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A Design Chart to Determine the Overall Thermal Resistance of a Building Envelope Cross-Section

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Abstract

The overall thermal resistance of a building envelope cross-section; vertical or horizontal, is crucial for providing insulation for indoor spaces to reduce heat transmission, which would lower energy usage. The main objective of this paper is to create a design chart that determines the overall thermal resistance of vertical or horizontal cross-sections that constitute a building envelope. Additionally, it can determine the appropriate insulation needed to achieve the desired overall thermal resistance. The design chart is made up of several integrated graphs that are created using various formulas, with each graph illustrating the resistance of a particular building material as a function of its thickness. Using the design chart to determine the overall thermal resistance of vertical or horizontal cross-sections is simple for architects to do without having to perform several calculations. It is also universal since it may satisfy the needs of the various energy regulations across the globe.

Keywords: Thermal Resistance, Design Charts, Insulating Materials, Thermal Properties, Building Envelopes.

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1. Introduction

The thermal properties of the building materials that constitute a vertical or a horizontal cross-section of a building envelope, i.e., wall or roof, affect the amount of heat transfer in all types of climates; hot, temperate, or cold. The overall thermal resistance R of a building envelope cross-section signifies its efficiency in reducing the total amount of conductive heat transfer. The insulating value increases as R increases, resulting in decreasing the cooling or heating capacities in hot and cold climates respectively [1]. For that reason local and international building and energy codes are concerned with the overall thermal resistance that could be adequate for a specific part of the building envelope to ensure energy efficiency [2], e.g., One of the ways that ASHRAE requirements are set down for all climatic zones is by determining the minimum allowable overall thermal resistance for the different cross-sections [3].

The main objective of this paper is to create a design chart that determines the overall thermal resistance of a building envelope cross-section without having to perform several calculations.

Nomenclature		
$\boldsymbol{R_T}$	overall thermal resistance	m² °C/W or m² K/W
$\boldsymbol{R_{si}}$	internal surface resistance	m² °C/W or m² K/W
$\boldsymbol{R_{so}}$	external surface resistance	m² °C/W or m² K/W

2. Methodology

Several calculations and simplifications were conducted to complete the proposed design chart that determines the overall thermal resistance as follows.

2.1. Scope and Limitations

The paper focuses on determining the overall thermal resistance of a vertical or a horizontal cross-section of a building envelope, i.e., wall or roof. Different building materials were involved to create the various graphs of the proposed design chart and the selection of these materials were based on the commonly used building materials in the conventional cross-sections, whether for walls or roofs.

The resistivity or the resistance values of these selected building materials are indicative values, which are mostly traded in the local or international building construction market [4].

2.2. Calculations

The different graphs of the design chart are resulting from the following formula [5].

$$R_T = R_{so} + R_1 + R_2 + \cdots\cdots\cdots + R_n + R_{si}$$

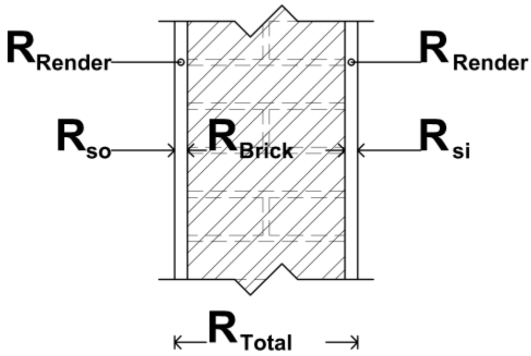


Figure 1: A wall cross-section example: resistances of the varying constituents are additive. Source: [6].

Each graph determines the resistance of one of the different building materials that constitute a building envelope cross-section R_n. R_n could be a constant for a specific cross-section, e.g., R_{si} for walls or roofs, or could be a constant according to its exposure, e.g., R_{so}, or could vary according to its variable thickness which is the normal case and it is calculated using the following formula that indicates that the resistance equals to the product of the resistivity of that building material r_n and its thickness d_n.

$$R_n = r_n \times d_n$$

Since the resistance of the varying constituents are additive [7], the determined resistance in each graph is equal to the sum of the resistance of the new material represented by this graph and the accumulative resistance determined from the previous graph(s) and it is calculated using the following formula.

$$R_{Graph\,n} = R_n + R_{Graph\,(n-1)}$$

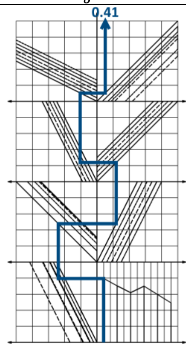
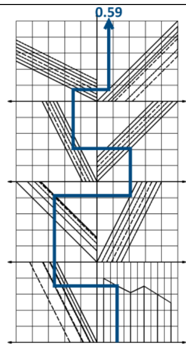
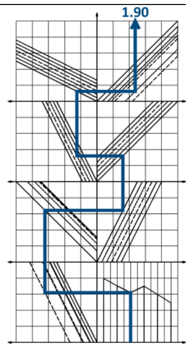
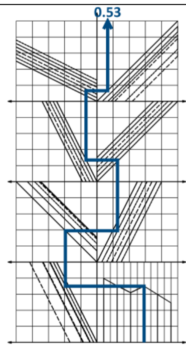
The final resistance R_T in the last graph is the aimed overall thermal resistance.

2.3. Verification of the used formulas

After the different graphs of the design chart had been created by the author, they were verified. This verification was done mathematically by matching the different values calculated from the formula of the overall thermal resistance; $R_T = R_{so} + R_1 + R_2 + \cdots + R_n + R_{si}$ for several cross-sections of varying constituents, up to those accumulative values determined from the different graphs of the proposed design chart.

These values are discovered to be identical and perfectly match, which verifies the formulas that were used for the different graphs of the design chart (see Table 1).

Table 1: Verification of the formulas used for the various design chart graphs.

Cross-Section #	Cross-Section Materials	$R_T = R_{so} + R_1 + \cdots + R_n + R_{si}$	$R_{Design\ Chart}$
Wall 1 **(Sheltered)**	Internal surface resistance + 2 cm render + 25 cm brick + 2 cm render + external surface resistance (see Figure 1)	$R_T = 0.199 + 0.04 \times 1 + 0.25 \times 0.7$ $= 0.41$ m² °C/W	
Wall 2 **(Normal)**	Internal surface resistance + 2 cm Gypsum Plaster + 25 cm brick + 2 cm Vertical Cavity + 2 cm Gypsum Plaster + external surface resistance	$R_T = 0.176 + 0.04 \times 2.17 + 0.25 \times 0.7 + 0.151$ $= 0.59$ m² °C/W	
Wall 3 **(Severe)**	Internal surface resistance + 2 cm Lime Render + 25 cm brick + 5 cm Expanded Polystyrene + 2 cm Lime Render + external surface resistance	$R_T = 0.155 + 0.04 \times 4.17 + 0.25 \times 0.7 + 0.05 \times 28$ $= 1.90$ m² °C/W	
Roof 1 **(Sheltered)**	Internal surface resistance + 2.5 cm Stone + 7.5 cm Sand + 10 cm Concrete + 2 cm render + external surface resistance	$R_T = 0.175 + 0.025 \times 0.6 + 0.075 \times 3.5 + 0.1 \times 0.6 + 0.02 \times 1$ $= 0.53$ m² °C/W	

3. Results

Figure 2 shows the design chart created by the author which is a combination of several graphs using the formula of calculating the overall thermal resistance in addition to some other calculations that enables the accumulation of the resistance of the different proposed building materials in case of their existence.

3.1. Description of the Design Chart

The design chart consists of eight graphs and each graph represents the overall thermal resistance of one or more of the different building materials that constitute a building envelope cross-section whether they are insulating materials, i.e., materials with high resistivity, or main building materials, i.e., materials with lower resistivity.

These eight graphs are combined and integrated together. And for achieving that integration, the sense or orientation of each graph may differ according to its location within the design chart; some of these graphs are maintained normally, such as graph 1 and graph 5, i.e., the X-axis is horizontal and its values increases to the right and the Y-axis is vertical and its values increases upwards, others are rotated, such as graph 2 and graph 6, others are flipped, such as graph 3 and graph 7, i.e., the values of the X-axis increases to the left not to the right, and others are flipped and rotated, such as graph 4 and graph 8. To determine the overall thermal resistance, the successive graphs, from graph 1 to graph 8, are used in the sequence shown in Figure 2.

Each graph, from graph 1 to graph 8, determines the resistance of a specific material(s) as follows.

Graph 1 determines the resistance R_1 which is the accumulative resistance of both external surface resistance R_{so} and internal surface resistance R_{si} of a cross-section whether it was a vertical or a horizontal cross-section, i.e., wall or roof. This accumulative resistance is shown for three cases; sheltered, normal and severe [8]. Graph 2 determines the resistance R_2 which is the resistance of render or plaster. Graph 3 determines the resistance R_3 which is the resistance of a vertical cavity (for walls). Graph 4 determines the resistance R_4 which is the resistance of concrete. Graph 5 determines the resistance R_5 which is the resistance of stone. Graph 6 determines the resistance R_6 which is the resistance of brick. Graph 7 determines the resistance R_7 which is the resistance of sand. Graph 8 determines the resistance R_8 which is the resistance of the used insulating material; strawboard, expanded polystyrene or extruded polystyrene.

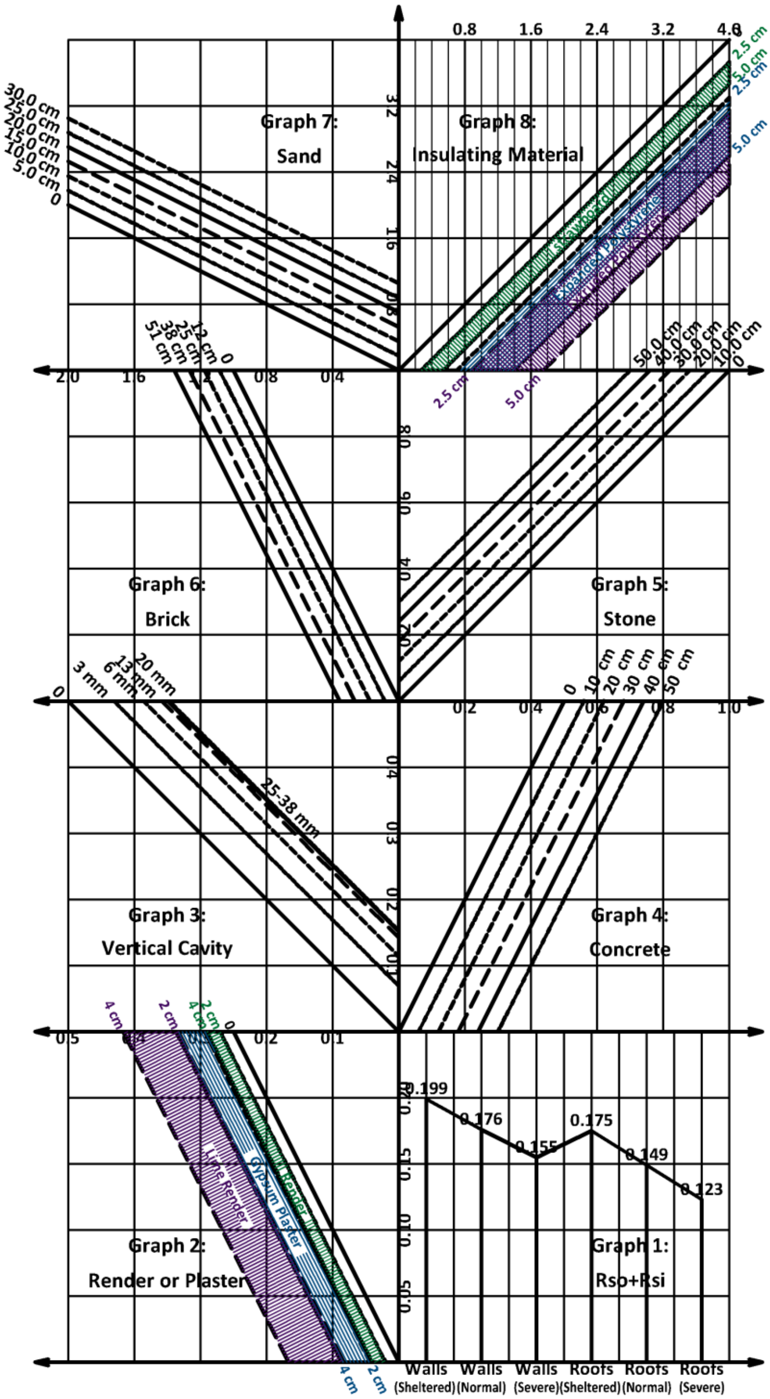


Figure 2: The design chart to determine the overall thermal resistance of a building envelope cross-section. Source: the author.

3.2. Use of the Design Chart

All the graphs of the design chart are used to determine the overall thermal resistance or to determine the appropriate insulation required to attain an aimed overall thermal resistance, e.g., to attain the energy code requirements for a specific cross-section within a specific location.

To determine the overall thermal resistance, choose the cross-section on the horizontal axis of graph 1 (at the bottom right). Draw a vertical construction line upwards till it intersects the broken line graph. From the point of intersection, draw a horizontal construction line to the left till it intersects one of the diagonal lines of graph 2. From the point of intersection, draw a vertical construction line upwards till it intersects one of the diagonal lines of graph 3. From the point of intersection, draw a horizontal construction line to the right till it intersects one of the diagonal lines of graph 4. From the point of intersection, draw a vertical construction line upwards till it intersects one of the diagonal lines of graph 5. From the point of intersection, draw a horizontal construction line to the left till it intersects one of the diagonal lines of graph 6. From the point of intersection, draw a vertical construction line upwards till it intersects one of the diagonal lines of graph 7. From the point of intersection, draw a horizontal construction line to the right till it intersects one of the diagonal lines of graph 8. From the point of intersection, draw a vertical construction line upwards till the overall thermal resistance is determined on the upper horizontal axis (see Figure 3).

To determine the appropriate insulation required to attain an aimed overall thermal resistance, follow the same steps until the step of extending a horizontal construction line to the right within the area of graph 8. Specify the aimed overall thermal resistance on the upper horizontal axis of graph 8 (at the top right). Draw a vertical construction line downwards till it intersects the extended construction line at the appropriate insulation (see Figure 3).

Example 1: Using the design chart, it is required to determine the overall thermal resistance of a wall (severe), given that the building materials that constitute its cross-section are: Internal surface resistance + 2 cm render + 25 cm brick + 5 cm strawboard + 2 cm render + external surface resistance.

Solution of example 1: Choose the cross-section on the horizontal axis of graph 1 (at the bottom right); "Walls (Severe)". Draw a vertical construction line upwards till it intersects the broken line graph. From the point of intersection, draw a horizontal construction line to the left till it intersects the diagonal line labeled 4 cm (render) of graph 2. From the point of intersection, draw a vertical construction line upwards till it intersects the diagonal line labeled zero (vertical cavity) of graph 3. From the point of intersection, draw a horizontal construction line to the right till it intersects the diagonal line labeled zero (concrete) of graph 4. From the point of intersection, draw a vertical construction line upwards it intersects the diagonal line labeled zero (stone) of graph 5. From the point of intersection, draw a horizontal construction line to the left till it intersects the diagonal line labeled 25 cm (brick) of graph 6. From the point of intersection, draw a vertical construction line upwards till it intersects the diagonal line labeled zero (sand) of graph 7. From the point of intersection, draw a horizontal construction line to the right till it intersects the diagonal line labeled 5 cm (strawboard) of graph 8. From the point of intersection, draw a vertical construction line upwards till the overall thermal resistance is determined 0.9 m² °C/W on the upper horizontal axis (see Figure 3).

Example 2: Using the design chart, it is required to determine the appropriate insulation required to attain an overall thermal resistance of an eastern wall (sheltered) equals 1.4 m² °C/W, given that the building materials that constitute its cross-section are: Internal surface resistance + 2 cm lime render + 25 cm brick + 2 cm lime render + external surface resistance.

Solution of example 2: Follow the same steps until the step of extending a horizontal construction line to the right within the area of graph 8. Specify the aimed overall thermal resistance on the upper horizontal axis of graph 8 (at the top right); 1.4 m² °C/W. Draw a vertical construction line downwards till it intersects the extended construction line at the appropriate insulation; 3 cm expanded polystyrene or 2.5 cm extruded polystyrene (see Figure 3).

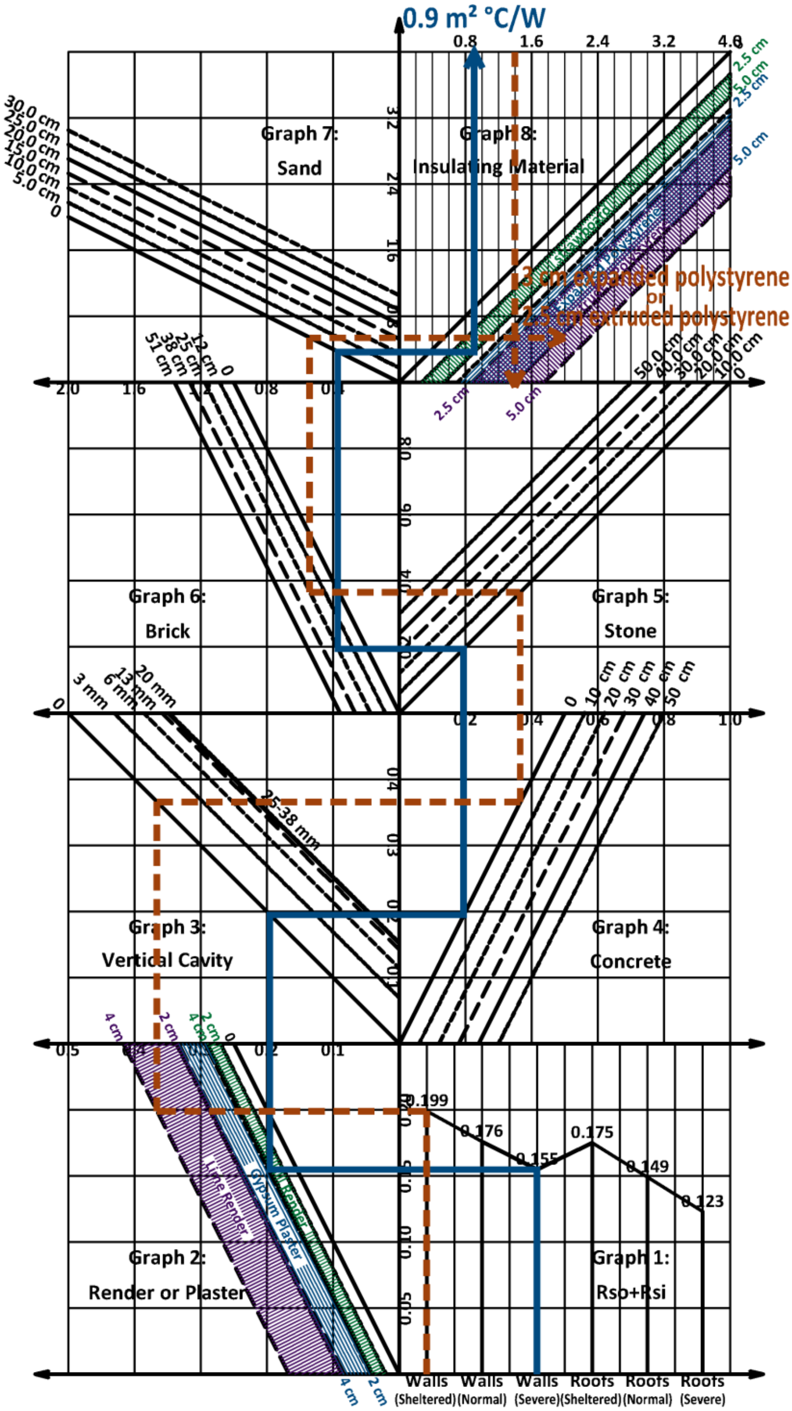


Figure 3: Examples of how to use the design chart to determine the overall thermal resistance or the appropriate insulation. Source: the author.

3.3. Notes on the Design Chart

Effect of the different variables on the overall thermal resistance. The design chart makes it clear that any change in any variable has an impact on the overall thermal resistance; this includes adding extra materials, increasing thickness, or adding resistivity. It should be noted, however, that increasing the thickness of materials with higher resistivity has a greater impact on the overall thermal resistance of a cross-section, i.e., using insulating materials.

4. Discussion and Conclusions

It is possible for architects to use the design chart created by the author as a simple tool to determine the overall thermal resistance of a vertical or a horizontal cross-section of a building envelope or to determine the appropriate insulation required to be added to a conventional cross-section to attain an aimed overall thermal resistance. This is beneficial especially in the stage of working drawings with no need for complicated calculations.

In future research, the design chart could be upgraded to include more building materials by adding more graphs; each determines the resistance of one of the new building materials that might be added to the previous included ones that constitute a building envelope cross-section. Another design chart could be developed whose main aim could be determining the appropriate insulation and that would involve including most insulating materials available in the building construction market, i.e., upgrading graph 8. Other researches might involve creating design charts that can determine the conductive heat transfer through a building envelope cross-section or can determine the heating or cooling capacity within a specific space(s). Other researches might involve the cost-effectiveness and energy savings as a result of using a specific type of glazing.

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