energy. The resultant inaccuracies in calculations of indoor temperatures can be significant, yet there is no robust method for determining the suitability of steady state analysis. Furthermore, it is unknown how climate change affects the suitability of using steady-state analysis. Presented here is a novel analysis of the dynamic nature of the interaction between a building and its environment. The temperature field inside the building wall is used to characterize the dynamic nature of heat transfer under different climatic conditions. Analysis is performed with current air and sol-air temperatures and predicted future air temperatures. Seasonal climatic variations, building construction type and the retrofit purpose are suggested to be key factors in the suitability of steady state analysis.

Keywords—Heat transfer, thermal inertia, climate change, diurnal temperature range, retrofit.

I. INTRODUCTION

In 2024, the average global temperature was more than 1.5°C higher than in the preindustrial baseline period of 1850–1900 [1], and could exceed 4°C higher by 2100 [2]. Mitigating this climatic change requires reducing fossil fuel use and overall energy consumption. Regardless of much further warming occurs, the impacts of the resultant extreme weather on human health and the built environment will continue to intensify [3]. It is therefore essential to adapt to the changing climate.

In 2022, building operation and construction accounted for 34% of global energy demand and 37% of global CO₂ emissions [4]. Retrofitting existing buildings for energy efficiency mitigates these climate impacts by reducing operational energy demand and avoiding the GHG emissions associated with new buildings [3]. Energy efficiency retrofits are also vital for reducing fuel poverty among vulnerable people [5].

In the UK, guidance for retrofitting dwellings for improved energy efficiency is provided by Building Regulations Approved Document L and Publicly Available Specification 2035 (PAS 2035:2023)[6]. In both

sources, the thermal performance of the building fabric is described by the steady-state thermal transmittance (U-value in building terminology). In steady state, one-dimensional heat transfer through a surface of a solid is described by the Fourier conduction law,

$$\dot{Q} = -\lambda A \frac{dT}{dx}, \quad (1)$$

where $\dot{Q}$ is the heat flow, λ is the thermal conductivity, A is the area of the slab and x is linear distance. Temperature is constant in time, i.e., $T = T(x)$, and so the temperature gradient through the solid is linear. For a slab of thickness X with surface temperatures T_0 and T_1 ,

$$\frac{dT}{dx} = \frac{\Delta T}{\Delta x} = \frac{T_1 - T_0}{X} = \text{constant}. \quad (2)$$

This leads to the definition of thermal transmittance, U ,

$$\dot{Q} = \frac{\lambda A (T_0 - T_1)}{X} \Leftrightarrow U = \frac{\dot{Q}}{A(T_0 - T_1)} = \frac{\lambda}{X}. \quad (3)$$

Hence, U is the steady-state heat transferred per unit time through a unit area of a slab whose faces differ by a unit temperature. In reality, heat transfer across a wall is dynamic, or unsteady, with temperatures varying in time t , i.e., $T = T(x, t)$. One-dimensional unsteady heat transfer is described by the Fourier continuity equation,

$$\frac{\partial^2 T}{\partial x^2} = \frac{\rho c}{\lambda} \frac{\partial T}{\partial t} = \frac{1}{\kappa} \frac{\partial T}{\partial t}, \quad (4)$$

where ρ is the density, c is the specific heat capacity and κ is the thermal diffusivity. In the steady state the volumetric heat capacity ρc has no effect as there is no change in the internal energy of the material. For a building, this means the flow of energy into or out of a room is constant. In dynamic heat transfer, the thermal capacity does have an effect. Internal energy does change in time, and, equivalently, temperature gradients are neither constant nor linear. This concept is illustrated in Figure 1.

Steady state analysis – as opposed to dynamic – can result in significantly inaccurate calculations of indoor temperatures and the energy required for space conditioning [7]. Such inaccuracies may lead to inefficient

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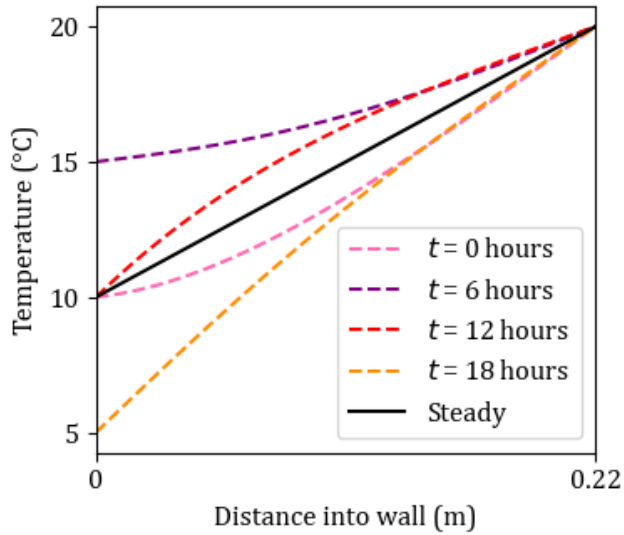


Fig. 1. Temperature gradients in a brick wall of thickness $X = 0.22$ m. Outer surface (left) varies sinusoidally between $T_1 = 5^\circ\text{C}$ and $T_1 = 15^\circ\text{C}$; inner surface (right) is fixed at 20°C . Dashed lines show the temperature gradient in the wall at different times throughout a 24-hour cycle, solid line shows the steady state component. A steady state thermal analysis ignores the dynamic behaviour shown by the dashed lines. This may be significant. (Thermal parameters: $\lambda = 0.84 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, $\rho = 1700 \text{ kg}\cdot\text{m}^{-3}$, $c = 800 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$, $\kappa = 6.18 \times 10^{-7} \text{ m}^2\cdot\text{s}^{-1}$.)

uses of energy and resources and can seriously impact the health and comfort of occupants.

There are many methods for assessing unsteady heat transfer through building envelopes, including the admittance method described by the Chartered Institute of Building Services Engineers (CIBSE) [8]. However, dynamic thermal analysis is time-consuming, and a steady-state simplification greatly reduces computational complexity. Given the huge scale of necessary domestic retrofit [9], [10], any time-saving approaches are welcome. For a wall in a building, the surface temperatures T_0 and T_1 will vary, but if the magnitude of variation is small, the steady assumption may be valid.

Problematically, no robust criteria for determining the suitability of a steady-state simplification have been investigated and established. The daily air temperature variation – the diurnal temperature range (DTR) – is understood to be important. If DTR is large, such as in desert environments, then a steady state analysis is inappropriate [11], but may be suitable if DTR is small. However, it is not suitable to rely solely on this environmental measure. Solar radiation is the most significant energy input into a building and affects the reliability of steady analysis, [12, p.35, p.43], so must be considered as well.

Crucially, the response of a building to ambient temperature variation depends on its construction. Heavyweight buildings, such as medieval churches and rammed-earth homes, respond much slower to temperature changes than lightweight buildings [13]. This property is called thermal inertia, and is related to the conductivity λ and volumetric heat capacity ρc of the envelope material. The effusivity $\eta = \sqrt{\lambda \rho c}$ relates to the

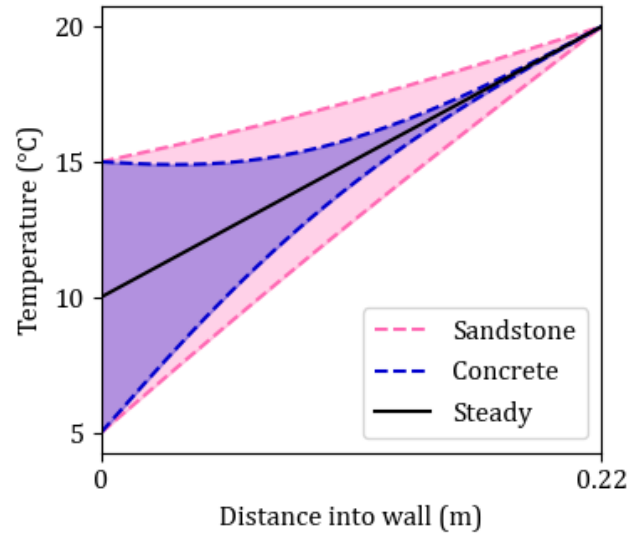


Fig. 2. Temperature gradients in sandstone and lightweight cast concrete walls of thickness $X = 0.22$ m. Outer surface (left) varies sinusoidally between $T_1 = 5^\circ\text{C}$ and $T_1 = 15^\circ\text{C}$; inner surface (right) is fixed at 20°C . Dashed lines show maximum deviations from the steady temperature gradient for the different walls. The temperature gradient in higher diffusivity sandstone shows greater deviation from the steady state gradient. Differences in thermal behaviour between different wall types could affect the suitability of a steady state analysis. (Thermal parameters for sandstone: $\lambda = 1.83 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, $\rho = 2200 \text{ kg}\cdot\text{m}^{-3}$, $c = 710 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$, $\kappa = 1.66 \times 10^{-6} \text{ m}^2\cdot\text{s}^{-1}$; for concrete: $\lambda = 0.20 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, $\rho = 620 \text{ kg}\cdot\text{m}^{-3}$, $c = 840 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$, $\kappa = 3.42 \times 10^{-7} \text{ m}^2\cdot\text{s}^{-1}$.)

ability to absorb and later release thermal energy; the diffusivity $\kappa = \sqrt{\lambda/\rho c}$ affects the phase shift and damping of a thermal excitation [14]. The thermal behaviour of walls of different diffusivities under the same external conditions is illustrated in Figure 2.

The spatial extent of the wall also affects the suitability of a steady state simplification. The relevant intensive (diffusivity) and extensive (thickness) wall properties are captured by the cyclic thickness, τ . For a wall of thickness X undergoing sinusoidally-varying heat transfer with period P , the cyclic thickness given by

$$\tau = \sqrt{\frac{\pi}{\kappa P}} X, \quad (5)$$

describes the damping of a thermal excitation. For $\tau > 3$, an excitation at one surface is effectively extinct at the other, and the slab is thermally thick [15].

Another key consideration is climate change. DTRs change with climate [2], and it is unknown how this may affect the suitability of steady state analysis for different geographic regions. Also unexplored is whether the need to adapt buildings for changing climates, i.e., to keep homes cool in summer [16], affects which thermal analysis approach is suitable.

Hence, the aim is to find a way of assessing the suitability of steady approach that incorporates the key properties of a building and its environment. Then, the suitability can be assessed for different construction types across different geographic regions. This should also allow

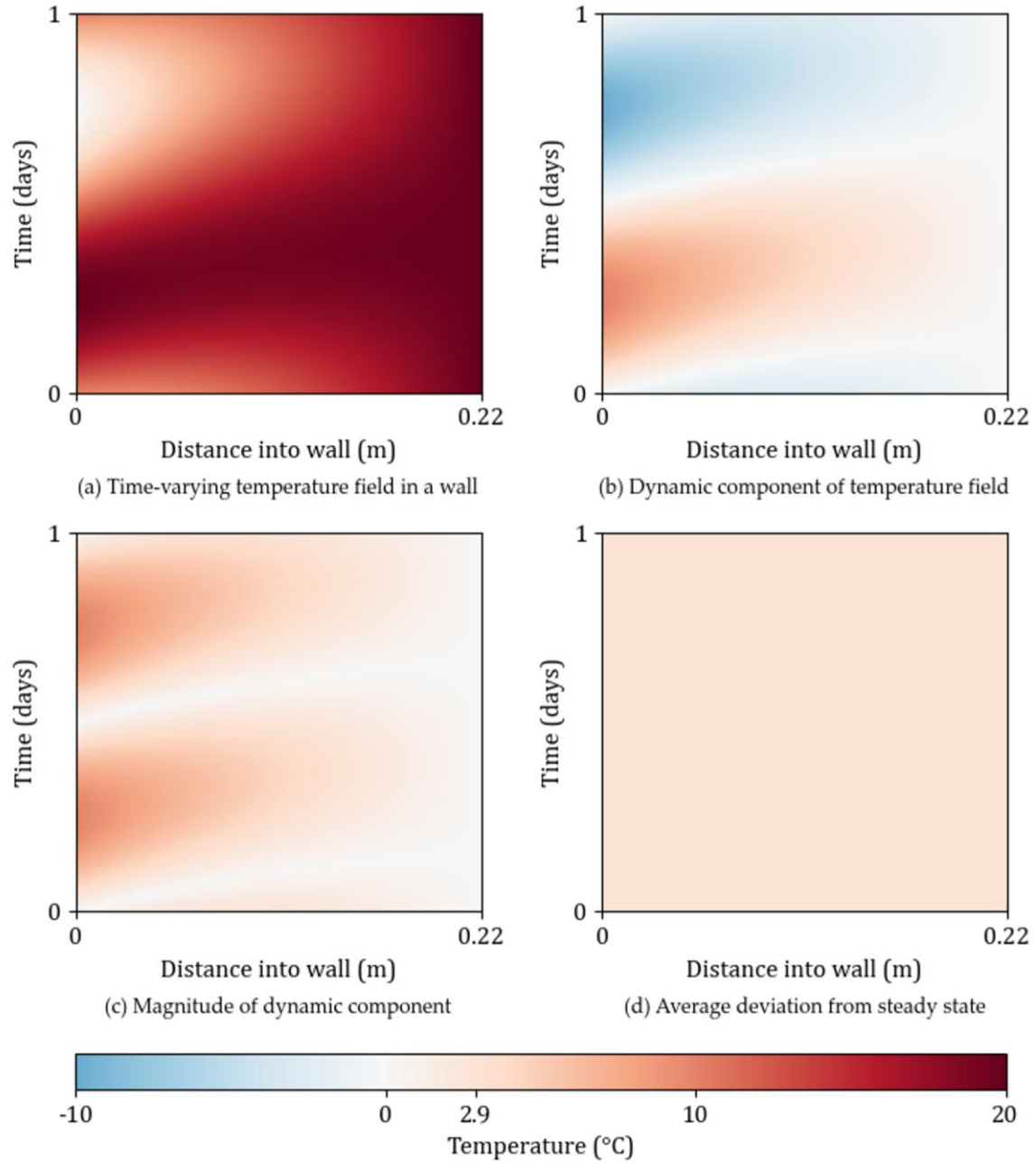


Fig. 3. Visualisation of the mathematical framework of the methodology. Shown are aspects of the dynamic temperature field in a brick wall of thickness $X = 22$ cm. Outer surface (left) varies sinusoidally between $T_0 = 0^\circ\text{C}$ and $T_0 = 20^\circ\text{C}$; inner surface (right) is fixed at $T_1 = 20^\circ\text{C}$. (a) The temperature field including steady and dynamic components. (b) The dynamic component described by (6). (c) The magnitude of the dynamic component. (d) The space- and time-averaged magnitude of the dynamic component, Θ , given by (7). In this case, $\Theta = 2.9^\circ\text{C}$ (or 2.9 K). This methodology can be used to indicate the suitability of using steady-state thermal analysis in retrofit decision-making.

investigation of how climate change impacts the suitability of steady state thermal analysis for different retrofits.

II. METHODOLOGY

The question of how an unsteady heat transfer differs from a steady state simplification is fundamentally a question about the temperature field in the wall. For a wall of thickness X with the temperature at $x = 0$ varying with amplitude $\tilde{T}_0$ and the temperature at $x = X$ held constant, the dynamic component of the field is

$$\tilde{T}(x, t) = \tilde{T}_0 \operatorname{Re} \left[-\frac{\sinh((\tau + i\tau)((x/X) - 1))}{\sinh(\tau + i\tau)} e^{i\frac{2\pi t}{P}} \right]. \quad (6)$$

See Appendix for full derivation of this expression.

The difference between the unsteady heat transfer and its steady approximation is the magnitude of the dynamic component of the temperature field. The space- and time-averaged difference over one period is then

$$\Theta = \frac{\tilde{T}_0}{XP} \int_{t=0}^{t=P} \int_{x=0}^{x=X} \left| \operatorname{Re} \left[\psi e^{i\left(\frac{2\pi t}{P}\right)} \right] \right|. \quad (7)$$

TABLE I
CHARACTERISTIC WALL DATA

Type	Thickness (m)	Diffusivity ($\times 10^{-7} \text{ m}^2 \text{ s}^{-1}$)	Cyclic thickness
Brick	0.22 ^a	6.18	1.69
Stone (Scotland)	0.70 ^b	16.6	3.79
Stone (Rest of UK)	0.50	16.6	2.79

^aApplicable to dwellings built before 1964 in Scotland, before 1966 in England and Wales, and before 1973 in Northern Ireland.

^bApplicable to dwellings built before 1929.

^cApplicable to dwellings built before 1967 in England and Wales and before 1974 in Northern Ireland.

Where

$$\psi = -\frac{\sinh((\tau + i\tau)((x/X) - 1))}{\sinh(\tau + i\tau)}. \quad (8)$$

These mathematics are illustrated in Fig. 3.

Thus, the unsteady nature of a heat transfer is characterized by the average value of the magnitude of the dynamic component of the temperature field, θ . This deviation from the steady state is herein sometimes termed unsteadiness for conciseness. The analytical solution given in (7) can only be used for a single-layer wall, but θ can be computed numerically for a multilayer wall.

The value of θ depends on the thermal properties of the building fabric and the environmental conditions, and therefore seems a suitable measurement for assessing the suitability of using steady state thermal analysis. Large values of θ indicate that the heat transfer deviates significantly from the steady state; small values of θ indicate that steady analysis may be appropriate.

Values for κ , X and $\tilde{T}_0$ are needed to investigate the deviation from steady state heat transfer using (7). (Note that the period P is 1 day (86400 s)). The deviation from steady was parametrised by numerically solving (7) for a range of $\tilde{T}_0$ and $\tau(\kappa, X)$. Additionally, θ was computed for specific building and climatic variables (described below).

A. Building wall data

For this initial investigation, a brick and a stone wall were chosen to probe differences across construction types. Furthermore, different thicknesses of stone walls were obtained from [17], and thickness for stone walls was found to vary between Scotland and the rest of the UK. Both types of stone wall were used in further analysis to capture the impact of regional variation in construction type. Thermal diffusivities were calculated from data in [8], with sandstone chosen as the representative stone type. These characteristic wall data are shown in Table I.

B. Current air and sol-air temperatures

Air and sol-air temperatures were used to analyse how accounting for solar radiation impacts the unsteadiness of heat transfer. Sol-air temperatures represent the combined heat flux due to air temperature and solar radiation.

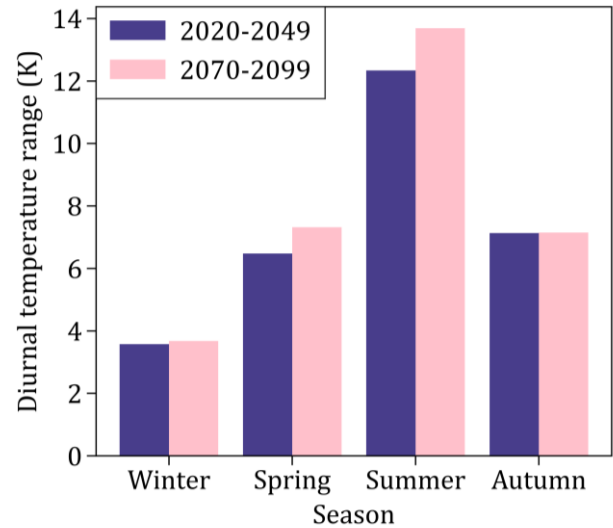


Fig. 4. Seasonal diurnal temperature ranges (DTRs) near Sheffield in 2020-2049 and 2070-2099 under SSP5-85 conditions. Increases in spring and summer DTRs could impact the suitability of using steady-state thermal analysis.

Hourly air and sol-air temperatures for each month are provided by CIBSE for 14 UK cities [18].

The data for Leeds were chosen, as these were closest to the geographic coordinates used to calculate the air DTRs. Data for Scotland were necessary to calculate the deviation from steady heat transfer in a thicker Scottish stone wall. Data for Glasgow were chosen, also allowing comparison of the unsteady nature of heat transfer in similar walls in different macroclimates. Sol-air and air temperatures for June, July and August were used to calculate summer sol-air and air temperature ranges for each city.

C. Future air temperatures

Surface air temperature data from the Coupled Model Intercomparison Project 6 (CMIP6) were used to investigate changes in building heat transfer in future climates. The data used were from a single CMIP6 model run under SSP5-8.5 conditions, the worst-case climate scenario as described by the Intergovernmental Panel on Climate Change (IPCC) [3].

Data for the geographic coordinates closest to Sheffield (Lat = 53.125° North, Lon = 359.0625°) were selected for analysis. DTRs were obtained by calculating daily differences between daily maximum and minimum near-surface air temperatures. These DTRs were then grouped by season and averaged over a 30-year period (because climatological normals are 30-year averages of weather variables). Due to the data available, the 30-year periods chosen were 2020–2049 and 2070–2099. So, the summer 2020-2049 DTR is the average temperature range for each day in June, July and August over the 30-year period. These seasonal DTRs are shown in Fig. 4.

Interestingly, though DTR is expected to increase in all seasons, increases in autumn and winter are marginal. Spring and summer DTRs are expected to increase by 0.845 K and 1.35 K respectively, which could impact the

TABLE II
CHARACTERISTIC UNSTEADINESS OF HEAT TRANSFER FOR DIFFERENT
WALL TYPES UNDER DIFFERENT CLIMATIC CONDITIONS

Temperature dataset	Diurnal range (K)	Unsteadiness (K)	
		Brick	Stone
Sheffield winter air ^d	3.58	0.515	0.382
Sheffield winter air ^e	3.68	0.529	0.393
Sheffield summer air ^d	12.3	1.77	1.31
Sheffield summer air ^e	13.7	1.97	1.46
Leeds air	13.5	1.94	1.44
Leeds sol-air	56.3	8.10	6.01
Glasgow air	11.2	1.61	0.893
Glasgow sol-air	53.1	7.64	4.23

^dRepresenting the period 2020-2049.

^eRepresenting the period 2070-2099.

suitability of using steady-state thermal analysis in building heat transfer.

Summer and winter data were used in further analysis to probe seasonal variability in the deviation from steady state. Note that the temperature variation $\tilde{T}_0$ in (7) is an amplitude, i.e., it is half the diurnal range. So, for summer 2020-2049, DTR is 12.3 K and $\tilde{T}_0$ is 6.15 K.

III. RESULTS

Results for the characterisation of the unsteadiness of heat transfer for the different climatic conditions and wall types are shown in Table II. Fig. 5 shows the results obtained from CIBSE data on a plot of unsteadiness against cyclic thickness.

Lower deviation from steady heat transfer is observed for walls of higher cyclic thickness, with stone walls performing better in this regard. In particular, the greater thickness of the Scottish stone wall has a significant impact; the unsteadiness is just 0.893 K for the summer air DTR of 11.2 K.

The impact of solar radiation on the dynamic component of heat transfer is dramatic, as was expected. For a brick wall in Leeds, the average deviation from steady is 1.94 K when considering air temperature alone, which may not be significant. However, when using the sol-air temperature, the average deviation from steady heat transfer is 8.10 K, which is unlikely to be insignificant. These results indicate the importance of microclimatic factors such as orientation and urban form when considering dynamic thermal analysis, similar to the findings in [19].

The heat transfer through brick and stone walls in the Sheffield winter climate is close to steady in both the 2020-2049 and 2070-2099 periods. These changes in winter DTR are unlikely to be impactful for most wall types. However, the change in DTR in summer may be significant depending on the construction type and microclimatic conditions.

The seasonal variation in DTR is significant. Steady state analysis may be suitable for buildings designed for temperate climates when the aim is to keep them warm in

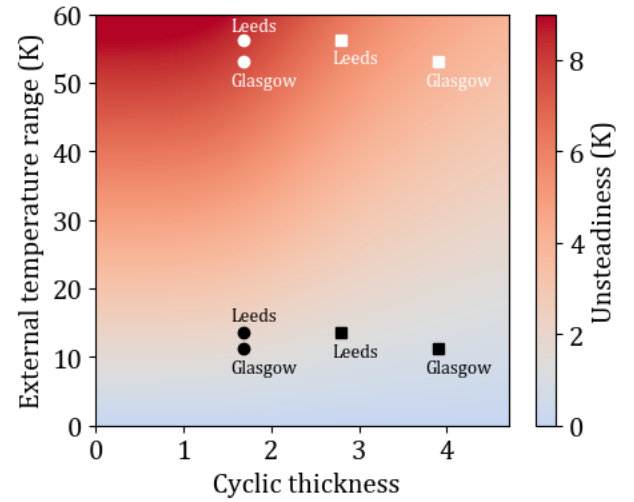


Fig. 5. The deviation from steady state heat transfer through a wall as a function of the external temperature range and wall cyclic thickness. Plotted on the diagram are values of this deviation – or unsteadiness – for typical brick (circles) and stone (squares) walls. Black and white shapes indicate air and sol-air temperatures respectively. The results demonstrate the impact of solar heat flux on the suitability of steady-state analysis. Also shown is how this suitability varies with wall construction type and regional climate.

winter [12, p.43]. However, adaptation to a warmer climate requires retrofitting buildings to keep them cool in summer [16]. The larger DTRs of summer and greater solar heat gains mean inertial effects are more consequential. Hence, when adapting buildings for heat mitigation, the methods of thermal analysis used may need to be adapted as well.

These results have implications for different building types across UK regions. For lightweight buildings, steady state analysis is unsuitable already [15, p. xvii], whereas it may be appropriate when retrofitting high thermal inertia buildings. However, spatial climate variability may mean that steady state analysis is appropriate for a particular construction type in one location but not another. Additionally, changes in climate may mean steady state analysis ceases to be suitable for a particular construction type at some point in the future.

This information can directly influence retrofit strategies. The current approach to thermal performance described in retrofit guidance such as PAS 2035 is uniform for buildings of all ages, construction types and locations. The proposed methodology adds nuance, indicating when dynamic thermal analysis should be used for buildings of a given location, orientation and envelope construction. Additional nuance can be provided depending on whether the retrofit is for energy efficiency during winter or preventing summer overheating.

IV. FUTURE WORK

DTRs are known to be changing globally, and are increasing in Europe [20]. Furthermore, the amount of shortwave radiation reaching Earth has varied significantly since the 1950s [21]. Given the importance of

air and solar heat fluxes for buildings, it is vital to know how sol-air temperatures will change in future.

In future work, sol-air temperatures at 100 km² resolution for 1951-1980, 2011-2040, and 2071-2100 will be calculated from historical data and SSP5-8.5 projections. The deviation from steady state heat transfer will be examined for different building envelopes and environments across the three time periods. The historical data will be used as a baseline to measure changes against.

Examination of how different construction types perform across different time periods can inform the analysis to use for different building retrofits. This knowledge can also be used to assess which architectures are better suited to respond to changes in climate.

V. APPENDIX

The periodic solution to the Fourier equation is given in [15, p.271] as

$$\tilde{\mathbf{T}}(x, t) = [B \sinh(\alpha x + i\alpha x) + C \cosh(\alpha x + i\alpha x)] e^{i(\frac{2\pi t}{P})}, \quad (9)$$

where $\alpha = \sqrt{\pi/\kappa P}$ and B and C are constants to be determined. Vector quantities are in bold.

The amplitude of the temperature variation at the exposed surface is $\tilde{T}_0$. Then

$$\tilde{\mathbf{T}}(0, t) = \tilde{T}_0 e^{i(\frac{2\pi t}{P})} = C \cosh(0) e^{i(\frac{2\pi t}{P})} = C e^{i(\frac{2\pi t}{P})}, \quad (10)$$

which implies $C = \tilde{T}_0$ or, trivially, $C = 0$. By definition, $\tilde{\mathbf{T}}(X, t) = 0$, so, with $C = \tilde{T}_0$,

$$[B \sinh(\alpha X + i\alpha X) + \tilde{T}_0 \cosh(\alpha X + i\alpha X)] e^{i(\frac{2\pi t}{P})} = 0 \quad (11)$$

$$\Rightarrow B \sinh(\alpha X + i\alpha X) + \tilde{T}_0 \cosh(\alpha X + i\alpha X) = 0 \quad (12)$$

$$\Rightarrow B = -\frac{\tilde{T}_0 \cosh(\alpha X + i\alpha X)}{\sinh(\alpha X + i\alpha X)}, \quad (13)$$

$$\therefore \tilde{\mathbf{T}}(x, t) = \left[-\frac{\tilde{T}_0 \cosh(\alpha X + i\alpha X)}{\sinh(\alpha X + i\alpha X)} \sinh(\alpha x + i\alpha x) + \tilde{T}_0 \cosh(\alpha x + i\alpha x) \right] e^{i(\frac{2\pi t}{P})}. \quad (14)$$

Identifying $\alpha X = \sqrt{\pi X^2/\kappa P}$ as the cyclic thickness τ and rearranging gives

$$\therefore \tilde{\mathbf{T}}(x, t) = -\tilde{T}_0 \frac{\sinh((\tau + i\tau)((x/X) - 1))}{\sinh(\tau + i\tau)} e^{i\frac{2\pi t}{P}}. \quad (15)$$

The observable value of the temperature field at position x and time t is given by the real part of this expression [15, p.350],

$$\tilde{T}(x, t) = \text{Re} \left[-\tilde{T}_0 \frac{\sinh((\tau + i\tau)((x/X) - 1))}{\sinh(\tau + i\tau)} e^{i\frac{2\pi t}{P}} \right]. \quad (16)$$

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