ADJUSTING THE DESIGN THERMAL CONDUCTIVITY CONSIDERED BY THE SPANISH BUILDING TECHNICAL CODE FOR FAÇADE MATERIALS

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AJUSTE DE LA CONDUCTIVIDAD TÉRMICA DE DISEÑO FIJADA POR EL CÓDIGO TÉCNICO DE LA EDIFICACIÓN PARA MATERIALES DE FACHADA

RESUMEN:
El Código Técnico de la Edificación vigente en España establece, como condiciones de referencia para determinar los valores térmicos de diseño de los productos de construcción, una temperatura de 10ºC y un contenido de humedad en equilibrio a 23ºC y 50% de humedad relativa. Sin embargo, estos valores de referencia no son coherentes con las condiciones climáticas reales del país, lo que se traduce en diseños optimistas de la envolvente térmica de los edificios y en consumos de energía superiores a los previstos en el diseño.
Este artículo analiza estas divergencias, revisa las debilidades del Código Técnico de la Edificación en la materia y estima la conductividad térmica real de los materiales de fachada mediante un nuevo procedimiento, capaz de obtener una precisión similar a la norma UNE-EN ISO 10456 con un menor esfuerzo de cálculo. Todo ello ha de contribuir a mejorar el diseño térmico actualmente establecido para los edificios españoles.

Palabras clave: Conductividad térmica de diseño; Temperatura; Humedad; Diseño de fachadas; Código Técnico de la Edificación

ABSTRACT:
The Spanish Technical Building Code establishes a temperature of 10°C and an equilibrium moisture content with a relative humidity of 50% and 23ºC, respectively, as reference to determine the design thermal values of construction materials. However, these reference values are not consistent with the actual climatic conditions of the country, resulting in optimistic designs of the building thermal envelopes and higher energy consumptions than expected by design.
This article analyses these differences, reviews the weaknesses of the Spanish Code in this area, and uses a recently developed procedure to determine the actual thermal conductivity of façade materials with similar precision and less calculation effort that the standard UNE-EN ISO 10456. All this would contribute to improve the thermal design currently defined for the Spanish buildings.

Keywords:
Design thermal conductivity; Temperature; Moisture content; Façade design, Spanish Technical Building Code (CTE)

1.- INTRODUCTION

One of the main design aims of the thermal envelope of buildings is to reduce the energy consumption necessary to achieve the inner thermal comfort [1-3]. One of the most important keys to achieve this aim is limiting the thermal transmittance of the enclosures that make up this envelope [4-6]. The thermal conductivity of construction materials determines this thermal transmittance, thus constituting the main hygrothermal characteristic to be considered for the building thermal design [7].

However, the thermal conductivity of the materials is affected by the environmental temperature and relative humidity present at each location [8-10]. In general, an increase of temperature or moisture content in the porous material increases its thermal conductivity value [11, 12]. In the current context of energy saving, the characterisation of the thermal conductivity under actual operating conditions is a key task for designing more suitable thermal envelopes, adjusted to its operating conditions [13, 14].

However, many building codes establish standardised conductivity values, based on reference conditions that do not represent those actually present at each location [15-18]. In Spain, the Building Technical Code (CTE) establishes as reference conditions 10°C and moisture content in equilibrium at 23°C and 50% relative humidity (CTE DB-HE1.6.1.7) [19].

The thermal conductivity under these specific conditions of temperature T (°C) and relative humidity φ (-) can be determined from the conductivity values provided by the material manufacturer (declared conductivity value), by using the standard UNE-EN ISO 10456 [20]. This standard presents a calculation procedure based on conversion factors related to the temperature (F_T), moisture content (F_M) and aging of the material (F_A), allowing to approximate the thermal conductivity under any operating conditions λ_2 (W/(m·K)), from the declared values under reference conditions λ_1 (W/(m·K)). As shown in Eq. (1), these conversion factors are obtained from tabulated coefficients for each material, f_t (K^{-1}) y f_ψ (m^3/m^3), and from the difference of temperature $T_2 - T_1$ (K) and moisture content $\psi_2 - \psi_1$ (m^3/m^3) in the material between the operating and reference conditions. When the conductivity value λ_1 considers the aging effects of the material (as usual in the declared values) it can be considered a F_A factor equal to 1 [20].

$$\lambda_2 = \lambda_1 \cdot F_T \cdot F_M \cdot F_A = \lambda_1 \cdot e^{f_t(T_2 - T_1)} \cdot e^{f_\psi(\psi_2 - \psi_1)} \cdot F_A \qquad (1)$$

The conditions of the Spanish buildings (undergoing moderate or high ambient temperatures and internal comfort conditions close to 20°C) cause that the enclosure materials are usually at temperatures above the 10°C set by the CTE. The relative humidity set by the CTE for inner zones without high production of moisture (55%) and the higher values of ambient relative humidity in the country make it unrealistic to consider a ϕ value equal to 50% in the envelope materials [21].

These problems increase the thermal conductivity of the materials in their actual service conditions, thus surpassing the value set by the CTE for the thermal design [11, 12, 22, 23]. So, this thermal calculation can cause unsuitable building designs, energy losses higher than initially planned, and increased energy consumption associated with the conditioning facilities.

In turn, the procedure defined by Eq. (1) is not functional to calculate the actual values of conductivity for every possible thermal design. Its application requires the laborious calculation of T and ϕ at each wall layer, and the moisture content in the porous medium of each material [24]. Since the moisture content in the porous materials is not proportional to the ambient relative humidity, empirical sorption isotherms are necessary to relate both magnitudes for each material [25-26]. In addition, any variation of the design conditions (environmental parameters, thickness or order of the material layers in the wall), would force to repeat these calculations. This limited functionality has led to simplify the thermal design of building regulations, assuming constant and standardised conditions to set the conductivity values (as happens in the CTE).

However, recently it has been developed a procedure that can estimate the thermal conductivity of building materials with a precision similar to the standard UNE EN ISO 10456 and with less computational effort [22]. By using the abovementioned procedure, this study corrects the conductivity values established by the CTE for façade materials in the Spanish provincial capitals and autonomous cities (hereinafter, simply capitals). For this purpose the environmental conditions that occur throughout the year at each location are evaluated, thus calculating the correction factor more conservative associated with each climate. Finally, the tools necessary to improve the thermal design of the building in the current CTE are provided.

2.- ANALYSIS OF THE REFERENCE CONDITIONS THAT ARE USED TO ESTABLISH THE THERMAL CONDUCTIVITY OF CONSTRUCTION MATERIALS IN SPAIN

The standard UNE-EN ISO 10456 establishes 4 types of reference conditions, used by manufacturers to determine the declared conductivity values (Table I). The declared condition "Ib" coincides with the reference conditions adopted by the CTE (10°C and a moisture content in equilibrium with a relative humidity of 50% at 23°C), allowing designers to use declared values directly in the thermal calculation, without additional adjustments [20].

PROPERTY	**SETS OF CONDITIONS**			
	I		**II**	
	a)	**b)**	**a)**	**b)**
Reference temperatura	10ºC	10ºC	23ºC	23ºC
Moisture	u_{dry}	$u_{23,50}$	u_{dry}	$u_{23,50}$
Ageing	aged	aged	aged	aged

U_{dry} is a low moisture content reached by drying according to specifications for the material concerned.
$u_{23,50}$ is the moisture content when in equilibrium with air at 23ºC and relative humidity of 50%.

Table I. Environmental conditions associated with the conductivity declared values, according to the standard UNE-EN ISO 10456:2012

Although the set of conditions "Ib" is commonly used as reference for the thermal design in countries characterised by low temperatures [18, 27], this condition is not suitable for the Spanish climate [28]. As stated in the CTE, the mean annual temperature in the 52 capitals of the country can range from 9.9ºC in Burgos to 18.5°C in Almería (reaching up to 21°C in the capitals of the Canary Islands). In addition, these temperatures can undergo pronounced seasonal variations, with differences up to 19°C between the summer and winter. The relative humidity undergoes similar oscillations with seasonal changes up to 35% and annual average values ranging from 56.4% in Madrid to 80.3% in Ceuta [21].

Meanwhile, the most common conditions for inside hygrothermal comfort are set in 20°C and relative humidity of 55% (established by the CTE for areas without high production of moisture as offices, shops, warehouses and residential buildings, i.e., Hygrothermic Class 3), maintained throughout the year by the building conditioning facilities [21]. All together, these boundary conditions suggest that the reference conditions adopted by the CTE to define the design conductivity of building materials (declared condition "Ib"), are unrealistic in most sites and most of the year.

To assess this divergence, the analysis of thermal transmittance associated with two façades (A and B), representative of those conventionally used throughout the country is proposed. Fig. 1 shows both constructive solutions, the thermal conductivity of the materials according to the "Ib" condition set by the CTE (λ_{Ib}), and the tabulated values f_t and f_ψ from UNE-EN ISO 10456 for its implementation in Eq. (1). These façade configurations are analysed in four Spanish cities (Burgos, Almeria, Madrid and Ceuta), considering the extreme monthly values of T and ϕ that occur throughout the year [21].

Since the CTE establishes the reference condition "Ib" for the entire country, transmittance U ($W/(m^2{\cdot}K)$) of each façade configuration is the same in the four cities analysed (Table II). For this calculation have been considered superficial thermal resistances equal to 0.04 and 0.13 $m^2{\cdot}K/W$ for indoor and outdoor environments, respectively [29]. The U value of both enclosures can also be calculated by considering the thermal conductivities under the declared conditions "Ia", "IIa" and "IIb" as well as under the most extreme environmental conditions at these cities.

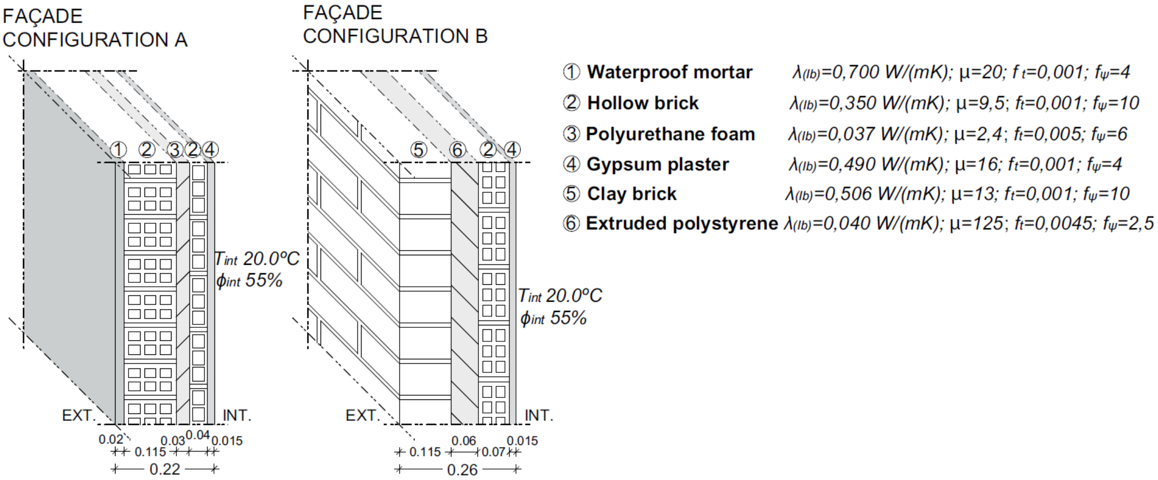

Fig. 1: Analysed façade configurations (A and B), and hygrothermal properties of its construction materials.

The conductivity of each material under these environmental conditions has been determined by using the laborious procedure established in the standard UNE-EN ISO 10456 (Eq. 1). Thus, it have been determined the conversion factors F_T and F_M associated with the temperature and moisture content on each layer of both façade configurations. The moisture content of each material was estimated by using the sorption isotherms provided by the WUFI Light 5.3 software, developed by the Fraunhofer Institute for Building Physics [30]. Each relative humidity value in the material corresponds to single moisture content, characterised by its sorption characteristic curve. The resistance factor to vapor diffusion μ (shown in Fig. 1), allows indexing each material selected in the broad database of the software. The T and ϕ values of each layer under the summer and winter conditions were obtained by using hygrothermal relations provided by the CTE, considering a Hygrothermic Class 3 for the indoor environment [21, 24].

Façade configuration A

				Thermal transmittance to be considered in thermal design (m^2K/W)				
	Month [21]	T (ºC)	ϕ (%)	U_{UNE}	U_{Ia}	$U_{Ib\ (CTE)}$	U_{IIa}	U_{IIb}
Burgos	Ene. (*)	2,6	86	**0,682**	0,663 (-2,8%)	0,674 (-1,2%)	0,690 (+1,2%)	0,702 (+2,9%)
	Ago.	18,3	62	**0,696**	0,663 (-4,7%)	0,674 (-3,2%)	0,690 (-0,9%)	0,702 (+0,9%)
Almería	Ene.	12,4	70	**0,692**	0,663 (-4,2%)	0,674 (-2,6%)	0,690 (-0,3%)	0,702 (+1,4%)
	Ago.	26,0	66	**0,703**	0,663 (-5,7%)	0,674 (-4,1%)	0,690 (-1,8%)	0,702 (-0,1%)
Madrid	Ene.	6,2	71	**0,698**	0,663 (-5,0%)	0,674 (-3,4%)	0,690 (-0,9%)	0,702 (+0,6%)
	Jul.	24,4	37	**0,699**	0,663 (-5,2%)	0,674 (-3,6%)	0,690 (-1,3%)	0,702 (+0,4%)
Ceuta	Ene.	11,5	87	**0,694**	0,663 (-4,5%)	0,674 (-2,9%)	0,690 (-0,6%)	0,702 (+1,2%)
	Ago.	22,2	87	**0,702**	0,663 (-5,6%)	0,674 (-4,0%)	0,690 (-1,7%)	0,702 (+0,0%)

(*)It has been added a vapour barrier to prevent condensation in the façade layers.

Façade configuration B

	Month [21]	T (ºC)	ϕ (%)	U_{UNE}	U_{Ia}	$U_{Ib\ (CTE)}$	U_{IIa}	U_{IIb}
Burgos	Ene.	2,6	86	**0,474**	0,466 (-1,7%)	0,470 (-0,8%)	0,489 (+3,2%)	0,493 (+4,0%)
	Ago.	18,3	62	**0,487**	0,466 (-4,3%)	0,470 (-3,5%)	0,489 (+0,4%)	0,493 (+1,2%)
Almería	Ene.	12,4	70	**0,482**	0,466 (-3,3%)	0,470 (-2,5%)	0,489 (+1,5%)	0,493 (+2,3%)
	Ago.	26,0	66	**0,495**	0,466 (-5,9%)	0,470 (-5,1%)	0,489 (-1,2%)	0,493 (-0,4%)
Madrid	Ene.	6,2	71	**0,477**	0,466 (-2,3%)	0,470 (-1,5%)	0,489 (+2,5%)	0,493 (+3,4%)
	Jul.	24,4	37	**0,492**	0,466 (-5,3%)	0,470 (-4,5%)	0,489 (-0,6%)	0,493 (+0,2%)
Ceuta	Ene.	11,5	87	**0,482**	0,466 (-3,3%)	0,470 (-2,5%)	0,489 (+1,5%)	0,493 (+2,3%)
	Ago.	22,2	87	**0,492**	0,466 (-5,3%)	0,470 (-4,5%)	0,489 (-0,6%)	0,493 (+0,2%)

Table II. Thermal transmittance of both façades considering different reference conditions for the thermal conductivity of materials, and comparative deviation of the transmittance values adjusted according to UNE-EN ISO 10456.

As shown in Table II, the thermal transmittance of these façades is modified by the operating conditions at each location and date of the year. Therefore, It can be identified important seasonal and geographical variations, which are not considered by the CTE when constant reference conditions are established.

In turn, the thermal transmittance associated with the declared conditions "Ia", "Ib", "IIa" and "IIb" becomes progressively greater, the higher the value of T and ϕ that characterises them. As a result, the U_{Ia} and U_{Ib} values (set at 10°C) are always lower than the calculated values according to the standard UNE, even in those locations and months with lower temperature (see Burgos, January). Meanwhile, the condition adopted by the CTE ("Ib") determine a transmittance value that ranges between 0.8% and 5.1% lower than the real value throughout the year, resulting in optimistic thermal designs and energy losses greater than those expected by design.

Considering the current efforts to achieve greater energy efficiency in buildings (with net-zero energy buildings, more demanding regulations or sophisticated tools for an accurate thermal design), these deviations are not negligible and therefore should be corrected. In this sense, only the set of declared conditions "IIb" determines higher transmittance values than standard UNE and therefore, conservative values for the thermal calculation during most of the year. However, the use of a single set of standardised conditions would maintain a constant conductivity value, without considering the specific climatic conditions at each site.

2.1.- FUNCTIONAL ESTIMATE OF DESIGN THERMAL CONDUCTIVITY THROUGH CORRECTION FACTORS

To achieve a thermal design adjusted to the climatic requirements at each site, the laborious calculation set out in the standard UNE-EN ISO 10456 should be replaced by a more practical and functional procedure. In this way, it has been recently developed a procedure that can avoid the calculation of temperature, relative humidity and moisture content of each material of the façade configuration, whose theoretical bases are itemised in the following references [22, 23].

For this, the procedure uses only the values of temperature and relative humidity that define the inner and outer conditions of the façade, thus calculating the mean vapour pressure in the wall P_v (Pa) by hygrothermal relations as those contained in the CTE [21]. As a result, the moisture content of all materials in a conventional façade could be approximated by Eq. (2).

$$\psi_{diseño} \approx \frac{\left(\frac{P_{v\,ext}+P_{v\,int}}{2}\right)}{610{,}5 \cdot e^{\left(\frac{17{,}269\cdot\left(\frac{T_{ext}+T_{int}}{2}\right)}{273{,}3+\left(\frac{T_{ext}+T_{int}}{2}\right)}\right)}} \cdot 0{,}0107 \qquad (2)$$

The same input data also allow correct the thermal conductivity established by the CTE for the façade materials ($\lambda_{Ib\,(CTE)}$), only by applying different simplifications on the method collected in the standard UNE-EN ISO 10456. Considering a Hygrothermic Class 3 as inner design conditions, Eq. (3) allows this correction with less calculation effort and similar accuracy to that of the standard UNE. Coefficients shown in Eqs. (2) and (3) are determined from approximations and averages, based on the tabulated values provided by the standard UNE [22, 23]. It may also be adapted to correct the conductivity values of other envelope parts (e.g., roofs), or façades without masonry layers.
Similarly, it may be necessary to adjust the abovementioned equations when natural insulating materials are used (such as sheep's wool), given the greater importance of its hygroscopic behavior in thermal performance.

$$\lambda_{diseño} \approx \lambda_{Ib\,(CTE)} \cdot CCF = \lambda_{Ib\,(CTE)} \cdot e^{0{,}0036\left(\frac{T_{ext}+20}{2}-10\right)} \cdot e^{4{,}96(\psi_{diseño}-0{,}0053)} \qquad (3)$$

Multiplying the conductivity value of the materials shown in Fig. 1 by this correction factor (CCF o conductivity correction factor), the new U_{CCF} values are consistent with the operating conditions provided at each location and month, significantly reducing the deviation due to the CTE (Table III).

Façade configuration A

					Thermal transmittance to be considered in thermal design (m^2K/W)		
	Month [21]	T (ºC)	ϕ (%)	CCF (3)	U_{UNE}	U_{CCF}	$U_{Ib\ (CTE)}$
Burgos	Ene. (*)	2,6	86	1,0166	**0,682**	0,684 (+0,3%)	0,674 (-1,2%)
	Ago.	18,3	62	1,0384	**0,696**	0,697 (+0,1%)	0,674 (-3,2%)
Almería	Ene.	12,4	70	1,0295	**0,692**	0,692 (+0,0%)	0,674 (-2,6%)
	Ago.	26,0	66	1,0551	**0,703**	0,707 (+0,6%)	0,674 (-4,1%)
Madrid	Ene.	6,2	71	1,0195	**0,698**	0,686 (-1,7%)	0,674 (-3,4%)
	Jul.	24,4	37	1,0425	**0,699**	0,700 (+0,1%)	0,674 (-3,6%)
Ceuta	Ene.	11,5	87	1,0315	**0,694**	0,693 (-0,1%)	0,674 (-2,9%)
	Ago.	22,2	87	1,0534	**0,702**	0,706 (+0,6%)	0,674 (-4,0%)

(*)It has been added a vapour barrier to prevent condensation in the façade layers.

Façade configuration B

	Month [21]	T (ºC)	ϕ (%)	CCF (3)	U_{UNE}	U_{CCF}	$U_{Ib\ (CTE)}$
Burgos	Ene.	2,6	86	1,0166	**0,474**	0,477 (+0,6%)	0,470 (-0,8%)
	Ago.	18,3	62	1,0384	**0,487**	0,486 (-0,2%)	0,470 (-3,5%)
Almería	Ene.	12,4	70	1,0295	**0,482**	0,483 (+0,2%)	0,470 (-2,5%)
	Ago.	26,0	66	1,0551	**0,495**	0,494 (-0,2%)	0,470 (-5,1%)
Madrid	Ene.	6,2	71	1,0195	**0,477**	0,478 (+0,2%)	0,470 (-1,5%)
	Jul.	24,4	37	1,0425	**0,492**	0,488 (-0,8%)	0,470 (-4,5%)
Ceuta	Ene.	11,5	87	1,0315	**0,482**	0,484 (+0,4%)	0,470 (-2,5%)
	Ago.	22,2	87	1,0534	**0,492**	0,493 (+0,2%)	0,470 (-4,5%)

Table III. Thermal transmittance of both façades considering the standard UNE-EN ISO 10456 and the proposed correction factor (CCF).

As shown, the identified correction factor is greater than 1 in all cases, suggesting the need to increase the conductivity values now considered by the CTE at all sites, even in the months of lower temperature and relative humidity. The deviation of the new U_{CCF} value (regarding the values calculated by the standard UNE-EN ISO 10456), does not exceed 1.7% for the façade configuration A, while using condition "Ib" (CTE) this deviation raises to 4.1%. In turn, the maximum deviation stands at 0.8% for the façade configuration B, compared with the 5.1% associated with CTE.

3.- ADJUSTING THE DESIGN THERMAL CONDUCTIVITY FOR FAÇADE MATERIALS IN SPAIN

Previous studies have also demonstrated the validity of these correction factors for other environmental conditions, locations and configurations facade. In all cases, the thermal transmittance obtained by this correction approximates the actual U value with greater accuracy than the calculation established by the CTE [22, 23]. However, so far these studies have been primarily focused on determining the CCF values associated with the annual average climatic conditions at the locations.

Although the average annual values can be used for a general correction of the thermal conductivity, it is necessary to evaluate the extreme climatic data at each location to set conservative design values throughout the year. For this purpose have been analysed the average monthly records of temperature and relative humidity at each Spanish capital, thus determining the CCF correction factors associated with each monthly environmental condition. The monthly climate data used for this calculation have been taken from the tabulated values shown in the CTE [21]. In general, the environmental conditions of T and ϕ that determine a higher correction factor are associated to July and August, mainly due to the high temperatures common in the Spanish locations during the summer (Table IV).

Location	***Month (*)***	***T_{ext} (ºC)***	***Φ_{ext} (%)***	***CCF***
Albacete	Agust	23,7	50	**1,0452**
Alicante	Agust	25,5	68	**1,0547**
Almería	Agust	26,0	66	**1,0551**
Ávila	July	19,9	39	**1,0351**

Badajoz	July	25,3	50	**1,0483**
Barcelona	Agust	23,0	72	**1,0506**
Bilbao	Agust	19,8	75	**1,0448**
Burgos	August	18,3	62	**1,0384**
Cáceres	July	26,1	37	**1,0456**
Cádiz	August	24,5	69	**1,0528**
Castellón	August	24,5	69	**1,0528**
Ceuta	August	22,2	97	**1,0534**
Ciudad Real	July	25,0	47	**1,0468**
Córdoba	August	26,7	49	**1,0508**
A Coruña	August	18,9	79	**1,0440**
Cuenca	August	22,1	46	**1,0410**
Girona	August	22,4	68	**1,0481**
Granada	July	24,3	42	**1,0439**
Guadalajara	July	23,5	53	**1,0458**
Huelva	August	25,7	54	**1,0505**
Huesca	August	22,7	53	**1,0442**
Jaén	August	27,1	45	**1,0502**
León	July	19,7	52	**1,0383**
Lleida	August	24,0	54	**1,0471**
Logroño	July	22,2	55	**1,0439**
Lugo	August	17,5	75	**1,0402**
Madrid	July	24,4	37	**1,0425**
Málaga	August	25,3	63	**1,0526**
Melilla	August	25,3	68	**1,0542**
Murcia	August	24,6	74	**1,0547**
Orense	July	21,9	61	**1,0450**
Oviedo	August	18,3	80	**1,0431**
Palencia	July	20,7	58	**1,0418**
Palma	August	25,3	71	**1,0552**
Las Palmas	September	23,9	69	**1,0516**
Pamplona	August	20,3	61	**1,0419**
Pontevedra	July	20,7	65	**1,0438**
S. Sebastián	August	18,7	83	**1,0447**
Salamanca	July	21,0	50	**1,0401**
St. Cruz Ten.	September	24,4	63	**1,0507**
Santander	August	19,5	78	**1,0450**
Segovia	July	21,6	47	**1,0404**
Sevilla	August	26,8	52	**1,0520**
Soria	July	19,9	53	**1,0389**
Tarragona	August	25,3	62	**1,0523**
Teruel	July	21,3	50	**1,0407**
Toledo	July	26,5	43	**1,0484**
Valencia	August	24,5	69	**1,0528**
Valladolid	August	21,3	46	**1,0395**
Vitoria	August	18,5	70	**1,0408**
Zamora	July	21,8	47	**1,0407**
Zaragoza	August	23,8	54	**1,0467**

(*)Worst T and ϕ conditions regarding those considered by the CTE ("Ib" conditions).

Table IV. Maximum annual values of the correction factor at the Spanish capitals, considering 20°C and relative humidity of 55% as inner conditions (Hygrothermic Class 3).

The maximum correction factors in the 52 Spanish capitals range between 1.0351 (Ávila) and 1.0552 (Palma de Mallorca), thus increasing the thermal conductivity values established by the CTE between 3.51 and 5.52%, respectively. To implement this procedure in the thermal design of building facades, it would only be necessary to multiply all the normative values of thermal conductivity by the correction factor corresponding to the location where the building is planned.

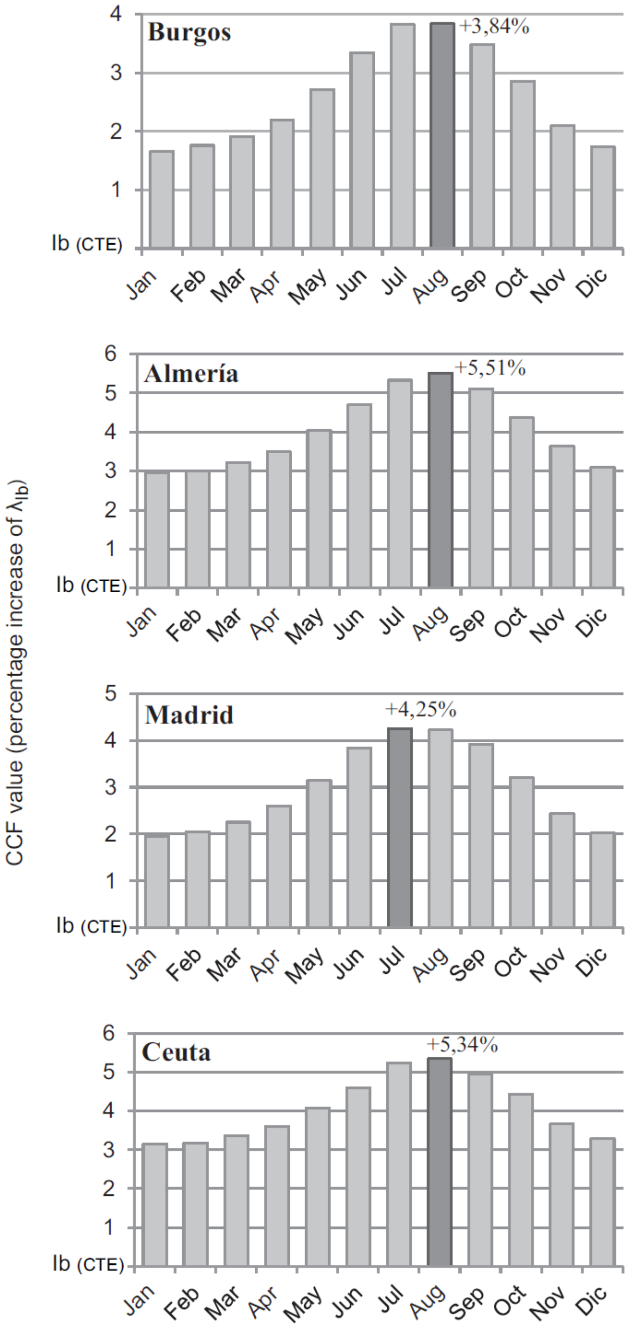

Fig. 2: Monthly evolution of the correction factor in four of the analysed Spanish capitals.

Fig. 2 represents the annual evolution of these correction factors, considering as an example the same capitals previously stated in Section 2 (Burgos, Almeria, Madrid and Ceuta). As shown, the corrections are smaller when the ambient conditions of construction materials are close to 10°C and relative humidity of 50% (conditions established by the condition Ib). All the monthly CCF values are greater than 1 in the 52 capitals, which confirms the unsuitable selection of the declared condition "Ib" for the Spanish climate, even in the winter months. The minimum correction factor has been identified in Ávila (January), with a value of 1.0156 (i.e., even in such situation it would be necessary to increase 1.56% the thermal conductivities considered by the CTE for façade materials.

To analyse the geographical distribution of these corrections, the maximum CCF values of Table IV have been used to develop an isopleth map, thus characterising the correction factor at each location by means of a linear interpolation of the obtained results (Fig. 3). This isopleth map can facilitate the procedure implementation in the Spanish Code and provide approximate corrections even far from the capitals. All this enables a functional adjustment of the thermal conductivity of façade materials in any Spanish location.

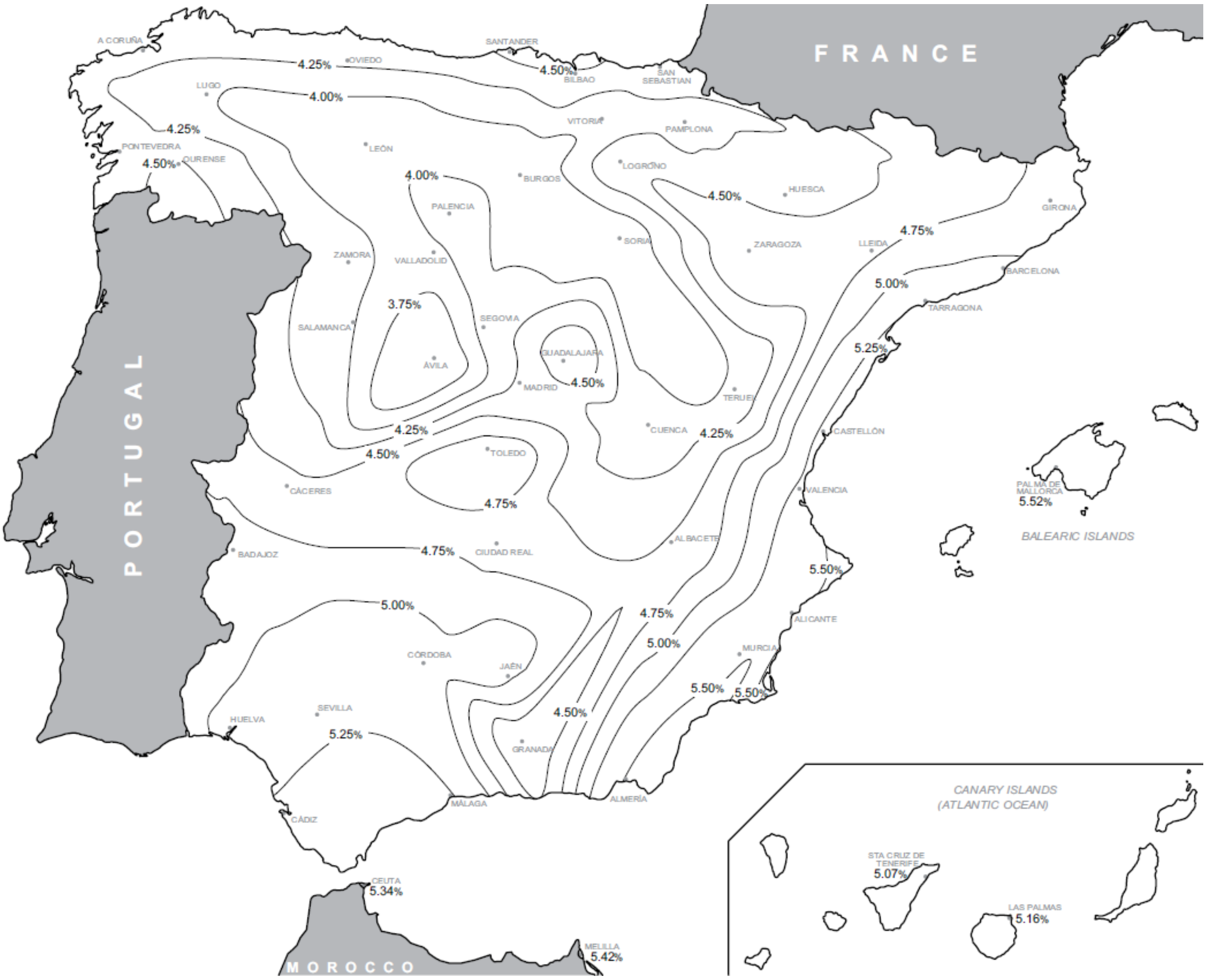

Fig. 3: Correction map for thermal conductivity of façade materials (percentage increase of λ_{Ib} value).

In this map can be seen the need for a higher correction of $\lambda_{Ib\ (CTE)}$ values in coastal areas of the Mediterranean Sea, Southwest of the Iberian Peninsula and in the Canary Islands (corrections up to +5%) as a result of the combination of high relative humidity and temperature. The minor correction can be identified in the North Sub-plateau and the Iberian System (less than +4%), although the analysis of a larger number of sites would characterise more comprehensiveness other areas such as the Pyrenees (where it is also expected a minor correction). The accuracy of this correction map can be increased if considered more exhaustive climate data (based on daily or even hourly records) and if a larger number of locations spread across the country are analysed. Recent studies developed in two Spanish regions (Aragon and Catalonia) are a good example of these potential improvements [23]. In turn, the calculation method allows these correction factors can be used for other inner conditions (different from Hygrothermic Class 3), only by adjusting the coefficients presented in Eqs. (2) and (3) [22, 23]. Similarly, new correction maps could be developed for other countries where the normative conditions for conductivity values are not representative of actual conditions (adjusting the coefficients of the equations presented in Section 2.1).

4.- CONCLUSIONS

In this study, it have been analysed the reference parameters established by the CTE to determine the design thermal conductivity of construction materials. It has been demonstrated as these parameters are not suitable for the climate of the Spanish territory, which can cause optimistic thermal designs based on unreal transmittance values. The use of a single set of reference conditions for the entire country also prevents adjusting the façade design to the climatic requirements at each location.

By using a novel procedure that allows a functional and accurate estimate of the design thermal conductivity, it has been proposed a correction of the values established by the CTE for facade materials. The correction factors that allow a conservative adjustment of the design thermal conductivity throughout the year have been identified by assessing the monthly environmental conditions in 52 Spanish capitals.

These correction factors increase the normative conductivity values of construction materials, depending on the climate conditions that characterise each analysed city (3.51% to 5.52%). In general, these corrections are higher in coastal areas and southern Spain, due to higher temperature and relative humidity common in these locations. For its possible implementation in the current regulations, these correction factors have been represented by means of an isopleth map.

These corrections must allow using more suitable conductivity values, adjusted to the actual operating conditions of construction materials at each location. All this represents a challenge for improvement the design of thermal envelopes in the Spanish buildings, thus adjusting its design to the required performance under any operating condition.

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