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Co-cooling, simulation-based exploration of a new method to measure the Heat Transfer Coefficient of a building envelope in hot climate and summer period

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Abstract

Discrepancy between designed and as-built building performance can be quantified by a Heat Transfer Coefficient measurement. A reference method for measuring this coefficient is the co-heating test. However, the use of this method is limited to certain weather conditions. This work proposes a new method, complementary to the co-heating test, to be performed in summer or in hot climates, called the co-cooling test. This method consists in cooling the building instead of heating it. This article presents a numerical setup to prove the feasibility of the co-cooling test, determining ad-hoc linear regression models. To better account for solar gains, an equivalent outdoor temperature is used. In the cases studied, the simple linear regression method using an equivalent outdoor temperature enables the Heat Transfer Coefficient to be determined with errors below 10 %.

Keywords

Co-cooling, Heat Transfer Coefficient, Co-Heating, Building envelope performance, Hot climate, Summer period.

Measured variables	Symbol	Unit
Power (cooling or heating)	Q_h	W
Heat transfer coefficient: U-value	U_{wall}	W/(K.m ²)
Surface area	A_{wall}	m ²
Heat transfer determine with the U-value	UA	W/K
Heat Transfer Coefficient of the envelop	HTC	W/K
Equivalent outdoor temperature of a surface <i>s</i>	$T_{eq,s}$	K
Equivalent outdoor temperature	T_{eq}	K
Interior air temperature	T_{int}	K
Exterior air temperature	T_{ext}	K
Sky temperature	T_{sky}	K
Indoor-Outdoor difference temperature	ΔT	K
Indoor air – Equivalent outdoor difference temperature	ΔT_{eq}	K
Overall solar aperture coefficient	A_{sw}	m ²
Direct and indirect horizontal solar gains	I_{rr}	W/m ²
Measured uncertainty	u_{meas}	-
Statistical uncertainty	u_{stat}	-
Total uncertainty	u_{tot}	-
Total expanded uncertainty	U_{tot}	-
Heat transfer coefficient (transmissions losses)	H_{ext}	W/K
Heat transfer coefficient (transmissions losses + ground)	H_{tr}	W/K
Building Loss Coefficient	BLC	W/K
Outdoor surface thermic resistance	R_{se}	K·m ² /W
Indoor surface thermic resistance	R_{si}	K·m ² /W
Wall thermic resistance	R_{wall}	K·m ² /W
Outdoor convective resistance	R_{ce}	K·m ² /W
Solar flux incident on wall	I_s	W/m ²
Energy absorption coefficient of the outside surface	α_e	-
Equivalent heat flux density due to the effects of precipitation on the exterior wall (evaporation of water, morning dew, frost, melting snow, etc.).	ϕ_v	W/m ²
Linearized external radiative surface resistance	$R_{r,j}$	K·m ² /W
Equivalent temperature of surface <i>j</i> as seen through the wall	$T_{env,j}$	K

Mean difference temperature over the 3 weeks tests	ΔT_{mean}	K
Mean difference equivalent temperature over the 3 weeks tests	$\Delta T_{eq,mean}$	K
Indoor surface temperature	T_{si}	K
Outdoor surface temperature	T_{se}	K

Table 1: Nomenclature

1. Introduction

In order to reduce the carbon emissions of the building sector, which represent approximately 40% of the global energy consumption, it is necessary to construct high performance buildings and to renovate the building stock [1]. Nowadays, in Europe with EPBD [2] and many other countries, buildings are labelled and regulated according to their performance determined during the design phase. However, several studies show a huge difference of performance, called the « performance gap », between the predicted and actual energy consumption of buildings [3], [4]. There are many potential reasons for these discrepancies, and they stem from the various stages in the building's life cycle: design (modelling errors), construction (incorrect use of materials or components, inappropriate setup), and in-use (weather, occupancy inevitably different from the design forecast). If the residential and tertiary sectors want to effectively reduce its energy consumption, then a key stage is to assess the real performance of the buildings at the end of new construction or at the end of the renovation stage to quantify a part of the performance gap [5].

Several methods exist to evaluate the real performance of buildings. The two main categories of in-situ methods are with and without occupancy. Methods with occupancy need non-intrusive instrumentation but can take place during a long period. Occupied methods mostly allow to determine an energy signature of a building [6], but current studies are working on methodologies to estimate buildings heat losses [7][8] [9] [10]. Methods without occupancy are more developed and mostly consist of heating the inside of a building. One of the most extended ones is the co-heating test, first developed by Lawrence Berkeley National Laboratory [11] [12] to determine the efficiency of duct heating and cooling systems, and then by others studies [13], [14], [15] to estimate thermal characteristic of the building envelop. This method is a quasi-stationary heating method, which allows calculating the Heat Transfer Coefficient (HTC [W/K]) with experimental data. Currently, HTC is one of the coefficients most used to determine the envelope thermal performance; this coefficient takes into account the entire building envelope loss (transmission and infiltration). Others in-situ method using dynamic schedule exist which make possible to determine the HTC of a building over a shorter period such as PRBS methods. These methods are very encouraging for meeting the needs of stakeholders in the future [16].

A downside of these methods is that they use heaters and need to have a significant indoor-outdoor temperature difference, of at least +5°C and usually +10°C in order to quantify with a reasonable uncertainty the HTC of the building. Therefore, those methods cannot take place during the summer, hot inter-season or warmer climate to avoid risk of building damage due to too high indoor temperature. In order to avoid this limit in warm period, the idea of this article is to explore a co-cooling method, which involves cooling the building instead of heating it. Like co-heating, this new method, studied in [17] [18], considers the building without occupancy and during a long period.

In the following sections, this article presents first the various existing methods and indicators for determining building performance, and the current limitations of these methods. Then the methodology and the cases study of the numerical approach are presented. Finally, the results are explained and put into perspective with discussion about the opportunities and the limits of this new method.

The originality of this article is so the development of an innovative method, the co-cooling test, consisting in cooling the building instead of heating it, to determine the HTC of a building when and where existing methods such as co-heating tests do not work. For this, a new regression method based on an equivalent outdoor temperature has been used instead of the outdoor temperature.

2. Indicators and methods to assess the thermal envelope performance

2.1. Coefficients defining the performance

There are several coefficients that determine heat transfer in the building envelope. These coefficients do not take the same heat losses into account. As shown in Figure 1, adapted from Thébault [19], the coefficients can be classified into four “Russian dolls” categories: H_{ext} , which takes into account transmission losses to the outside through outside walls and roof only; H_{tr} , which, in addition to H_{ext} , takes into account losses to the ground and neighbouring rooms; and HTC, which in addition takes into account infiltration losses. Finally, the Building Loss Coefficient (BLC) takes into account all losses through the envelope, i.e. transmission, infiltration and ventilation losses. The HTC coefficient is the most frequently used, being the easiest to measure.

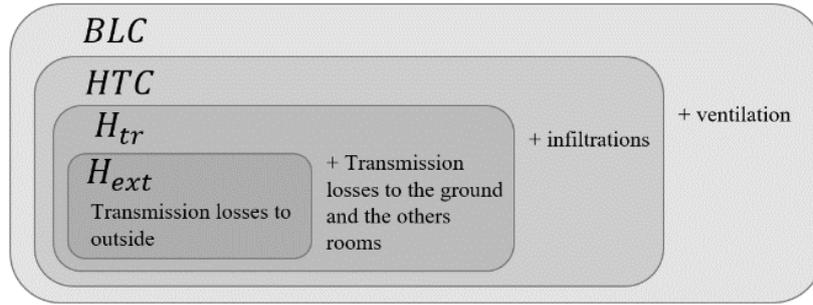


Figure 1: Diagram of building envelope performance coefficients adapted from S. Thébault, 2018

2.2. Approaches to estimate the envelop thermal performance indicator in the design phase

2.2.1. Deterministic approach

ISO 6946 standard [20] defines a deterministic method for determining building envelop performance. This standard specifies the use of the theoretical values of the heat loss coefficients (U) of the materials theoretically present in the building and enables the heat loss coefficient of the building envelope without infiltration and ventilation to be determined from Equation (1).

$$UA = \sum U_{wall} \cdot A_{wall} \quad (1)$$

This standard also specifies values for external and internal surface thermal resistances (R_{se} and R_{si}) as shown in Figure 2 depending on the orientation and direction of heat flow. These thermal resistance values are given for specific climatic conditions, a constant exterior surface temperature of 10°C and interior surface temperature of 20°C, no solar radiation, and a wind speed of 4 m/s adjacent to the exterior surface. This method is used at the design phase to predict the future performance of the building.

2.2.2. Simulated stationary weather approach

A simulated stationary weather approach has been defined to estimate the reference HTC through a Dynamic Building Energy Simulation the heating needs of the case studies. Those are subject to a steady state climatic load. Since there is only one outdoor temperature, the reference HTC is determined using equation (2) as the quotient of the heat demand supplied inside the building (Q [W]) and the indoor/outdoor temperature difference (ΔT [°C]) as Ghiaus and Alzetto developed in [21] and as stated in the NF EN ISO 13789 – 217.

$$HTC = \frac{Q_h}{|\Delta T|} \quad (2)$$

2.3. The Co-heating test

The co-heating test is used as a reference in the buildings performance sector [22]. According to recent studies [22], [23], this method has an uncertainty of 10% on the HTC under the specified measurement

1 conditions. The co-heating test is based on the principle of a balanced energy flow in a quasi-stationary state
 2 system. Across a long period, the heating energy used to heat the dwellings at a constant temperature is
 3 considered equal to the heat loss of the dwellings, as the thermal inertia can be neglected. During the test, the
 4 buildings is heated at a constant temperature higher than the exterior one, with heaters during several weeks
 5 (usually three weeks). To perform a co-heating test, the building must be unoccupied for the duration of the test,
 6 ventilation switched off and ventilation openings blocked. A blower door test is also carried out to assess the
 7 airtightness of a building.

8 Bauwens [15] indicates in their co-heating review three methods to determine the Heat Transfer Coefficient
 9 (HTC) of a building thanks to a co-heating test. All three are regression based, and variables values are averaged
 10 across a 24-hour period. The first method (Equation (3)) is a simple linear regression between the indoor /
 11 outdoor air temperature difference ΔT and the input heating energy Q_h . The constant c represents internal
 12 constant loads or heat gains not linked to temperature difference. Most of the time this constant is fixed to 0 to
 13 have better result [24]. The second method (Equation (4)) is a multiple linear regression with two variables
 14 considered independent: the temperature difference ΔT and the global horizontal solar radiation I_{rr} . The result
 15 of this regression gives the HTC and the solar aperture, A_{sw} , which, according to Bauwens [15] has lost its
 16 physical meaning and is very dependent on the solar radiation projection. The third and last method introduces
 17 in Equation (5), called the Siviour method, is based on dividing all terms in Equation (4) by ΔT . The two
 18 variables are in this case $I_{rr}/\Delta T$ and $Q_h/\Delta T$. The last two models account for solar gains in the co-heating test.

$$Q_h = HTC \cdot \Delta T + c \quad (3)$$

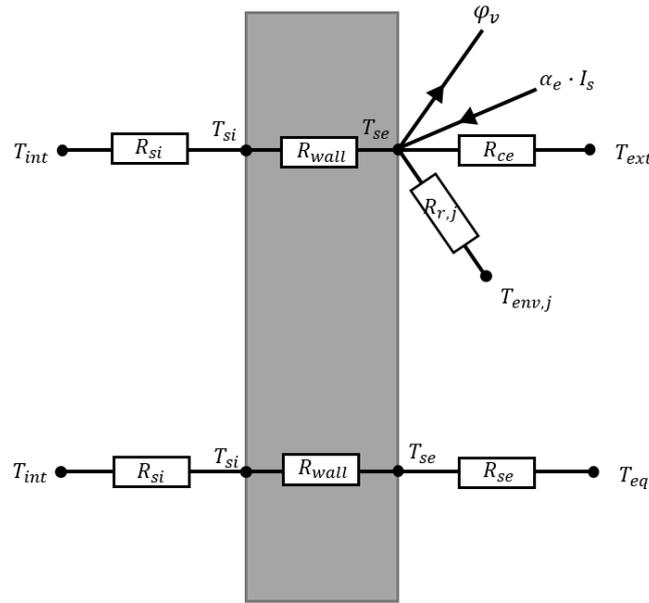
$$Q_h = HTC \cdot \Delta T - A_{sw} * I_{rr} + c \quad (4)$$

$$\frac{Q_h}{\Delta T} = HTC - A_{sw} * \frac{I_{rr}}{\Delta T} \quad (5)$$

19

20 2.4. The equivalent outdoor temperature

21 Some alternative methods under development, such as SEREINE method [19], [25] are using an equivalent
 22 outdoor temperature instead of the classical outdoor air temperature used in co-heating. The equivalent outdoor
 23 temperature aims to take into account impact of environment such as solar radiation, sky radiation. This
 24 equivalent outdoor temperature can be estimated using SENS sensors [26], which measure the temperature of
 25 two different surfaces (one black, one white) with known emissivities. These sensors, oriented in the direction
 26 of each façade, allow all flows from the outside environment to be grouped together, as shown in Figure 2. The
 27 equivalent external temperature of each wall, $T_{eq,s}$, can be determined according to Equation(6). An equivalent
 28 external temperature, that is representative of the walls of the building, is determined by weighting the
 29 equivalent external temperatures of each wall by their areas and their coefficients of loss according to Equation
 30 (7). One of the main assumptions is to estimate the absorptivity of the walls measured.



1

2 **Figure 2 - Equivalent electrical diagram of heat transfer in an opaque wall diagram adapted from Bouchié R. 2014**

$$T_{eq,s} = T_e + \frac{\alpha_{e,s} \cdot I_s}{h_{ce} + h_r} \quad (6)$$

$$T_{eq} = \frac{\sum_i T_{eq,i} \cdot U_i \cdot S_i}{\sum_i U_i \cdot S_i} \quad (7)$$

3

4 2.5. Cooling methods

5 Co-heating and other unoccupied methods are limited by the need for sufficient indoor-outdoor temperature
6 difference and low solar gain [27]. These criteria makes it impossible to carry out co-heating or SEREINE tests
7 throughout all year in temperate climates, or in tropical climates when outdoor temperatures are too high [28].
8 In warmer climates, such as the Mediterranean, the potential test period is even shorter, or even impossible in
9 some Australian climates [29]. It would therefore be interesting to find innovative methods that would allow
10 performance testing to be carried out during the summer and in hot climates. To be able to perform building
11 performance tests when the outdoor temperature is too high, one idea is to reverse the difference between the
12 indoor and outdoor temperatures, i.e., to cool down the building instead of heating it.

13 Early experimental tests to validate the concept were carried out on a cube scale [17] and on a 40m³ Passys
14 cell [18]. In both campaigns, a cold generator was positioned outside the envelope of the zone studied. The
15 generated cold power is measured from the flow rate and the temperature difference of the cooling fluid between
16 its inlet and outlet of the envelope. These two studies showed very encouraging results for the use of cooling
17 methods to determine the building envelope performance. Those works also highlights some bottlenecks of the
18 approach. The first one is the difficulty of generating as much power as for heating. The second difficulty is the
19 condensation. If condensation appears due to a too low fluid temperature, latent heat of condensation might
20 generate an energy sink inside the air volume of the measured envelope. So this need to be estimated and
21 considered in the energy balance, since all the energy provide or released by the heating/cooling system will not
22 pass through the envelope as it is assume.

23 A numerical study of a cooling method called "reverse co-heating" has also been carried out at the
24 University of Salford by Chard [30]. This method corresponds to an air conditioning co-heating test. Chard
25 presents and investigates the validity of the cooling technique for different English and Australian climates for

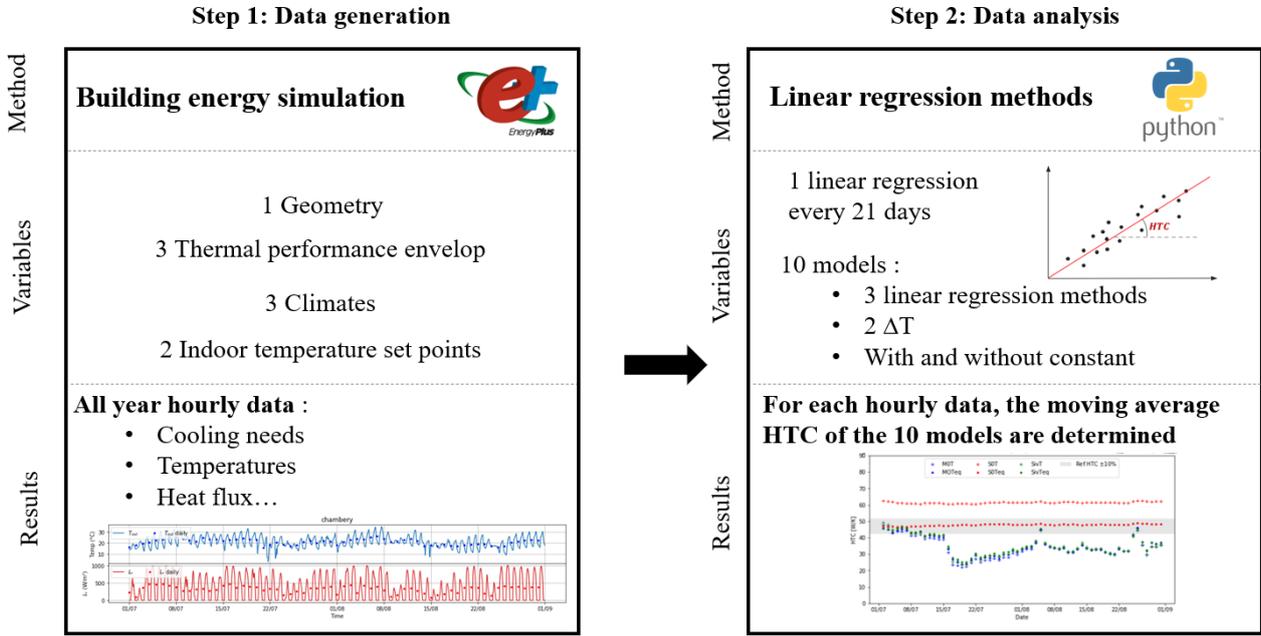
1 the three linear regression methods presented in section 2.3. The method deployed in the English climate has
 2 shown to be unsatisfactory. English weather conditions in summer do not allow for sufficiently large
 3 temperature differences between the inside and outside of the building. In fact, one of the limitations of the
 4 cooling methods is that they cannot cool the interior of the building below 16°C or 17°C, since the working
 5 temperatures of the heat transfer fluids used in today's air conditioning systems do not go below 15°C. Chard
 6 concludes that numerical results based on Australian climate data are not very convincing either. The strong
 7 collinearity between the supposedly independent variables irradiance and temperature difference in the multiple
 8 linear regressions (equation (4)) might be one of the problems. The use of classical linear regression methods
 9 (equations (3), (4) and (5)) for co-heating does not seem to be suitable for co-cooling. New linear regression
 10 methods need to be explored to validate the feasibility and interest of cooling methods.

11 This paper continue the research started in [17] and [18]. It aims to explore the co-cooling potential thanks
 12 to a numerical approach and by proposing an alternative to classical linear regressions. A revised energy balance
 13 equation is proposed, from which HTC estimates can be derived. The method is henceforth named co-cooling
 14 and its validity is thoroughly studied in a numerical test set-up. Novelty is to introduce the use of outdoor
 15 equivalent temperature to to reduce the effect of collinearity in the regression. The equivalent outside
 16 temperature would also enable us to take better account of the radiative transfers.

17 **3. Methodology**

18 **3.1. General overview**

19 The aim of this work is to explore the feasibility of a co-cooling test through a numerical setup. The method is
 20 decomposed in 2 main steps, see Figure 3. The first step is to generate appropriate data of building thermal
 21 behaviour and energy consumption for different case studies. For this, EnergyPlus a Building Energy Simulation
 22 software is used [31] [32]. The second step is to compare different numerical regression models to estimate
 23 HTC of each case study.



24
 25 **Figure 3: Presentation of the two steps methodology**

26 **3.2. First step: variety of case study**

27 The case studies are based on a two-storey individual house geometry with three different thermal
 28 properties (IBB-47, IBB-100 and IBB-282) on 3 weather files (Abu-Dhabi, Nice and Chambery) and with two
 29 indoor temperature set points. These case studies simulated are described in 4.1

3.3. Second Step: Data analysis with linear regression models

Different linear regression models are applied on the generated data. Table 2 summarises the variants applied and the names of the models.

Linear regression method	Type of temperature difference	Models name
Multiple linear regression ($Q_h = HTC \cdot \Delta T - A_{sw} * I_{rr}$)	ΔT	M0T
	ΔT_{eq}	M0Teq
Simple linear regression ($Q_h = HTC \cdot \Delta T$)	ΔT	S0T
	ΔT_{eq}	S0Teq
Sivour method ($\frac{Q_h}{\Delta T} = HTC - A_{sw} * \frac{I_{rr}}{\Delta T}$)	ΔT	SivT
	ΔT_{eq}	SivTeq

Table 2: Name of regression models for each case study and climate

Linear regression method

Three different linear regression methods are studied in this numerical approach, they correspond to the methods used in co-heating [15], corresponding to Equations (3), (4) and (5) explained in section 2.2.2. considering the constant c fixed to 0.

Temperature difference

As section 2.4 explains, due to the significance of radiative exchange in summer, an alternative to the indoor/outdoor temperature difference is to replace the outdoor temperature with an equivalent outdoor temperature. The hypothesis is that the equivalent outdoor temperature would make it possible to take better account of solar gains and the radiative effects of the sky while avoiding collinearity problems in the linear regressions, as raised by Chard [30] in section 2.5.

For each linear regression, two temperature differences are examined. The first type is the so-called "classical" ΔT . It corresponds to the one used in co-heating tests. This "classical ΔT " is determined by equation (8) and is the difference between the indoor and outdoor air temperatures. The other type of temperature difference is called "equivalent" ΔT_{eq} , and corresponds to the difference between the indoor air temperature and the equivalent outdoor temperature, determined by Equation (9). The outdoor equivalent temperature, T_{eq} , is determined as shown in equations (6) and (7), using the outside temperature, solar gain and the wall's convective and radiative transfer coefficients, which are data taken from the EnergyPlus simulation software during the simulation run.

$$\Delta T = |T_{int} - T_{ext}| \quad (8)$$

$$\Delta T_{eq} = |T_{int} - T_{eq}| \quad (9)$$

3.4. Data Analysis

3.4.1. Moving window HTC

The "moving window HTC" methodology is used in this numerical study, as is also used in [33]. This allows estimating many HTCs for each case study simulation run. As illustrated in Figure 4, each HTC is estimated from a 21-day window. The window is shifted one day at a time to cover the two summer months. This methodology makes it possible to determine the evolution of the HTC as a function of different weather conditions.

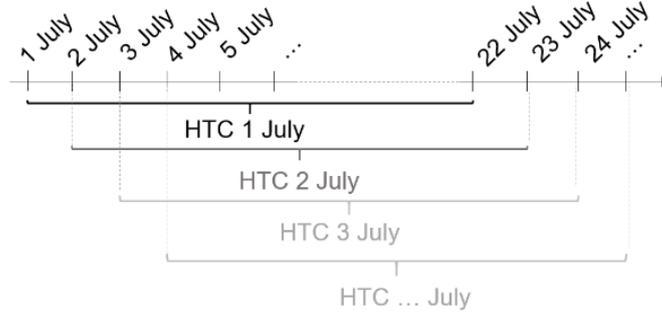


Figure 4 - Moving window HTC explanation

3.4.2. HTC uncertainty quantification

Methodology

To compare the different methods and to know the precision with which the HTC result can be given, it is necessary to determine the HTC uncertainty. The work developed by [34] for co-heating tests has been extended to the case of co-cooling tests. The total HTC uncertainty is the quadratic sum of two uncertainties: the statistical uncertainty, u_{stat} , caused by the chosen linear regression method and the measurement uncertainties, u_{meas} , of the input values.

Statistical uncertainty

Statistical uncertainties represent the variability of the statistical models used. For a Siviour analysis, the explicit formulation in [34] can be directly applied, but the general form of statistical uncertainty described in Thébault and Bouchié [35] might be better suited and can be simply adapted for all 3 types of equations. Any multi-linear model can indeed be written as follows:

$$Y = X \cdot \theta \quad (10)$$

where $Y \in \mathbb{R}^n$, $X \in \mathbb{R}^{n \times p}$ and $\theta \in \mathbb{R}^p$ the parameters to estimate. n is then the sample size (number of daily measurements) and p the number of independent parameters in the model (i.e. HTC , A_{sw} or $intercept$ c).

- For the simple linear regression, equation (3): $Q_h = c + HTC \cdot \Delta T_{eq}$ (or with the independent

variable ΔT version), it follows $X = \begin{bmatrix} 1 & \Delta T_{eq,1} \\ 1 & \Delta T_{eq,2} \\ \vdots & \vdots \\ 1 & \Delta T_{eq,n} \end{bmatrix}$ and $\theta = \begin{bmatrix} c \\ HTC \end{bmatrix}$

- For the multi-linear regression, equation (4): $Q_h = c + HTC \cdot \Delta T_{eq} - A_{sw} * I_{rr}$, it follows:

$$X = \begin{bmatrix} 1 & \Delta T_{eq,1} & -I_{rr_{i,1}} \\ 1 & \Delta T_{eq,2} & -I_{rr_{i,2}} \\ \vdots & \vdots & \vdots \\ 1 & \Delta T_{eq,n} & -I_{rr_{i,n}} \end{bmatrix} \text{ and } \theta = \begin{bmatrix} c \\ HTC \\ A_{sw} \end{bmatrix}$$

- For the Siviour formulation, equation (5): $Q_c / \Delta T_{eq} = HTC - A_{sw} * I_{rr} / \Delta T_{eq}$, it follows:

$$X = \begin{bmatrix} 1 & -\Delta T_{eq,1} / I_{rr_{i,1}} \\ 1 & -\Delta T_{eq,2} / I_{rr_{i,2}} \\ \vdots & \vdots \\ 1 & -\Delta T_{eq,n} / I_{rr_{i,n}} \end{bmatrix} \text{ and } \theta = \begin{bmatrix} HTC \\ A_{sw} \end{bmatrix}.$$

1 An estimate of the HTC statistical uncertainty can therefore be inferred in a general form from the variance-
 2 covariance matrix $var(\hat{\theta})$ [35], where where $\hat{\theta}$ is the estimate of θ , and $\hat{\epsilon}$ the residuals equal $Y - X\hat{\theta}$ (assumed
 3 homoscedastic and non-autocorrelated):

$$var(\hat{\theta}) = var(\hat{\epsilon}) \cdot (X^T X)^{-1} \quad (11)$$

$$var(\hat{\theta}) = \frac{\sum_{i=1}^n (Y_i - X_i \hat{\theta})^2}{n - p - 1} \cdot (X^T X)^{-1} \quad (12)$$

4 The variance of each parameter of interest, whether it be the HTC, the intercept c or A_{sw} follows immediately.
 5 Finally, the HTC statistical uncertainty is given by:

$$u_{stat}(HTC) = \sqrt{var(HTC)} \quad (13)$$

6 All popular statistic python or R packages provide the parameter statistical uncertainty calculation
 7 automatically. In this work, the statistical uncertainty quantification is done with the coheating-analysis python
 8 package, based on the statsmodels package.

9 *Input measurement uncertainty*

10 In line with the guide to the expression of uncertainty in measurement [36], the sources of uncertainty
 11 in the input data are related to the precision, the accuracy and the calibration of the measurement equipment.
 12 This uncertainty evaluation includes both Type A (based on the statistical analysis of series of observations, as
 13 is performed for sensor calibration) and Type B (based on any other means of evaluation). In this work, the
 14 main significant sources of uncertainty in the data are the sensor uncertainty and, as the G.U.M. describes it, the
 15 “non-representative sampling” of the measurands, i.e. a spatial discrepancy of the measured variables. The
 16 former is a type A kind of evaluation, the latter a type B. The uncertainty of each measured variable is therefore
 17 given by:

$$u(x) = \sqrt{u^2(x)_{spatial} + u^2(x)_{calib}} \quad (14)$$

18 The resulting uncertainty $u_{meas}(HTC)$ is calculated from Equation (15), which derives from a first-order Taylor
 19 expansion [36] and that uses the partial derivative of the HTC estimation from (15)

$$\frac{\partial HTC}{\partial x}(x) = \frac{HTC(x + u(x)) - HTC(x - u(x))}{2u(x)} \quad (15)$$

$$u_{meas}(HTC) = \sqrt{\left[\frac{\partial HTC}{\partial T_i}(T_i) \cdot u(T_i)\right]^2 + \left[\frac{\partial HTC}{\partial P_h}(P_h) \cdot u(P_h)\right]^2 + \left[\frac{\partial HTC}{\partial T_{ext/eq}}(T_{ext/eq}) \cdot u(T_{ext/eq})\right]^2 + \left[\frac{\partial HTC}{\partial I_{rr}}(I_{rr}) \cdot u(I_{rr})\right]^2} \quad (16)$$

20 In this numerical approach, the calibration uncertainties have been chosen according to Table 3 [25] and
 21 supposed normally distributed.

VARIABLE (x)	T_i	T_{ext}	T_{eq}	I_{rr}	Q_h
$u(x)_{calib}$	0.5 °C	0.5 °C	0.5 °C	1%	2%

22 **Table 3: Sensor calibration uncertainty choose in the numerical approach.**

23 *Total Uncertainty*

24 The total uncertainty of the HTC estimation is derived from the two types of uncertainty Equations (13) and (16)
 25 as a quadratic sum of them. We therefore have the combined uncertainty u_{tot} :

$$u_{tot}(HTC) = \sqrt{u_{meas}^2 + u_{stat}^2} \quad (17)$$

26 Then, it is possible to determine the expanded uncertainty on a confidence interval U_{tot} :

$$U_{tot}(HTC) = k \cdot u_{tot} \quad (18)$$

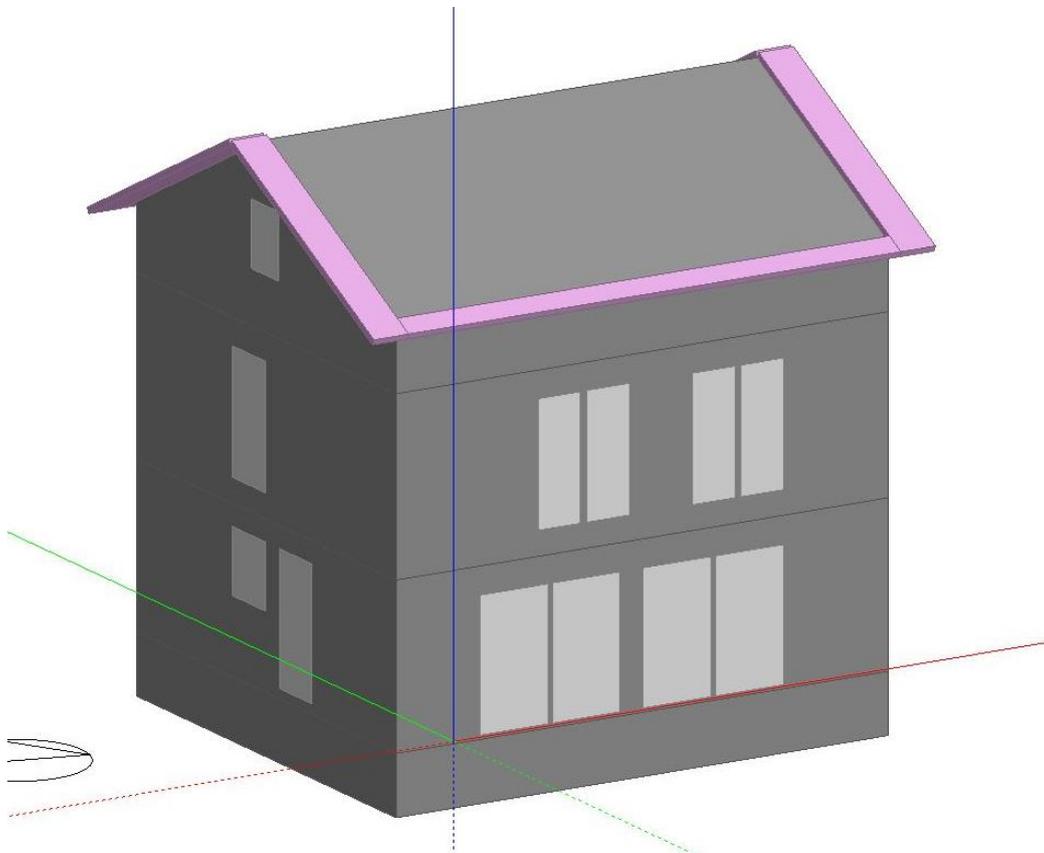
1 A coverage factor k of 2 is reasonable for the definition of the expanded uncertainty [36] as it defines an
2 uncertainty interval that is expected to encompass a large fraction of the distribution of estimated values.. From
3 now on, HTC estimates will be given with their expanded uncertainty: $HTC \pm U_{tot}(HTC)$.

4. Modelling of the case Studies

4.1. Description of the case study envelopes

4.1.1. General overview

7 The three houses are based on the INCAS-IBB house on the CEA experimental platform at the Institut
8 National de l'Energie Solaire (INES). The platform is located at Le Bourget du Lac in the French Alps (N:
9 45°650, E: 5°867). The building (Figure 5) is oriented at 15.3° on a north-south axis. The house has a concrete
10 structure and a high level of insulation. The surface area of a floor is 46 m² and the heated volume is
11 approximately 250 m³.



12
13 **Figure 5: A view of the IBB house model in Design Builder**

14 This experimental house has two main levels. The ground floor comprises a kitchen, a living room, an entrance
15 hall, a storeroom and a toilet. The first floor has three bedrooms, a bathroom and a toilet. IBB house has a crawl
16 space and attic space. For more details, plans are given in Figure 6.

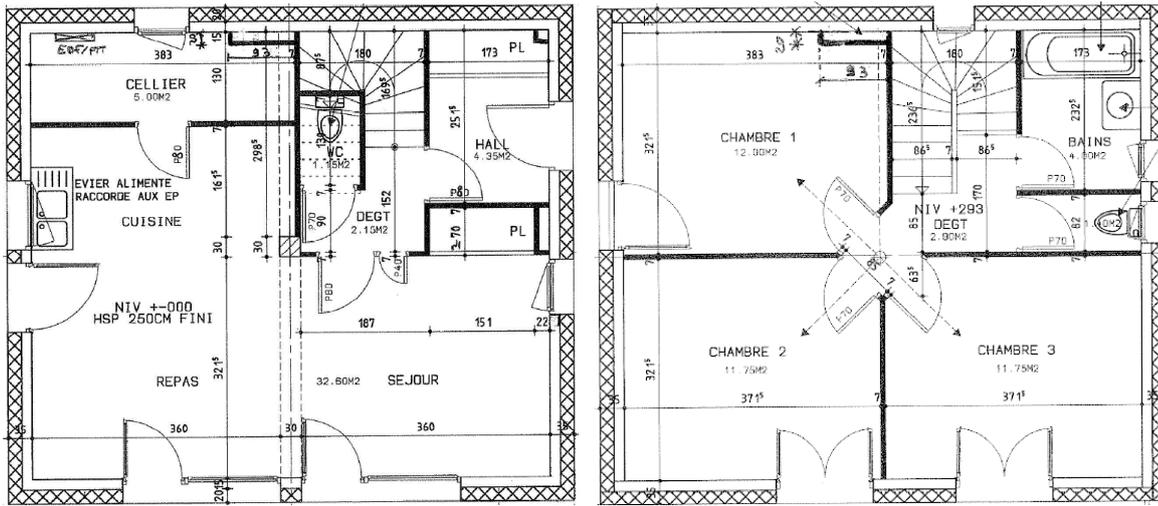


Figure 6 - House Plan (Ground Floor left, 1st floor right)

4.1.2. IBB-47: Real house thermal properties

The first case corresponds to the numeric representation of the real case of the INCAS-IBB house of 2019 made in DesignBuilder except the ground floor which normally connect to the crawl space is considered in the simulation as adiabatic. We have chosen not to take into account infiltrations and losses through the ground because both conditions have an impact that is challenging to consider both in the reference value and in the measured value (here by simulation), as indicated in [37]. The thermal properties of this case are summarised in Table 4.

4.1.3. IBB-100 and IBB-282 – Thermally degraded characteristics

Study cases IBB-100 and IBB-282 have the same geometry as IBB-47 house, except that the performance of their thermal insulation is degraded to study houses with a lower performance. The thermal properties of the walls of IBB-100 and IBB-282 are summarised in Table 4.

	House	IBB-47	IBB-100	IBB-282
U with indoor and outdoor surface resistances [W/(m².K)]	Exterior wall	0.144	0.435	2.306
	Roof	0.128	0.374	1.727
	Fenestration	1.3	3	5

Table 4: Thermic propriety of the three houses

4.1.4. Assumptions to numerically mimic a co-cooling test

Similarly, to a co-heating test into the building, ventilation defined as zero to simulate ventilation being switched off, and ventilation vents blocked. Furthermore, in our case, we are considering closing the shutters to avoid as much as possible direct solar gain, which is very important during the summer. Noteworthy is that the infiltration airflow is numerically set to zero as to focus on transmission losses only. An adiabatic floor is assumed. This assumption eliminates heat exchange with the ground and the crawl space. This means the transmission loss coefficient H_{ext} is also equal to the HTC.

4.2. Data generation

4.2.1. Simulation Tool

A dynamic thermal simulation calculation engine, EnergyPlus [38], is used. This software is used throughout the building energy science community and has the advantage of being open source and validated by the scientific community for example see [32], [39]. In this work, the simulations are carried out using version 22.1 of the software. The generation of the data used has a time step of 10 minutes.

In an objective of results comparison, both co-heating and co-cooling simulations are run. For each co-heating or co-cooling test, a simulation is run under EnergyPlus over a 3-week test period. A warm-up is performed for each simulation, with a minimum of 6 warm-ups days and a maximum of 150 warm-ups days.

The model contains six thermal zones corresponding to the ground floor, the three bedrooms, the bathroom and the attic. The indoor temperature is set by a thermostat and is assumed to be homogeneous and constant throughout the heated space made of the ground floor and the first floor. Cooling or heating needs are determined by EnergyPlus. The sky temperature model chosen is Berdhal-Martin [40]. The indoor and outdoor convection algorithm are TARP [41], which corresponds to convection variability based on temperature difference.

4.2.2. HTC reference values: data generation

In order to establish a reference value for the three houses, stationary weather simulations are carried out as explained in section 2.2.2. . The aim of the stationary weather simulations is to eliminate all heat transfers that are not related to the indoor-outdoor temperature difference. More specifically, the stationary test is carried out under the same conditions (unoccupied, no ventilation, shutters closed, etc.) as the co-cooling and co-heating tests.

A different weather file will be employed, which sets the wind speed to 0 m/s, the direct and diffuse irradiance to 0 W/m² and no precipitation. Air temperature, wet air temperature, relative humidity and air pressure are set to constant values in this file. The sky temperature is set constant and equal to the outdoor temperature. Table 5: Reference value data hypothesis in the weather file and in the simulation summarises the various assumptions made during the simulation and in the weather file.

Two values are determined, called "HTC heating" and "HTC cooling". These values correspond to the HTC calculated from stationary weather simulation with the following indoor and outdoor temperatures: $T_{ext} = 10\text{ }^{\circ}\text{C}$ $T_{int} = 30\text{ }^{\circ}\text{C}$ for heating and $T_{ext} = 35\text{ }^{\circ}\text{C}$ $T_{int} = 15\text{ }^{\circ}\text{C}$ for cooling. The reference value is taken as the value for the heating simulation, which is considered the most reliable simulation. An uncertainty of 10% around this reference value is chosen. This uncertainty is chosen as indicated in a recent article [42] which states that co-heating manages to determine the HTC within an interval of 10%.

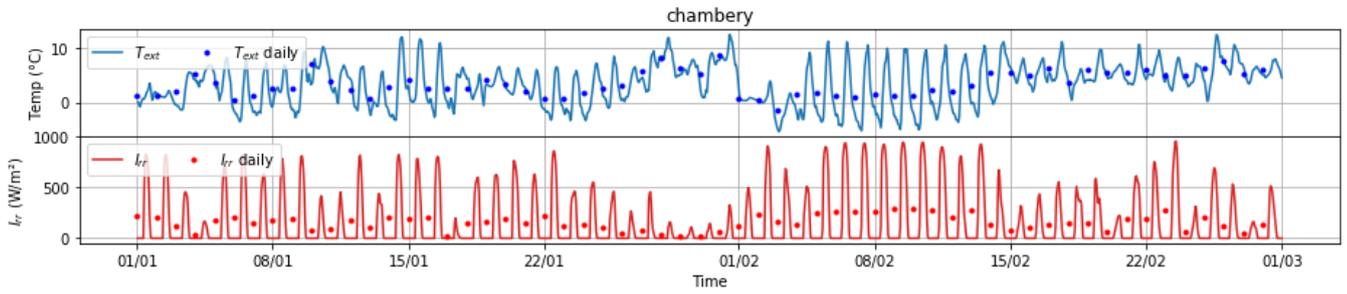
File	Physical quantity	Value
Weather file	Field Atmospheric Station Pressure	99332 Pa
	Field Dry Bulb Temperature	Constant
	Field Dew Point Temperature	Constant
	field Relative Humidity	50%
	Field Extraterrestrial Horizontal Radiation	0 W/m ²
	Field Extraterrestrial Direct Normal Radiation	0 W/m ²
	Field Horizontal Infrared Radiation Intensit	0 W/m ²
	Field Global Horizontal Radiation	0 W/m ²
	Field Direct Normal Radiation	0 W/m ²
	Field Diffuse Horizontal Radiation	0
	Field Wind Direction	0 m/s
	Precipitation	0 mm
	Simulation	Sky temperature
Interior Temperature		Constant

Table 5: Reference value data hypothesis in the weather file and in the simulation

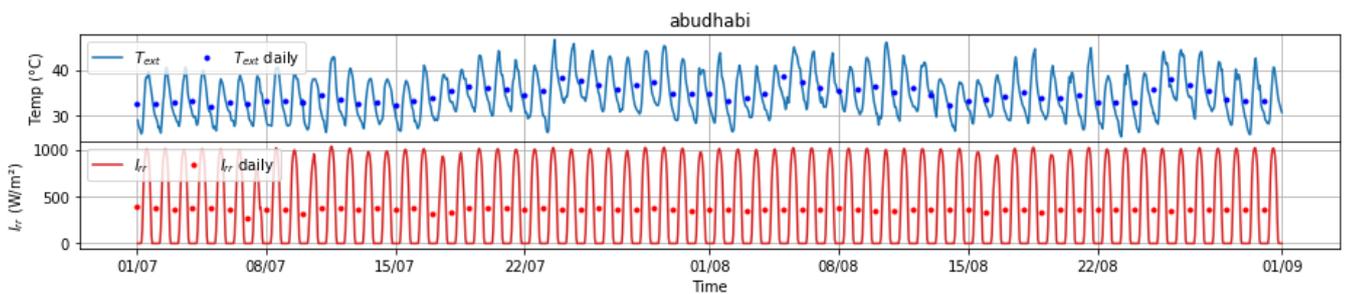
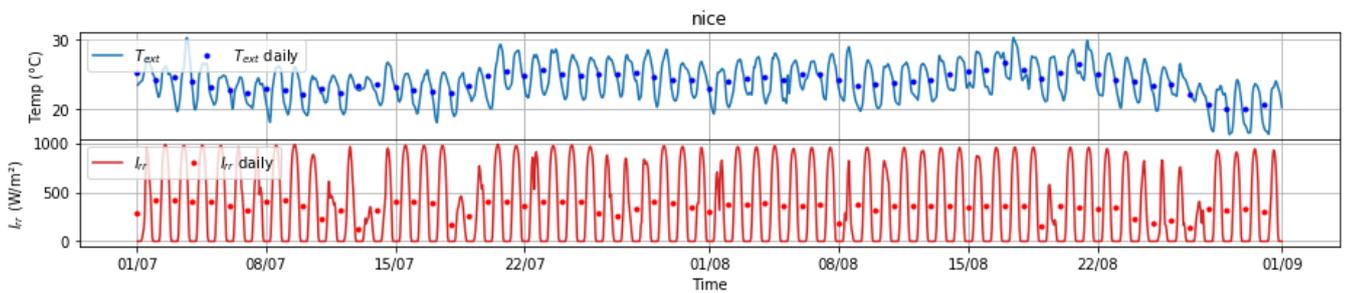
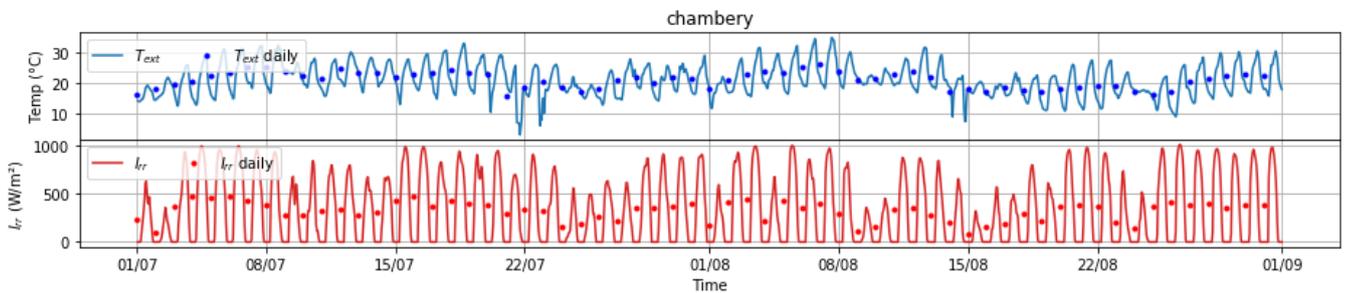
4.3. Weather data used

Three different climates are studied for the hot / summer period during this work, they correspond to three different types of climates, that of Chambéry, Nice and Abu-Dhabi. Corresponding respectively to climates, Cfc, Csa and Bwh according to the Köppen-Geiger classification [43]. Cfc corresponds to a temperature climate with a short and fresh summer, Csa to a temperate climate with a hot summer and Bwh stands for a dry and hot climate. The average values of climatic conditions for the weather data used are shown in Figure 7 for the winter period choose for Chambéry, and Figure 8 for the 3 summer periods choosed and summarized for the 4 weather files in Table 6. As depicted in Figure 8, there is a significant fluctuation in the outdoor temperature and the irradiance of Chambéry in summertime. By contrast, Nice's climate has a more stable average outdoor

1 temperature but there is a considerable variation in the average daily irradiance. Abu-Dhabi's climate shows
 2 quite repetitive days in terms of outside temperature and irradiance.



3
 4 **Figure 7 : Evolution of irradiance and daily average outdoor air temperature over the period January 1 - March 1 in the**
 5 **Chambery climate**



6
 7
 8
 9 **Figure 8 : Evolution of irradiance and daily average outside air temperature over the period July 1 - September 1 on the**
 10 **climate of Chambery (top), Nice (middle) and Abu-Dhabi (bottom)**

	Winter (Jan. 1st – March 1st) Chambery	Summer (July 1stn – Sep. 1st)		
		Chambery	Nice	Abu-Dhabi
Average Solar radiation (Direct +Diffuse) [W/m²]	154,5	317,3	334,0	360,4
Mean outdoor temperature [°C]	3,4	20,9	23,9	34,6
Mean dew point temperature [°C]	0,1	15,2	17,8	22,2

11 **Table 6 : Summary of weather conditions for the 4 weather files used**

5. Results

5.1. Case study reference values

The first objective is to have a reference value for each modelled envelope. For this, the heating stationary weather approach is used as described in sections 2.2.2. and 4.2. The stationary weather approach is also run in a cooling mode to compare the results with the heating mode. Co-heating simulations are also run, and HTC are estimated with the 3 linear regression models described in 2.3 and is the mean value of the moving window method in Chambery climate over January. Table 7 summarises these values determine for the three houses. The stationary weather simulations in heating and cooling mode give similar values, with a 3—4% difference for each 3 cases. The reference value for IBB-47 is 47 W/K, IBB-100 is 100 W/K and for IBB-282 is 282 W/K. As a reminder from Section 4.2.2. , an uncertainty of +/-10 % is considered on this reference value, this uncertainty is explained by the typical variability and uncertainty of co-heating tests in the literature [34] [33].

Simulated co-heating tests are also run to validate the reference value. The co-heating HTCs are similar to stationary weather method HTCs. For example, the stationary weather approach on IBB-47 gives a value of 47 W/K and the co-heating test values give an HTC value of 45 W/K for simple linear regression or 48 W/K for the multiple linear regression and for the Siviour method. There is a difference between the HTC values determined by the co-heating tests using simple regression and multiple regression compared with the stationary weather methods. However, this difference is within the 10% variability of co-heating tests. The variability of co-heating tests and the definition of a reference value are an area of research which is outside the scope of this article.

Case study envelop	Stationary Weather		Co-heating tests		
	Heating (Reference)	Cooling	Simple Reg. Equation (3)	Multiple reg. Equation (4)	Siviour Equation (5)
IBB-47	47	49	45	48	48
IBB-100	100	103	99	104	101
IBB-282	282	292	302	310	287

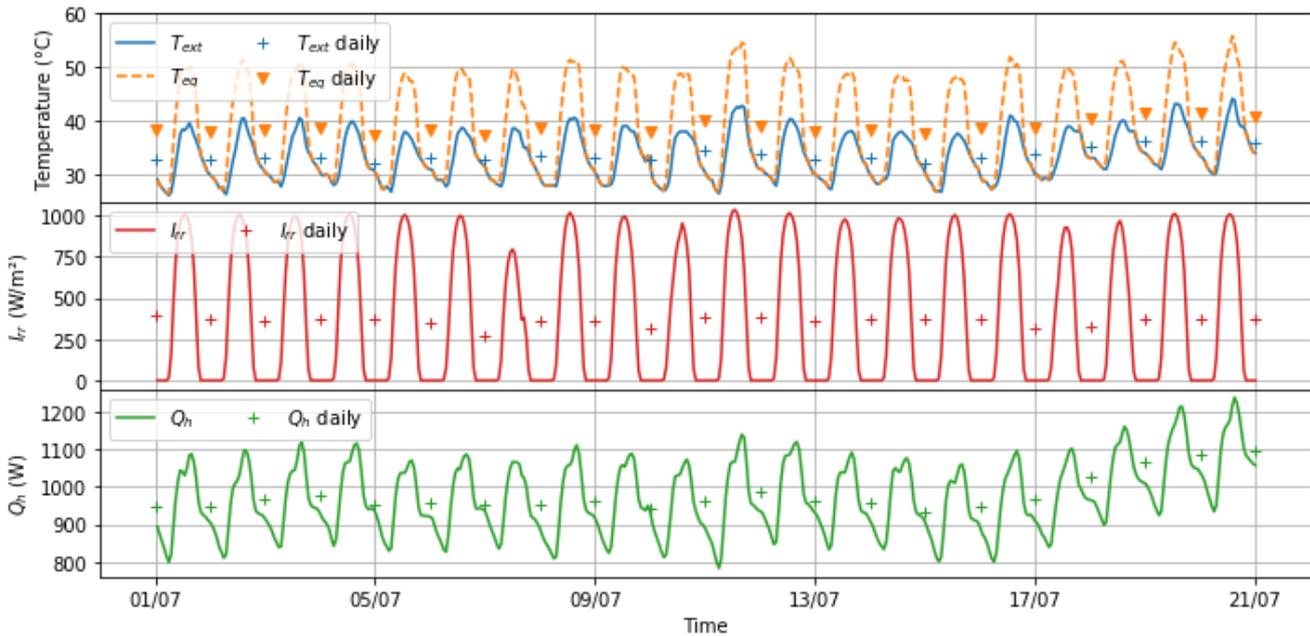
Table 7: HTC estimation in W/K for the stationary method and co-heating tests for the 3 cases studies.

5.2. Simulated Co-cooling test: an illustration in Abu-Dhabi

An initial simulated co-cooling test was carried out on the Abu-Dhabi climate from the 1st to the 21st of July with an 18°C internal temperature set point. The hourly evolution and daily average of climatic conditions and cooling capacity are shown in Figure 9. In this figure, are plotted on the upper graph the outdoor temperature in continuous blue line, the outdoor equivalent temperature in dotted orange line as introduced in 2.4, in the middle the global horizontal solar radiation and in the bottom the cooling power. The outdoor conditions are similar from one day to another with outdoor temperature varying mainly from 27 to 40°C with sunny days.

The cooling needs exhibit a daily pattern characterized by an initial rise, peaking at 1100W with the sunrise, followed by a decline along two slopes. The first slope corresponds to the solar radiation decrease, while the second occurs after sunset. It is interesting to check that for the last days from the 17th of July, the outdoor daily maximum temperature increases from 40 to 44°C, which directly affect the daily cooling maximum power from 1100 W to 1200 W.

1



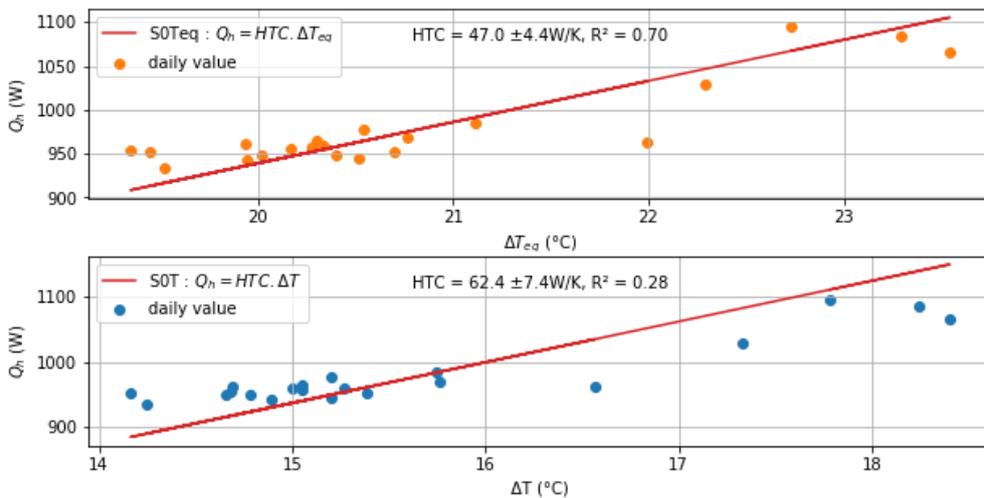
2

Figure 9: Evolution of climatic conditions and cooling power for a co-cooling test in Abu-Dhabi with $T_{int}=18^{\circ}\text{C}$

3

In Figure 10 **Erreur ! Source du renvoi introuvable.**, the daily cooling capacity for the test period is plotted as a function of the daily averaged temperature differences ΔT (lower graph) and ΔT_{eq} (upper graph) in order to perform the simple linear regressions corresponding to the methods with the standard outdoor temperature or the outdoor equivalent temperature respectively. With the outdoor equivalent temperature (S0Teq), HTC is estimated at 47 W/K ($\pm 9\%$), i.e. equal to the reference value whereas the HTC estimated with the standard outdoor temperature (S0T) is 62.4 W/K ($\pm 12\%$), i.e. 30% higher than the reference value. In addition, the “Teq method” gives a higher coefficient of determination and a lower uncertainty than the one with standard outdoor temperature. There is however room for adjustment for the regression models, when even 30% of the variability remains unexplained by model S0Teq.

11



12

Figure 10: Linear regression of a simulated co-cooling test on IBB-47 House in Abu-Dhabi at $T_{int}=18^{\circ}\text{C}$. Up : simple linear regression with ΔT_{eq} (S0Teq) and down : simple linear regression and ΔT (S0T)

13

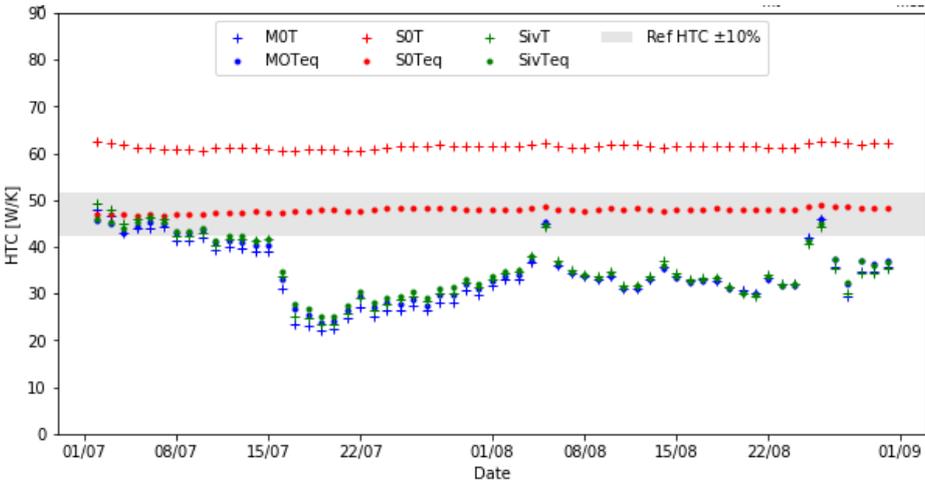
5.3. Weather and regression model influence on HTC estimates under Abu-Dhabi climate.

14

Figure 11 shows the moving window HTC as introduced in section 3.4 from the 1st of July to the 1st of September using different linear regression methods for IBB-47 house on the Abu-Dhabi climate at 18°C . The

15

1 shaded area represents an interval of +/-10% around the reference value determined in section 5.1. S0Teq, is
 2 the only method with all the HTC evaluation in the range of +/-10% of the reference value.



3
 4 **Figure 11: Moving window HTC of simulated co-cooling tests for different linear regression methods on the Abu-Dhabi**
 5 **climate at 18°C during July and August**

6 Table 8 summarises Figure 11, giving the average HTC values, standard deviations, and uncertainties for
 7 each linear regression method over the two months period on which 62 HTC estimation have been performed.
 8 Only the S0Teq method gives both a stable result (standard deviation of 0.6 W/K) and an average HTC over the
 9 period of 48 W/K, which is very close to the reference result of 47 W/K. The other linear regression models,
 10 except S0T, give highly variable HTC results with standard deviation around 6 W/K over the time-period and
 11 are not accurate, with HTC_{mean} of around 35 W/K. The S0T method gives a stable yet strongly overestimated
 12 result compared with the reference with $HTC_{mean} = 61$ W/K.

13 The expanded measurement uncertainties for methods other than S0T and S0Teq are greater than 25%, which
 14 represents an expanded uncertainty of more than 8 W/K. The S0T and S0Teq methods have a lower uncertainty.
 15 For S0T method, the expanded uncertainty is 8 W/K, which means that this method does not fall within the
 16 reference value range. Finally, the S0Teq method has an expanded uncertainty of 5 W/K, which represents an
 17 uncertainty of just under 10% of the HTC. In summary, the S0Teq method has the lowest uncertainty of all the
 18 methods studied.

Regression method	Method name	Mean HTC [W/K]	HTC standard deviation [W/K]	Uncertainty extended coverage HTC [W/K]	Uncertainty error [%]
Mul. Reg. ΔT	M0T	34	6,4	8,9	27
Mul. Reg. ΔT_{eq}	M0Teq	35	6,0	8,3	25
Simp. Reg. ΔT	S0T	61	0,5	6,9	11
Simp. Reg. ΔT_{eq}	S0Teq	48	0,5	4,3	9
Siviour ΔT	SivT	35	6,4	9,0	27
Siviour ΔT_{eq}	SivTeq	35	5,9	8,4	24

19 **Table 8: Summary table of moving window HTC simulated co-cooling at 18°C in the Abu-Dhabi climate in July and August**

20 Only the simple linear regression method at ΔT_{eq} (S0Teq) works in study case IBB-47 with the Abu-Dhabi
 21 climate, next step presented in the following paragraph permits to test this method for the other cases studies
 22 and climates.

23 **5.4. Climate influence on HTC estimate quality**

24 To assess the accuracy of a simulated co-cooling test under south-European climates, the numerical
 25 experiments are extended to Nice and Chambéry's climates. **Erreur ! Source du renvoi introuvable.**

1 summarises the results of the simulated co-cooling tests using the simple regression method with ΔT_{eq} over a
 2 two-months summer period according to the three climates detailed in section 4.3.

3 In the Nice climate, which is colder than Abu-Dhabi climate, with a temperature difference of less than
 4 6°C for both temperatures set points, the HTC results are still accurate with a relative gap of 2% as for Abu-
 5 Dhabi Climate. HTC estimation for Nice climate is a bit more variable through the simulated co-cooling test
 6 than those for the Abu-Dhabi climate. Standard deviation is two to three times greater than for the Abu-Dhabi
 7 climate.

8 For Chambéry climate, which is colder than Nice one, the temperature difference average, at 18°C
 9 temperature set point is lower than 3°C. Despite this small difference temperature, results give an HTC average
 10 result in the range of 20% difference to the reference value for all the tests run. However, it seems impossible
 11 to carry out conclusive tests for a set point temperature of 20°C on Chambéry climate. The HTC values
 12 determined are far from the reference value (over 30% relative difference). The average temperature difference
 13 between indoors and outdoors over the test period is close to zero, which means that outdoor temperature is
 14 partly greater partly lower than the indoor temperature. This implies that the heat flux through the envelope
 15 regularly reverse from one to the other. Furthermore, the tests on Chambéry climate had the greatest temporal
 16 variability in HTC.

17 Generally speaking, the smaller the temperature difference, the less accurate the HTC value is, the greater
 18 the uncertainty and the less stable the HTC is according to the tests.

19 5.5. Envelope performance influence on HTC estimate quality

20 The results for the other two envelopes, IBB-100 and IBB-282, are summarised in the lower part of Table
 21 9. Regardless of the case study, the developed method (S0Teq) under the Abu-Dhabi climate gives results very
 22 close to the reference value. HTC estimates are less than 2% difference for the IBB-100 and around 10% for
 23 IBB-282. For both cases, there is a great stability of the HTC over the period studied with a standard deviation,
 24 indicating temporal variability, less than 1 W/K for IBB-47 and less than 2 W/K for IBB-282.

25 For the Nice climate, conclusions are similar, the method manages to estimate the HTC value in a range
 26 below 10% with a difference of 3% for IBB-100 and less than 6% for IBB-282. For both envelopes, the standard
 27 deviation is two to three times greater than the one for Abu-Dhabi, but the HTC value is still in the range of
 28 10% difference with the reference value.

29 For the Chambéry climate, as for the IBB-47, HTC estimates are further from the reference than the other
 30 climates due to its lower outdoor temperature. It should be noted that in the case of IBB-282 under the Chambéry
 31 climate, HTC estimation is closest to the reference value compared to IBB-47 and IBB-100.

32

House	Climate	Setpoint temperature [°C]	Mean ΔT_{mean} [W/K]	Mean HTC (s0teq) [w/k]	HTC standard deviation [W/K]	Relative gap with reference value [%]	Uncertainty extended coverage HTC [W/K]	Uncertainty error [%]
IBB-47	Abudhabi	18	16,7	48	0,5	2	4	9
		20	14,7	48	0,6	1	5	10
	Nice	18	5,5	48	1,3	2	9	18
		20	3,5	48	1,7	2	22	10
Chambéry	18	2,3	41	2,8	12	11	27	
	20	0,4	33	5,3	30	11	10	
IBB-100	Abudhabi	18	16,7	102	0,8	1	9	26
		20	14,7	101	0,9	1	10	9

	Nice	18	5,5	99	1,7	1	18	32
		20	3,5	97	2,3	3	22	34
	Chambery	18	2,3	84	4,8	16	22	18
		20	0,4	69	8,6	31	22	27
IBB-282	Abudhabi	18	16,7	312	1,8	11	28	18
		20	14,7	309	1,9	10	30	9
	Nice	18	5,5	296	5,2	5	52	18
		20	3,5	295	5,1	4	64	22
	Chambery	18	2,3	257	9,7	9	62	24
		20	0,4	232	14,7	18	63	24

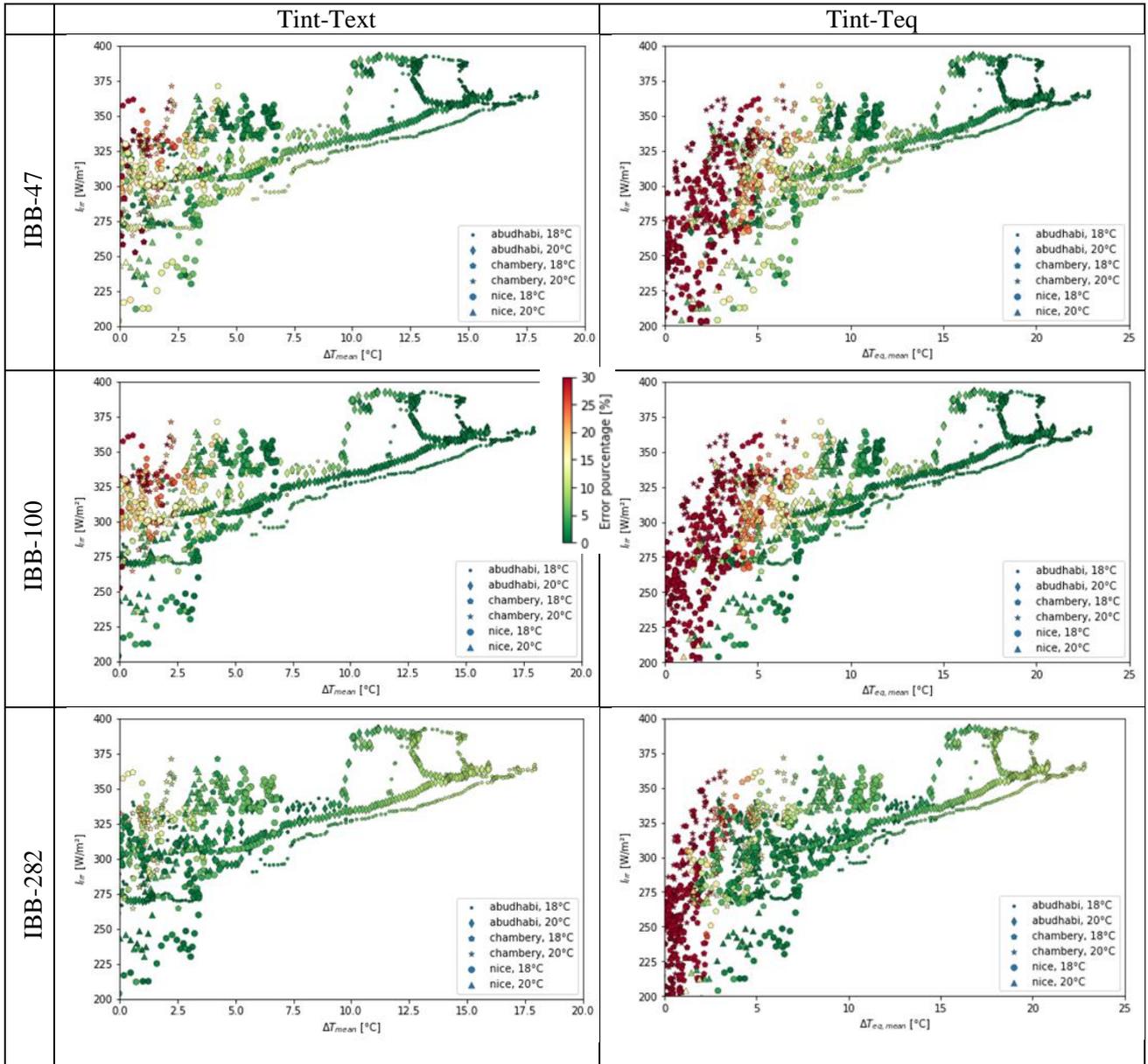
Table 9: Summary of the HTC's estimated with a simple regression method and ΔT_{eq} (S0Teq) during simulated co-cooling test for 3 houses, on 3 climates at the set temperature of 18°C and 20°C

5.6. Conditions of measurement for accurate co-cooling tests

Similarly, to co-heating tests [27], [34], the accuracy of the linear regression method seems to be linked to the value of the temperature difference. The aim of this section is to explore the feasibility of a co-cooling test by investigating climatic conditions and minimal indoor/outdoor temperature differences. To this end, a test is performed every day of the year for the 18 cases study. Only tests with a positive outdoor-indoor temperature difference average are displayed. To analyse these, Figure 12 shows scatter plots where each point are coloured by the HTC relative difference to the reference value and is positioned on a map depending on the average irradiance on y-axis and on the average indoor-outdoor temperature difference on the x-axis. Given that the simple regression method is using the equivalent outdoor temperature (S0Teq), two indoor-outdoor temperature difference are analysed: the mean difference temperature (ΔT_{mean}) (left graphs) and the mean equivalent temperature difference, $\Delta T_{eq,mean}$ (right graphs).

Figure 12 confirms that the greater the indoor/outdoor temperature difference, the better chance it is to have an accurate estimation of the HTC value. Aiming at an indoor-outdoor temperature difference limit regardless of the envelope performance, it can be inferred that test results with a ΔT_{mean} larger than 7°C deviate by less than 10% from the reference value. In summer, the average equivalent outdoor temperature $\Delta T_{eq,mean}$ is greater than the mean difference temperature (ΔT_{mean}) due to the solar radiance. It can be seen on the graphs with $\Delta T_{eq,mean}$. Temperature differences $\Delta T_{eq,mean}$ larger than 7°C are required to determine the HTC of simulated co-cooling test with a relative error of less than 15%, and a $\Delta T_{eq,mean}$ greater than 10°C for a relative error of less than 10%. To grasp the feasibility of co-cooling tests under the three climates studied, we can summarize that during the June--September period with a temperature set point of 18°C, operational limit of $\Delta T_{eq,mean}$ larger than 7°C has occurred 72% in Nice, 13% in Chambery and 100% in Abu Dhabi.

It is more difficult to define a limit on the irradiance. First, there are few points with low irradiance and none of them with high ΔT_{mean} . This is because irradiance is often linked to the outside temperature and very hot days, but cloudy days are uncommon. Nevertheless, it looks like at low irradiance, a lower indoor/outdoor temperature difference might be necessary to have a more accurate HTC evaluation. Points with irradiance below 250W/m² in average, are below 20% difference to the reference value for all point on the ΔT_{mean} graph, and for points with a $\Delta T_{eq,mean} > 3^\circ C$. For the less insulated house, IBB-282, a lower indoor/outdoor temperature difference is admissible to estimate the HTC.



2 Figure 12: Deviation of the estimated HTC with S0Teq method as a function of solar gains and air temperature difference
 3 ΔT_{mean} (left) and equivalent difference temperature $\Delta T_{eq,mean}$ (right), for three houses IBB-47 (Top), IBB-100 (middle) and
 4 IBB-282 (bottom), under the three climates (Abu-Dhabi, Nice and Chambery) and with 2 temperature set points (18°C, 20°C)

5

1 6. Discussion

2 6.1. Study limits

3 For the purposes of this discussion section, it is important to keep in mind the overall aim of the work and
4 some important assumptions that have been made. The main objective is to explore the possibility to determine
5 an HTC of a building envelope through a co-cooling test. Regarding the assumptions, the data used to determine
6 HTC through linear regression are coming from simulated data generated by building simulation models run
7 with EnergyPlus engine. This mean that indoor air temperature is homogeneous in each thermal zone with
8 homogeneous heat flux through each piece of wall described in the model. So, this does not account for, among
9 other things, heterogeneity of indoor temperature in a room or heterogeneity of heat flux through a surface due
10 to the wall composition, and no thermal bridges are modelled. It can indeed be expected that real-life heat flux
11 in a wall will present variable time characteristics. Yet, the case study here is in some sense a worst-case
12 scenario: the envelope has a high thermal inertia, which is known to be influential on the accuracy of co-heating.
13 As for the heterogeneity of indoor air temperature in real-life tests, this is taken into account in the uncertainty
14 calculation and will simply result in a slightly higher uncertainty and is therefore not a strong limitation of this
15 study.

16 Other strong assumptions have been made in this work such as the absence of air leakage modelling and
17 an adiabatic ground floor. These assumptions do not call into question the meaning of the results. However, it
18 is likely that in a real case the results are more nuanced in terms of the accuracy of the method developed.

19 A last assumption that we want to introduce is about the estimation of the outdoor equivalent temperature
20 for which it is necessary to know the different wall surfaces and U values, that are well known in our simulated
21 cases. Again, in a real-life application, this uncertainty would be accounted for and propagated in the uncertainty
22 estimation, which would show as a slightly larger HTC uncertainty.

23 It should be noted that in our case study and for the co-cooling technique, simulations have been done for
24 buildings with shutters closed to avoid as much as possible direct solar gain, which is very important in summer.
25 However, for the future application of the co-cooling test, it should be borne in mind that the HTC calculated
26 corresponds to the HTC of the house with the shutters closed. This will have relatively little impact on buildings
27 with thermally efficient windows but will have a greater impact on buildings with less thermally efficient
28 windows.

29 As well as Matthew Li [33], differences between the ISO-calculated HTC and HTC determined by
30 simulated co-heating have been observed. To obtain a reference HTC value, Li proposes two approaches, the
31 first one is to characterize the surface resistance relatively to environmental conditions, the second one is to
32 define a scenario specific HTC reference. However, in a recent article Juricic [25] proposes another approach
33 which consists of defining a conventional H_{tr}^* based on the equivalent temperature. This is why in this work a
34 "stationary weather" method presented in section 2.2.2. has been chosen to determine heat losses with a known
35 indoor-outdoor temperature difference which is not influenced by radiative and convective heat transfers. The
36 co-cooling aggregates all the heat transfers into an equivalent outside temperature. That is why we believe that
37 this reference value physically represents the same coefficient as the HTC determined from co-cooling.
38 However, as indicated in section 5.1 , we think, as Li [33] does, that it could be an entire research work on the
39 topic of a "True" or "reference" HTC.

40 The encouraging results showed in the previous section need to be consolidated, firstly, with extended
41 simulation with modelled integrating non cooled adjacent room, a non-adiabatic floor or infiltration flow rate
42 varying depending on the weather conditions and indoor-outdoor temperature difference. Secondly, some
43 experiments on real house will be necessary to continue this work and the one done in [18] [17].

6.2. Why the simple linear regression with ΔT_{eq} seems to be the most reliable model?

Only the simple linear regression method with ΔT_{eq} (S0Teq), gives consistent values for the three houses. This paragraph outlines possible explanations as to understand why this method seems to work for co-cooling test.

Simple regression using ΔT (S0T) overestimates the HTC. This can be explained by the fact that this method does not consider solar gains, which have much higher impact in summer. To summarise, part of the cooling power required to keep the building at a constant temperature is not dependent on the outside temperature but is dependent on the additional energy provided by the sun on all opaque walls through radiative transfer.

As for multiple regressions and Siviour's methods, which do consider solar gain, it was expected to be strongly correlated with weather conditions, as shown in Figure 11. These two regression methods take the same variables as explanatory inputs (irradiance, temperature, and cooling capacity) but do not account for long-wave radiation from the sky. The issue here is that these input variables are highly correlated in summer, which jeopardises the validity of any multi-linear regression. For an inference to be made from a regression, a major assumption is indeed that the explanatory variables are independent, which is not always the case in winter and not the case in summer. To quantify the effect of the suspected collinearity on the quality of the regressions, a variance inflation factor (VIF) is calculated. It gives a measure of the influence of the collinearity on the variance of the inferred HTC estimate. An examination of the multiple regression models revealed that the VIF of I_{rr} and ΔT exceeded 200. A VIF greater than 5 or 10 according to [44] and [45] indicates a high degree of collinearity between the explanatory variables, resulting in poor HTC accuracy and greater coefficient variability. This phenomenon of multi-collinearity is also noted in the work of E. Chard [30], with similar results found. According to the author, the multi-collinearity of the variables is one of the reasons for the poor results of co-cooling with multiple regression methods over Australian climates.

The simple regression method using the equivalent outdoor temperature (S0Teq) overcomes all these problems by aggregating the radiative and convective transfers to which the building envelope is exposed into a single variable.

6.3. Should there be an intercept in a co-cooling regression model?

In the simple linear regression (eq. 3) and in the multiple linear regression (eq. 4) defined in 2.3, an intercept is introduced. It can be seen as a constant heat loss or gain that are not related to the indoor/outdoor temperature difference. Some phenomena such as the effect of the sky in the case of an open sky cooling the building by long wave radiation, or heat loss through the ground can be integrate in this intercept.

In the results sections, only results with intercept fixed to 0 have been shown, to simplify the result presentation and because co-heating tests do not yield better HTC estimations with an intercept [24]. However, the uncoupled phenomena considered in the intercept of linear regressions are different between co-cooling and co-heating tests, as summarised in Table 10.

The effect of adding an intercept in the linear model have also been investigated and shortly presented here. The results show that the HTC estimates are less accurate than with no intercept, as illustrated in Table 11, with errors larger than 30%.

Co-heating ($T_{ext} < T_{int}$)	Co-cooling ($T_{int} < T_{ext}$)
<p style="text-align: center;">Uncoupled losses (More heating required)</p> <ul style="list-style-type: none"> • Losses through the ground • Losses through sky radiation • Losses through unheated space 	<p style="text-align: center;">Uncoupled losses (More cooling required)</p> <ul style="list-style-type: none"> • Losses through the ground (depending on ground temperature) • Losses through uncooled space • Equipment not measured • Losses due to uncorrected solar gain

Non-coupled inputs ("free heating")	Uncoupled inputs ("free cooling")
<ul style="list-style-type: none"> • Equipment not measured • Uncorrected solar gains • Gains in neighbouring heated space 	<ul style="list-style-type: none"> • Gains from neighbouring cooled space • Gains from sky radiation

1 **Table 10: Differences in phenomena unrelated to the indoor-outdoor temperature difference between the coheating and co-**
2 **cooling tests**

Constant	Linear regression method	Mean HTC [W/K]	Htc standard deviation [W/K]	Uncertainty extended coverage htc [W/K]	Uncertainty error [%]
Constant fixed to 0	Simple linear regression with ΔT_{eq}	48	0,5	4,3	9
	Multiple linear regression with ΔT	31	5,2	8,3	16
Constant unfixed to 0	Multiple linear regression with ΔT_{eq}	32	5,5	8,5	27
	Simple linear regression with ΔT	32	5,5	8,0	26
	Simple linear regression with ΔT_{eq}	33	5,6	8,1	25

3 **Table 11: Summary table of moving window HTC simulated co-cooling at 18°C in the Abu-Dhabi climate in July and August**
4 **for regression methods with unfixed to 0 constant.**

5 6.4. Variation of uncertainties

6 The uncertainties of the new method, S0Teq, increase as the mean ΔT of the test decreases. The expanded
7 uncertainties of simulated co-cooling tests at ΔT_{mean} above 10°C are similar to the uncertainties of co-heating
8 tests of around 10% [46] [22]. The cooling power uncertainty has been evaluated at 2% in this work, but it is
9 quite possible that this uncertainty could be higher (section 6.6), which would increase the total uncertainty of
10 the HTC.

11 In addition, given the limitations of the simulation assumptions (adiabatic ground and no infiltration), the
12 uncertainties of a case without those assumptions are expected to be larger than those found in this work.

13 6.5. Climatic conditions to a co-cooling test

14 With the case studies and assumptions considered, a ΔT_{mean} greater than 7°C, allows to estimate HTC
15 within a 10% range of the reference value. If deviations of 20% from the reference value can be accepted, it is
16 possible to carry out co-cooling tests down to a ΔT_{mean} of 5°C. It is difficult to compare these values to co-
17 heating requirements as strong assumptions have been made in this co-cooling exploration work. Some deeper
18 investigation needs to be carried out. Similar to co-heating, co-cooling tests require specific climatic conditions.
19 These are mainly found in hot climates and during the summer for Mediterranean climate. Co-cooling might
20 complements co-heating tests, given that co-heating cannot be carried out throughout the year and in all
21 climates, particularly where co-heating seems to be difficult to perform Australia as mentioned in [29],
22 Mediterranean countries or South states in the USA.

23 Furthermore, as introduced in paragraph 5.6, at low irradiance, a lower temperature difference seems to be
24 necessary to estimate the HTC at equivalent accuracy. It might be interesting to explore if a limit linking the 2
25 parameters might be define such as an affine function. This could extend the perimeter of validity of the co-
26 cooling method to more climates.

27 6.6. Operational limits to a co-cooling deployment

28 Regarding the operational setup, it seems more difficult to setup a co-cooling than co-heating. First, it is
29 more difficult to find a cooling system that is both portable and whose energy consumption can be measured

1 accurately, unlike the Joule-effect heating system used in co-heating tests. One possible method is to inject a
2 cold fluid into a building's heating/cooling network and determine the refrigerant power delivered inside the
3 house by measuring the inlet and outlet temperatures of the refrigerant and its flow rate as explored in [18] [17].
4 A second method consists in using a cooling system that is already in the building. This method has the
5 advantages that cooling systems are often already present in hot climates where co-cooling tests are applicable,
6 but the difficulty remains in precisely measuring the cooling energy transmitted to the building by the
7 refrigerant.

8 To set up a co-cooling test, the equivalent exterior temperature must be measured. This means adding
9 specific sensors such as SENS sensors developed in the scope of the SEREINE method [26]. This represents an
10 additional cost and complexity compared to co-heating tests. The equivalent temperature is determined from
11 five SENS collectors in the same orientation on each facade and on the south face of the roof. By measuring the
12 temperature of the white and black faces of each facade orientation and the albedo of the facades, it is possible
13 to determine the equivalent outdoor temperature. According to [26], when sensors were developed, the
14 uncertainty of this temperature was around 2.5°C. However, as part of the method chain, the uncertainty of these
15 sensors is around 0.5°C [25].

16 It is hardly possible to achieve set temperatures lower than 18 or 17°C with air conditioners working with
17 refrigerants at 14 or 15°C. It is therefore complicated to achieve a sufficient temperature difference in summer
18 in most of North European climates. Co-cooling tests are therefore expected to be more easily applicable to
19 desert or Mediterranean climates during the summer.

20

1 7. Conclusion

2 This paper introduced the co-cooling method, a new method of in-situ measurement to determine the heat
3 transfer coefficient (HTC) of a building envelope by cooling it, and numerically explored its feasibility. To this
4 end, a numerical test bench approach was built to test an individual dwelling with three different levels of
5 insulation, under three different climates. Different linear regression models to analyse the data have been tested.
6 This new method makes it possible to measure the actual performance of buildings in hot climates and in
7 summer. To do so, similarly to a co-heating test, the building must be immobilised for several weeks, except it
8 is cooled down to a constant temperature by installing temperature and cooling power sensors. An equivalent
9 outside temperature is used instead of a classical outdoor air temperature in the linear regression methods. From
10 daily averaged data, a linear regression is performed to estimate the Heat Transfer Coefficient of the building
11 envelope.

12 According to this work, for a co-cooling test, only the simple linear regression method yields acceptable
13 estimates, when the equivalent indoor/outdoor temperature difference is used to predict the cooling power. The
14 other methods showed a very poor accuracy either because they did not appropriately account for radiative
15 transfers or because of the significant collinearity between the explanatory variables of the regression.

16 Co-cooling meets the growing need to determine the real energy performance of building envelopes in all
17 climates and all year round. To the best of our knowledge, it is the only method that can measure building
18 performance in summer or in hot climates. With an outside-inside temperature difference of minimum 7°C for
19 well-insulated buildings and a cooling temperature setpoint of around 18°C, due to the working temperatures of
20 air conditioning refrigerants, this method seems mainly suited to very hot climates. Nevertheless, it pushes the
21 frontier of envelope thermal characterisation in new climates. The validity perimeter of this co-cooling method
22 remains yet to be explored as the results suggest that a lower temperature difference could be sufficient for
23 climates with lower irradiance.

24 Noteworthy is that the co-cooling has proven to be functional in all three variants of the case study with
25 disparate insulation levels. To confirm the feasibility of co-cooling and its generalisation, more complex case
26 studies should be tested, such as cases with heat exchange to the ground floor or with non-cooled adjacent zones.
27 In addition to the climatic conditions required, some other challenges exist, such as to set up a mobile cooling
28 system and to determine its cooling power precisely.

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32 9. Disclosure statement

33 No potential conflict of interest was reported by the authors.

34 10. Data availability statement

35 The data that support the findings of this study are available from the corresponding author, AJ, upon
36 reasonable request. The three EnergyPlus models used in this work are available on Github at the following
37 address: [https://github.com/Kevin-Campagna/EnergyPlus-model-for-Co-cooling-simulation-based-
38 exploration-of-a-new-method-to-measure-the-HTC/tree/main](https://github.com/Kevin-Campagna/EnergyPlus-model-for-Co-cooling-simulation-based-exploration-of-a-new-method-to-measure-the-HTC/tree/main)

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