JOURNAL OF BUILDING PHYSICS

Pedagogical Note

Journal of Building Physics
2022, Vol. 46(2) 245–256

DOI: 10.1177/17442591221093057
journals.sagepub.com/home/jen
SAGE

Didactic device for teaching the importance of the time-dependent model for heat transfer calculations in constructive systems of buildings

Guillermo Ramírez-Zúñiga[1,2], Guillermo Barrios[1], Guadalupe Huelsz Lesbros[1] and Vanessa Sattele[3]

Abstract
There is a worldwide effort aimed at reducing energy consumption in buildings. Part of this effort includes bioclimatic design in the curricula for architects and engineers. The selection of constructive systems for the building envelope according to the climate is of significant importance for bioclimatic design. This has to be done by calculating the heat transfer through the constructive system using the time-dependent model. However, because the time-dependent model is easier to use it is also more commonly employed. To contribute to the teaching of the importance of using the time-dependent model, a didactic device and a practice were proposed. This paper presents the physical problem and the heat transfer models; the didactic device's design process, its components and operating method; as well as the methodology for the practice. The didactic device and

[1]Instituto de Energías Renovables, Universidad Nacional Autónoma de México; Privada Xochicalco s/n, Colonia Centro, Temixco, Morelos, Mexico
[2]Universidad Tecnológica Emiliano Zapata del Estado de Morelos, Avenida Universidad Tecnológica 1, Colonia Palo Escrito, Emiliano Zapata, Morelos, Mexico
[3]Facultad de Arquitectura, Universidad Nacional Autónoma de México; Avenida Universidad 3000, Colonia UNAM CU, Coyoacán, Ciudad de México, Mexico

Corresponding author:
Guillermo Barrios del Valle, Instituto de Energías Renovables, Universidad Nacional Autónoma de México; Privada Xochicalco s/n, Colonia Centro, Temixco, Morelos 62580, México.
Email: gbv@ier.unam.mx

Correction (September 2022): Article page numbers have been corrected online to reflect correct volume/issue pagination. See https://journals.sagepub.com/doi/full/10.1177/17442591221144160 for details.

practice were created by the interaction of experts and students who gave their opinions and suggestions during different workshops.

Keywords
Didactic device, practice, heat transfer, building envelope, time-independent model, time-dependent model, instrumentation

Introduction

It is estimated that worldwide energy consumption in buildings represents about 30% of the world's total energy consumption (International Energy Agency (IEA) (2020). There is an effort aimed at reducing energy consumption in buildings. Part of this effort is the introduction of energy efficiency measures that contribute to sustainable buildings, such as bioclimatic design, into the curriculum of architects and engineers. An important part of bioclimatic architecture design is focussed on the building envelope which is made up of all constructive systems that form the building's walls, roofs, floors, windows, doors, etc. The building envelope also separates the interior from the exterior. A construction system (CS) is the set of ordered materials used to form those walls, roofs, etc. The envelope is important for the building's thermal and energy performance because the energy exchange between the exterior and the interior occurs through it.

The calculation of the heat transfer through the CS is required to be able to select the CS with the adequate thermal performance. For this purpose, there are two models according to time dependency: the time-independent and the time-dependent models. The time-independent model is also known as the steady state model and the time-dependent model is known as the dynamic model.

The time-independent model is widely used to calculate the heat transfer through the building envelope because of its ease of calculation. To calculate the heat transfer through the building's envelope, this model only requires the knowledge of the thermal resistance of the envelope. However, the time-independent model is appropriate when the amplitude of the outdoor air temperature is smaller than the difference between the indoor and outdoor mean temperature, and also when solar radiation is low (Kuehn et al., 2001). These conditions occur during severe winters in latitudes greater than those of the tropics. On the opposite, when the amplitude of the outdoor air temperature is larger than the difference between the indoor and outdoor mean temperature and the solar radiation is high, the time-dependent model should be used (Al-Sanea, 2000; Huelsz et al., 2014; Thomas et al., 2020). As in these conditions the buildings have larger energy consumption for air-conditioning the indoor than in developed countries, this is the most employed model in these countries. McLoed and Jopfe described in detail an experiential learning using the icebox challenge. In this challenge the students use the time-independent model for the analytical calculation of the insulation needed to keep a block of ice inside a box in the open exposed to the sun radiation and wind during 24 hours (McLeod and Hopfe, 2021). However, these conditions do not occur during the summer, and cannot be found during any season in the intertropical zone where Mexico is located. Therefore, the time-independent model is not appropriate for evaluating and selecting CSs for the intertropical zone.

Because of its ease of calculation, the time-independent heat transfer model is taught in many of the courses imparted to architects and engineers when calculating the heat transfer through the building envelope. Fortunately in the case of Mexico, there is a growing number of teachers who instruct their students on the use of the time-dependent model and its importance for calculations in the case of Mexican climates. However, generally speaking, architecture students are not habituated with the use of equations and find it difficult to fully understand them.

A didactic device is proposed to contribute to the teaching of the importance of using the time-dependent model in calculating the heat transfer through a wall or roof of the building envelope when there are large variations in the outdoor air temperature (as compared to the difference between the average of the outdoor air temperature and that of the indoor air temperature). A detailed review in the literature, patent databases and commercial devices designed for the teaching of heat transfer through solids was carried out. No didactic device was found to be suitable for the teaching of this specific concept. Thus, a didactic device (DD) was designed and built to fulfil this need. A practice that employs this DD was also designed. This paper describes the development of the DD and its corresponding practice.

Background

In this section the physical problem addressed and the heat transfer models used to calculate the heat transfer through a building envelope CS are presented.

Physical problem

The physical problem is the heat transfer through a CS of the building envelope as sketched on the left side of Figure 1.

The heat flux on the outside surface of a CS q_o (W/m^2) can be calculated as

$$q_o = h_o(T_{sa} - T_{so}), \tag{1}$$

where h_o $(W/m^2 °C)$ is the outside film heat transfer coefficient, T_{sa} $(°C)$ is the sol-air temperature and T_{so} $(°C)$ is the outside surface temperature of the CS. The sol-air temperature is an equivalent temperature that substitutes the outdoor air temperature and takes into account outdoor air temperature, solar radiation absorbed by the CS and radiative heat exchanged between the CS and the surfaces in front of it (American Society of Heating, Refrigerating and Air- Conditioning Engineers (American Society of Heating Refrigerating and AirConditioning Engineers [ASHRAE], 2013

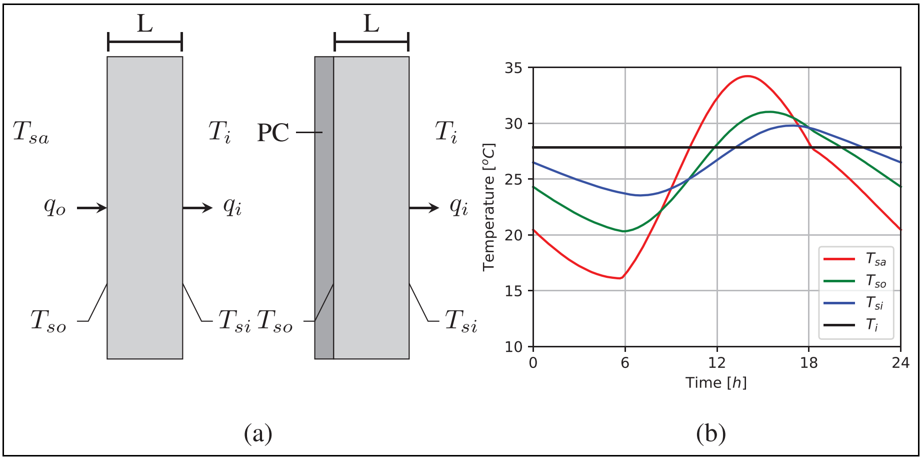

Figure 1. (a) Schemes for a real constructive system (left) and a sample of the constructive system in the didactic device (right). The sol-air temperature T_{sa}, outside surface temperature T_{so}, inside surface temperature T_{si}, indoor air temperature T_i, the heat flux on the inside surface of a constructive system q_i and the thickness of the constructive system L are represented in this scheme. The Peltier cell (PC) in the didactic device is also shown. The dimensions of the constructive system are given in different scales for each scheme. (b) The behaviour of the temperatures for a constructive system of a south wall on a typical day in April in Cuernavaca, Morelos, Mexico for an air conditioned room from numerical simulations with Ener-Habitat (Instituto de Energas Renovables Universidad Nacional Autnoma de Mxico (IER-UNAM, 2018).

The heat flux on the inside surface of a CS q_i (W/m^2) can be expressed as,

$$q_i = h_i(T_{si} - T_i), \tag{2}$$

where h_i $(W/m^2{}^\circ C)$ is the inside film heat transfer coefficient, T_{si} $(^\circ C)$ and T_i $(^\circ C)$ are the inside surface and indoor air temperatures, respectively.

As an example of the variations of T_{sa}, T_{so}, T_{si} and T_i during 1 day for an air-conditioned room, Figure 1(b) shows these variations for a CS of a south wall on a typical day in April in Cuernavaca, Morelos, Mexico. These temperatures are obtained from numerical simulations with Ener-Habitat (Instituto de Energías Renovables, Universidad Nacional Autóma de México (IER-UNAM), 2018)

In the DD the physical problem is reproduced using a constructive system sample (CSS). On the left side of Figure 1(a) a scheme of the real CS is shown, and on the right side a scheme of the CSS is presented. For the DD the CSS is much smaller than the real CS. Its small size also accounts for its low thermal mass which makes it possible to carry out the experiment in about 20 minutes. The heat transfer in the CSS should occur mainly in the transverse direction as it does in the real CS. So, the relation between the thickness and the surface area of the CSS was determined during the design process by trial and error.

In the CS the variation of T_{so} is produced by the variation of T_{sa}. In the DD the variation of T_{so} is produced by an array of Peltier cells (PC) in direct contact with the outside surface of the CSS. The PC simulates a sinusoidal variation of T_{so} over time by specifying the maximum value and the period of the electric power applied. The inside surface of the CSS faces up and is in contact with the air from the room where the experiment is performed. Due to the short duration of the experiment, T_i can be considered to be constant even if the room is not air conditioned. Thermocouples are placed on both surfaces of the CSS to measure T_{so} and T_{si}, and a heat flux sensor is placed on the inside surface of the CSS to measure q_i.

Heat transfer models

The heat transfer through the CS of the building envelope can be calculated with two models according to the time dependency of the variables: the time-independent and the time-dependent models. In general, architecture and engineering students are more familiarized with the time-independent model given its ease of use. This model is a good approximation for weather conditions with small oscillations of T_{sa}, which only occur during severe winters. For most weather conditions the oscillations are large as it is shown in Figure 1(b) for Cuernavaca, Morelos, Mexico.

In the time-independent model $q_o = q_i$ and both are calculated when T_{sa} and T_i are known as

$$q_o = q_i = \frac{T_{sa} - T_i}{R_t}, \tag{3}$$

where R_t $(m^2\,°C/W)$ is the total thermal resistance. For a mono-layered CS R_t is given by

$$R_t = \frac{1}{h_o} + \frac{L}{k} + \frac{1}{h_i}, \tag{4}$$

where L (m) is the thickness of the CS and k $(W/m, °C)$ is the thermal conductivity of the CS material. When the known variables are T_{so} and T_{si}, $q_o = q_i$ are calculated as

$$q_o = q_i = \frac{T_{so} - T_{si}}{R}, \tag{5}$$

where $R = \frac{L}{k}$ is the thermal resistance of the CS.

In the time-dependent model, q_o and q_i are a function of time. In general they are not equal for any given time and they must be calculated using numerical methods. This difficulty encourages architects and engineers to continue using the time-independent model. The DD and its practice are designed with the purpose of helping architecture and engineering students understand the importance of choosing the time-dependent model. This model should be used when calculating the heat transfer through a wall or roof of a building envelope during weather conditions that present large variations in the outdoor air temperature as compared to the difference between the average of the outdoor air temperature and that of the indoor air temperature.

Didactic device

This section presents the design process, components and operating method of the DD.

Design process

Once the need to design a specific DD was identified a multidisciplinary group composed of experts on heat transfer, instrumentation, control, architecture and industrial design was formed. The goal was to design a DD capable of performing two experiments, one that maintained a constant temperature difference across a given CSS, and another with a periodic temperature difference across the CSS. For both experiments the DD measures the surface temperature on both sides of the CSS as well as the heat flux across it on the surface that represents the inside surface of the real CS, as shown in Figure 1(a).

Different versions of the DD were developed. The first one had a manual control that was built as proof of concept. After that, different control strategies were tested and the size of the CSS was increased to reduce the heat transfer of the CSS onto its borders. In later versions, changes were implemented according to the observations made by students who carried out pilot tests. Three workshops were done. The first was carried out with engineering students and the other two with architecture students. Changes suggested during the workshop for the DD were mainly focussed on the way the user interacts with the device as well as the possibility to duplicate its display via an HDMI output. Changes to the practice guide were also made.

The final prototype of the DD was designed taking into account aesthetic, ergonomic, functional and production factors that are appropriate for the context and users of the device. The main aspects that influenced the design were the need for robustness, ease of use and low-cost production methods. The design also allows for easy handling, assembling and maintenance of its internal components with the inclusion of an internal frame mounting system where all electronic elements can be rearranged. The DD also incorporates funnels designed to cool the thermal system and internal electronic components.

The industrial design process relied on a multidisciplinary approach where scientists and engineers worked along with designers to produce the final prototype of the DD. An iterative process was undertaken with the users. It consisted on defining initial function requirements, brainstorming sessions, sketching, creating quick mock-ups and evaluating them. This process resulted in the completion of the first functional prototype. Low-cost production methods such as laser cutting and 3D printing were preferred. This made it possible for certain elements to be modified during the design process. In the case of the user interface, quick mock-ups were tested by the user. The final prototype incorporated easy to understand visual icons as well as an intuitive workflow which allows students to manipulate the device without undergoing a specific training process. It is worth mentioning that a patent for the device has been requested (Huelsz et al., 2014).

Components

The DD is composed of four systems:

1. Graphical user interface (GUI) system: is the interface between the user and other systems of the DD. This system employs a Raspberry Pi 3 and a 7-inch touch screen. It was developed using the Tkinter GUI toolkit for Python (Roseman, 2021).
2. Control and data acquisition system: controls the temperature of the Peltier cells of the thermal system and acquires data from its sensors. It is composed of the Raspberry Pi 3, an Arduino Mega with accessories, and sensors. The Raspberry Pi 3 transmits instructions to the Arduino Mega and displays and saves data in a USB flash drive. The Raspberry Pi HDMI port can be used to connect an external screen. The Arduino Mega controls the Peltier cells and uses a 4-Channel T-Type Thermocouple MAX31856 SPI Digital Arduino Shield and an amplifier gain circuit designed to measure heat flux. The Raspberry Pi 3 and the Arduino Mega communicate via I2C. The sensors include a PHFS-01e Fluxteq heat flux sensor with a thermocouple, as well as four T-type thermocouples.
3. Power system: has two energy sources, one provides 5 V and 12 V for the control and data acquisition system, and the second provides 24 V for the thermal system. The total power of the DD is 500 W.
4. Thermal system: is composed of the CSS, the insulation around the borders of the CSS, the four Peltier cells (120 W Peltier cells), an aluminium plaque, a heatsink with a fan and a second fan. The aluminium plaque, the heatsink and the fans dissipate the heat generated by the Peltier cells. The insulation around the CSS allows the heat flux to occur mainly in one dimension as in the real CS.

The exploded view of the thermal system is shown in Figure 2(a), including the location of the sensors. A photograph of the DD is presented in Figure 2(b). It shows the device's housing, the CSS surface exposed to the environment, the insulation around the CSS borders, the heat flux sensor on the CSS surface, and the touch screen. The housing was printed with polylactic acid and assembled with conventional screws. The housing has vents on its four walls to propitiate airflow into the DD in order to dissipate the heat generated by the Peltier cells and the other electronic components.

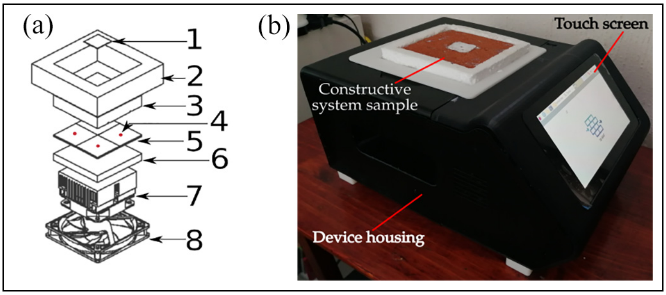

Figure 2. (a) Exploded view of the thermal system: 1) Heat flux and temperature sensor, 2) thermal insulation, 3) CSS, 4) Temperature sensors, 5) PC, 6) aluminium plaque, 7) heatsink with fan and 8) second fan. (b) Photo of the DD assembled.

Operating method

The operating method is sketched in Figure 3. The DD is powered on with a switch on the back of its housing. Once the DD is powered on the welcome screen is displayed. After a few seconds the mode selection screen allows the user to choose between the time-independent mode and the time-dependent mode. When selecting the time-independent mode the output power selection screen is displayed, allowing to set the power level between 0% and 99%. When selecting the time-dependent mode, the output power and period selection screen is displayed allowing to set the power level between 0% and 99% and the period in the range of 1–99 minutes. Once the corresponding selection is made, the start button activates the data display screen. This screen displays a graphic with the heat flux and temperature data plotted as functions of time, shown in real-time. Simultaneously, data are being saved in the USB flash drive. All measurements are stopped by tapping the home button, after which, the mode selection screen is displayed. The DD is powered off pushing the switch on its back.

Practice

The practice and the DD were designed with the aim of helping architecture and engineering students understand the importance of using the time-dependent model for the calculation of heat transfer through a CS of a building envelope. A detailed guide is provided for the students which includes the theory and the description of the device. The methodology for the teaching practice is presented here.

The practice is divided into two parts. In the first part (P1) the student uses the time-independent mode (selected from the operation mode screen) to set a constant value for the output power which allows T_{so} to be constant but different to T_{si}. The student observes the values of T_{so}, T_{si} and q_o as a function of time, which is displayed on the DD screen. When the student notes that the transient in T_{so} and T_{si}

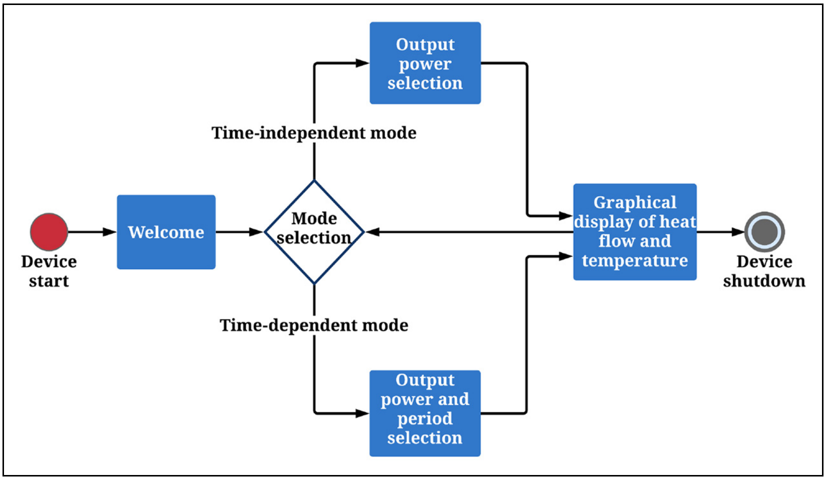

Figure 3. Sketch of the DD operating method.

has died out and the steady state has been reached for at least 2 minutes, he or she can finish the first part of the practice and return to the operation mode screen. In the second part of the practice (P2), the student uses the time-dependent mode to set the maximum output power level and the period that produces an oscillatory T_{so}. When the student confirms, as displayed on the screen, that the transient in T_{so} and T_{si} has died out and the oscillatory state has been reached for at least two periods, as shown in Figure 4, he or she can then return to the welcome screen and power off the DD to end the practice.

The student can download the results of each part of the practice using a USB stick and can plot the results for P1 and P2. Figure 5(a) and (b) show examples of these plots for the first and the second part, respectively. Following the teaching practice guide the student can then calculate the thermal resistance R of the CSS using equation (5). The student substitutes q_o, T_{so} and T_{si} by the corresponding average value of the measurements from the last 2 minutes of P1. that is, The student is using the time-independent model which is valid for the steady state achieved in the last 2 minutes. Afterwards, he or she is guided to calculate the heat transfer on the inside surface of the CSS as a function of time using R and the values of T_{so} and T_{si} for each step-time measured in P2. That is, The student is using the time-independent model to calculate q_i in a condition where the variables do change with time. The calculated heat flux value is named q_{i_c}. After this, the student is encouraged to plot q_{i_c} together with the measured q_i in the second part of the practice and to comment on found qualitative differences. Figure 5(c) shows an example of this plot.

The student is then guided to calculate the thermal energy transferred in the periodic state from the outside to the inside of the CSS E^+ using the measured q_i, that

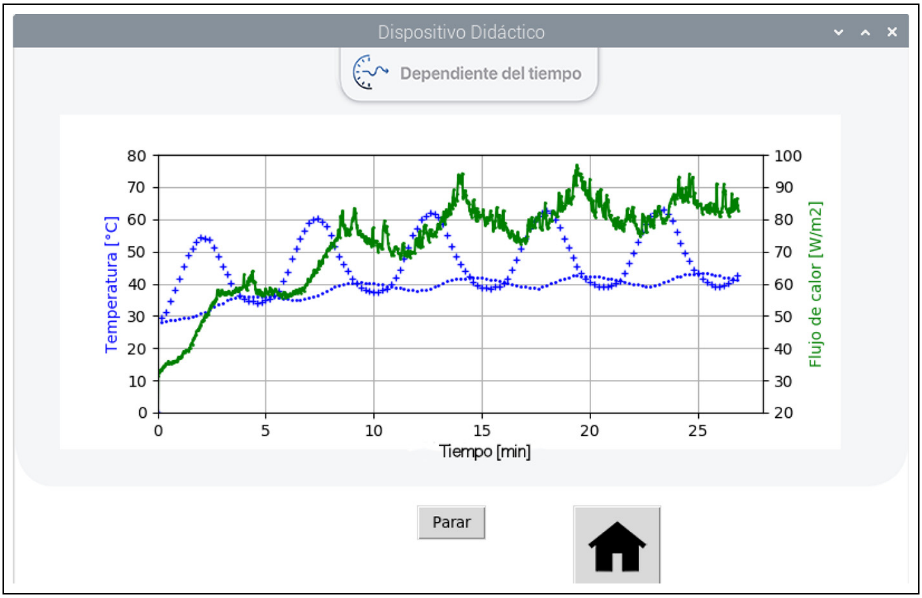

Figure 4. Example of the screen showing the values of T_{so} (blue points), T_{si} (blue cross) and q_o (green line) as a function of time in the second part of the practice. Legends are in Spanish and the coloured dots correspond to the legend of each axis.

is, when $q_i>0$, as well as the thermal energy transferred in the periodic state from the inside to the outside of the CSS E^-, that is, when $q_i<0$. Afterwards, he or she is directed to calculate the aforementioned quantities while using the calculated q_{i_c}, named E_c^+ and E_c^-, respectively. The student can then make the comparison between E^+ and E_c^+ as well as that between E^- and E_c^-. Finally, the student is encouraged to draw his or her own conclusions.

Typical results obtained in this practice show that the calculated values using the thermal resistance, that is, implicitly using the time-independent model of the heat transferred through the CSS are at least 30% higher than the measured heat transferred through the CSS.

Closing remarks

The didactic device and the practice presented in this paper are the result of the interaction between experts in different fields. These include experts on heat transfer who conceived the didactic device's principles of operation; as well as experts on instrumentation, control and industrial design. This team designed and constructed the device. The engineering and architecture students, and the teachers

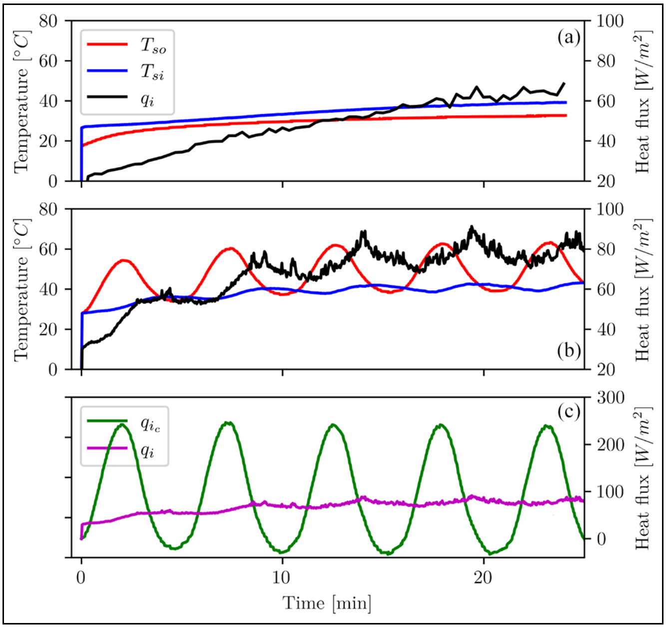

Figure 5. Practice graphs where students plot (a) T_{so} (red), T_{si} (blue) and q_i (black) in P1, (b) same measurements for P2 and (c) q_{i_c} and q_i, all plots are shown as a function of time.

who participated in the workshops also made invaluable comments and contributions to the project.

Throughout the workshops, most of the engineering and architecture students expressed that the use of the didactic device and the practice did in fact help them to understand the importance of using the time-dependent model when calculating the heat transfer through the constructive system.

The COVID-19 pandemic has created unique working challenges that we have overcome by making use of existing technologies while teaching from home. Thus, the modification of the present didactic device using the technology known as Internet of Things (IoT) will make it possible for it to be used remotely. Thanks to this students will be able to perform their practices from the safety of their homes. This opens the possibility for other institutions and students to receive the benefits of using the didactic device without having physically own it.

Acknowledgements

Authors would like to thank Pablo Elías who was the first colleague to point out the necessity for a device that helped in the teaching of this subject. Authors acknowledge Guillermo Hernández and Héctor D. Cortés for the instrumentation and control of the first versions of the didactic device, as well as Adriana Lira for analyzing the opinions shared by the architecture students. Authors also acknowledge Francisco López-Alquicira, Efraín Puerto, Arturo Irineo, Juan Antonio Abarca, José Luis Figueroa, Eduardo Ramos-Mendoza, Sergio Ríos, Leonardo Gómez-Flores, Estefanía López Barrera and Lucero Betancourt for their participation in the development of the didactic device.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the PE101617-PAPIME-DGAPA-UNAM project.

ORCID iDs

Guillermo Barrios https://orcid.org/0000-0003-2738-297X
Guadalupe Huelsz Lesbros https://orcid.org/0000-0002-0624-0203

References

Al-Sanea SA (2000) Evaluation of heat transfer characteristics of building wall elements. *Journal of King Saud University – Engineering Sciences* 12(2): 285–312. https://doi.org/10.1016/S1018-3639(18)30720-7

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (2013) *Handbook Fundamentals*, SI edn. ASHRAE.

Huelsz G, Barrios G and Rojas J (2014) Differences on results from steady-state and time-dependent wall/roof heat transfer models in Mexican climates. *Energy Procedia* 57: 1825–1833. https://www.sciencedirect.com/science/article/pii/S1876610214014131

Instituto de Energías Renovables, Universidad Nacional Autónoma de México (IER-UNAM) (2018) Ener-Habitat. Available at: http://www.enerhabitat.unam.mx (accessed 1 October 2020).

International Energy Agency (IEA) (2020) World energy balances 2019. Available at: https://iea.blob.core.windows.net/assets/8bd626f1-a403-4b14-964f-f8d0f61e0677/World_Energy_Balances_2019_Overview.pdf (accessed 1 January 2020).

Kuehn T, Ramsey J and Threkdeld J (2001) *Thermal Environmental Engineering*. Upper Saddle River, NJ: Prentice Hall.

McLeod RS and Hopfe CJ (2021) Experiential learning in building physics: The icebox challenge. *Journal of Building Physics* 45(3): 391–401. https://doi.org/10.1177/17442591211017948

Roseman M (2021) Tkdocs. Available at: https://tkdocs.com/index.html (accessed 1 September 2021).

Thomas LP, Marino BM and Muñoz N (2020) Steady-state and time-dependent heat fluxes through building envelope walls: A quantitative analysis to determine their relative significance all year round. *Journal of Building Engineering* 29: 101122. https://doi.org/10.1016/j.jobe.2019.101122