Simulating the dynamic behavior of heat exchange

Mkhinini Maher 1st Affiliation
ESPRIT School of Engineering
ESPRIT
Ariana, Tunisia
maher.mkhinni@esprit.tn

Ameni Dridi 2nd Affiliation
ESPRIT School of Engineering
ESPRIT
Ariana, Tunisia
Ameni.dridi@esprit.tn

***Abstract*— Thermally Activated Building Systems (TABS) are developed using a technology that reduces building energy consumption[1]. This heating and cooling technology integrated into the building structure allows heat to be exchanged by radiation and heat to be stored in the thermal mass of the building. The large thermal mass of TABS and its interaction with the building structure make energy assessment and design procedures difficult.**

In this case, the development of the TABS simulation model is essential to study their design and control.

The solution is therefore to develop an exchanger substitution model from the transfer functions, which allows us to quickly simulate the dynamic behaviour of the TABS heat exchanger.

Keywords*— *Mathematical modeling, Substitution model, Heat exchanger, Transfer function model, Greenfloor,Energy saving.

I. Introduction

Today , the heat exchange represents an essential element of heating, air-conditioning systems, as well as refrigerating systems. It ensures the heat transfer between two fluids without getting them mixed up. This transfer takes a fundamental place through a wall of high-conducting capacity. There are different kinds of heat exchangers used in different fields. This paper aim to provide heat exchangers, from the way it functions to its efficiency, going through its different types.

In this work, two major problems will be discussed, the first one deals with complications caused by corrosion (material problem) while the second one is the problem of energy cost and the impact on the environment. That's why, we will conceive of and develop a model to substitute the heat exchanger following the Greenfloor system (based on transfer functions) which would allow to simulate the dynamic behaviour of the heat exchanger faster than old simulators based on finite elements method The first part of this paper is reserved to the description of the heat exchanger , the second one explains the finite elements model, the model of heat exchanger and the last part will be reserved to the conclusion.

II. Description of the Heat Exchanger

The model of heat exchanger -subject of our study- is a concrete slab containing air conduits (ducts) Cold air circulates in these ducts which will cool down the slab[1], and will then get to the building as shown in figure 1.

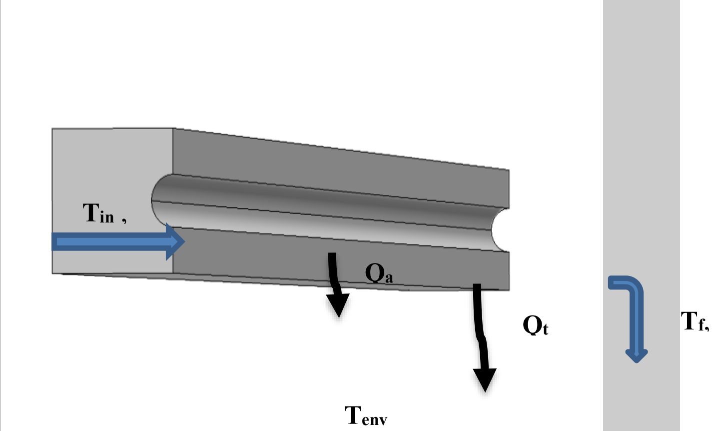

Fig 1. Exchanger

This exchanger follows three parameters (entries) which are:

- (T_{in}): the air temperature at the entry of the duct
- ($\dot{m}$) air flow in the duct
- (T_{env}). the temperature of the room beneath the slab

The system's behaviour is analysed through 4 outputs, namely:

- The flux of the heat absorbed by the slab (Q_a),
- The flux of the heat transmitted by the slab to the room (Q_t),
- The flux of the heat transmitted to the room by ventilation at the outlet of the exchanger or blown flow (Q_s)
- Air temperature at the exit of the duct (T_f).

III. Finite Element Model (COMSOL)

A. The model simulated on comsol :

This study is divided on two folds description and calculations[2]:

Manuscript 334 submitted to 2023 9th International Conference on Control, Decision and Information Technologies (CoDIT). Received February 28, 2023.

The piece in question recreates the characteristics of Greenfloor in an office in a new building, namely:

- The concrete is 22-cm thick (No other materials).
- The duct's diameter is 8 cm. Ducts are centered in the thickness of the slab.
- The duct is 5 meters long.
- Suppose there are 3 frames in this office, and 3 ducts per frame, with a space of 0.45 m separating 2 ducts.
- The fluid is air.
- The air blowing rate in the office measures 300 $m^3.h^{-1}$ (varies between 150 and 450 $m^3.h^{-1}$ in practice, depending on the envelope's quality). Consequently, air speed in a duct reaches1.84 $m.s^{-1}$
- Air temperature at the entry of the gain varies between 279.15 and 297.15 kelvin.
- The temperature of the room beneath the slab varies between 289.15 and 307.15 kelvin.

The behaviour and flow of the fluid are not simulated in 3D:

- A 1D model for the fluid ;
- A 3D model for the solid where the volume of the pipe is extruded;

The piece in question has two axis of symmetry, hence the simplified geometry of the following figure.

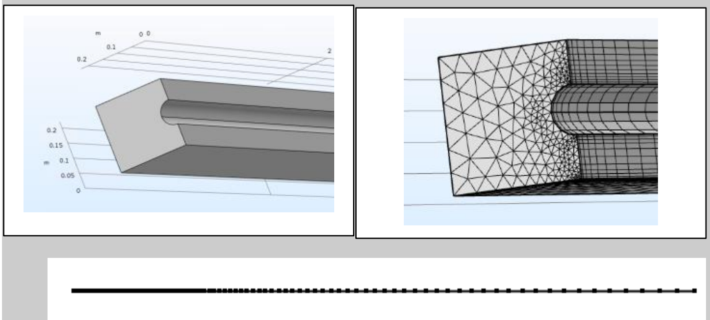

Fig2: Geometry and mesh of the 3D exchanger by COMSOL

The grid has 14.3 k-elements in 3D, 100 in 1D.
The tool « general extrusion » allows to[6] :

- Use the calculated fluid temperature in the 1D model to set a heat flow in the 3D model As shown in figure 3

Note : The convective coefficient is the same in both models.

- Measure the average temperature in three spots (there are: high, middle and below) in the 3D model and use it as an entry in the 1D model.

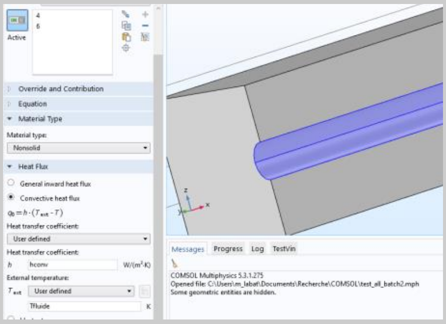

Fig3: Screenshot showing the merging between the 1D model (fluid) and the 3D model (concrete)

B. Calculations

The coefficient of convective transmission is determined by correlation on the number of Nusselt Nu, defined by the following equation:

$$Nu = \frac{h_c D}{\lambda_f} \qquad (1)$$

Bearing in mind that the Reynolds Re number is defines by equation (2) as follows:

$$Re = \frac{U\,D}{\nu_f} \qquad (2)$$

For turbulent flow in a circular pipe, as described by the following expression :

$$Nu = \frac{\frac{f}{8}(Re-10^{-3})Pr}{\left(1+12.7\frac{f}{8}\right)^{1/2}\left(Pr^{2/3}-1\right)} \qquad (3)$$

Where Pr represents the number of Prandtl and f the coefficient of friction, such as:

$$f = (0.79\ln(Re) - 1.64)^{-2} \qquad (4)$$

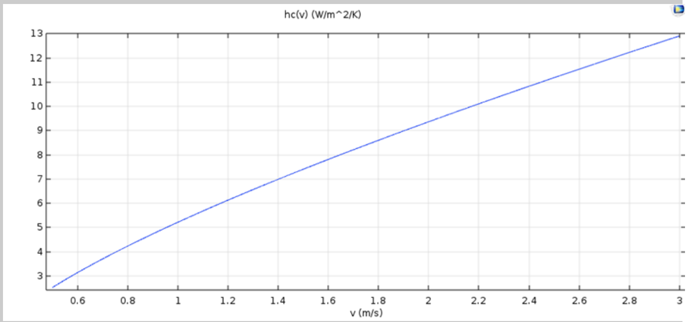

Fig4: Evolution of the convective coefficient depending on air speed

The figure 4 represents the evolution of the convective coefficient depending on the air speed. From the curve, we can deduce that the convective coefficient evolves in a logarithmic shape. The variation of the convective coefficient for an air speed that ranges between 0.6 m/s and 3 m/s is an increasing curve going from 2.5 w/m²/K to 13 w/m²/K.

Manuscript 334 submitted to 2023 9th International Conference on Control, Decision and Information Technologies (CoDIT). Received February 28, 2023.

C. Sequencing onCOMSOL :

Many works have been published to explain the behavior of signal's frequancy in terms of time, The goal of this research is to obtain a periodic output signal.:For this , three steps should be taken which explained on three points:

1. A first simulation has been done based on5000 h contantes values which are applied on three inputs ,and the time not be concidered. The goal is to obtain the firt conditions which should be used in the next steps.
2. A study on only 1 variable parameter (for example , T_{in}). will be takn .
3. The same step will be perfomed on the other parameters.

IV. Model of Heat Exchanger :

A. Model hypothesis:

- Uniform temperature in the slab and in the air inside the duct.
- Heat exchange by radiation is insignificant compared to exchange by convection/conduction.
- Constant coefficient of convective exchange
- Negligible boundary effects (1D model)

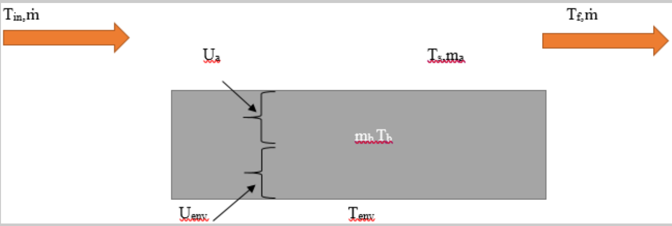

Fig 5 Second model of the heat exchanger

$$T_f = H_1(Q_a) + H_2(T_{env}) \quad (5)$$

$$Q_t = H_3(Q_a) - H_4(T_{env}) \quad (6)$$

$$Q_a = \dot{m} \times Cp_a \times (T_{in} - T_f) \quad (7)$$

Figure 6 represents the schema on Simulink of the model to be identified:

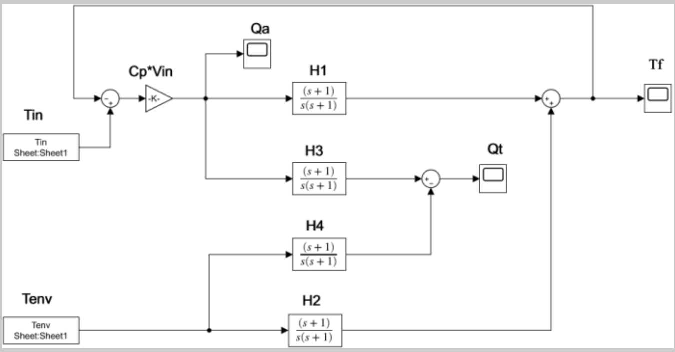

Fig6: Simulink schema of the heat exchanger

B. Methods

In order to identify the transfer functions which allow simulating the heat exchanger's dynamic behavior, we should run several simulations on the COMSOL software with different types of inputs[5].

Then we launched the transfer functions' identification using MATLAB software.

Two different methods were used in the process of identification. The first method first consists in simulating the dynamic behavior with a single variable input (the other inputs are constant) on COMSOL, then identifying each input/ output combination's transfer function.

The second method consists in running a single simulation in which all the inputs vary simultaneously, then identifying all the transfer functions that link the inputs to the outputFigures and Tables

After identifying the transfer functions, the results are filtered by eliminating all transfer functions with positive or complex poles or zeros.

Subsequently, we calculate the error between the identified transfer functions reply and the signal generated by COMSOL to see whether r not the identified transfer functions simulate the dynamic behavior of the heat exchanger

In order to recreate the exchanger's interchange model we use the transfer functions retained for each input-output combination, thus launching a simulation of the exchanger's dynamic behavior, on COMSOL, when all the inputs vary simultaneously.One can conclude by comparing the generated signal to the substitution model response to determine whether or not the identified model can simulate the dynamic behaviour of the exchanger[7].

V. The Entries of This Method :

We used different input signals to identify transfer functions.

A. Pseudo -random binary signal :

The pseudo-random binary signal (SPAB) is a signal that contains only two values: Either a maximum value and a minimum value of the signal.

The variation of the signal between the maximum value and the minimum value is random. An example of this signal is shown by Figure 7.

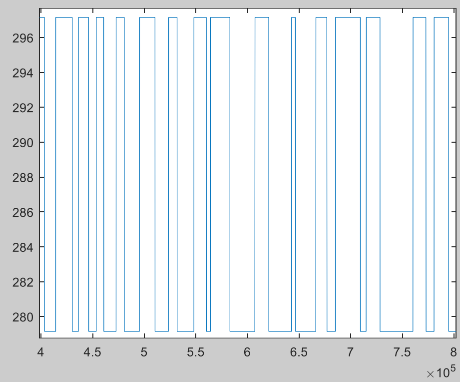

Fig7: SPAB input for environnment temperature

Manuscript 334 submitted to 2023 9th International Conference on Control, Decision and Information Technologies (CoDIT). Received February 28, 2023.

The SPAB signal can be a cause of multiple frequencies in a single signal sequence. Therefore, a test to well-determine frequency range should be used. In our case, the operating frequency array ranges from 10^{-7} Hz and 10^{-2}Hz. Figure 7 shows the spectrum of the signal used to identify the transfer functions of the exchanger.

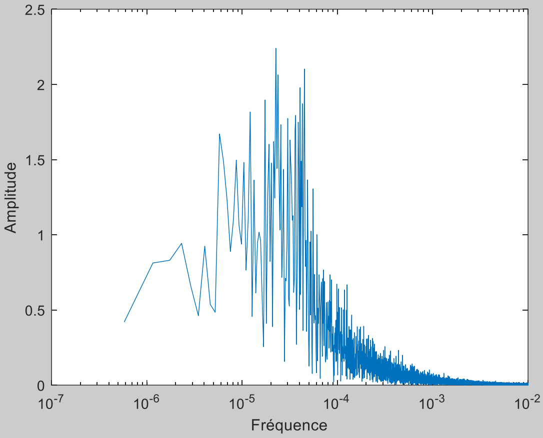

Fig8: SPAB signal spectrum used for identification

B. Variable frequency cosine :

The variable frequency cosine (CosFB) has the same characteristics as the cosine signal, except that it has not only an amplitude that varies over time but also a variable frequency.

The signal used for simulations has a frequency that varies in the operating frequency range of the heat exchanger [10-7, 10-2] Hz.

We added a 90 ° phase shift for the signal to start at the time t = 0 at its average value. This signal is shown in Figure 8.

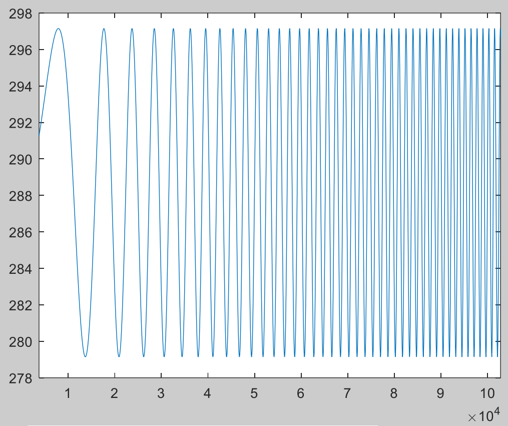

Fig9: Variable frequency cosine signal.

Figure 10 below represents the spectrum of the signal used for the heat exchanger transfer functions identification. The signal frequency range is between 10-7Hz and 10-2 Hz frequencies.

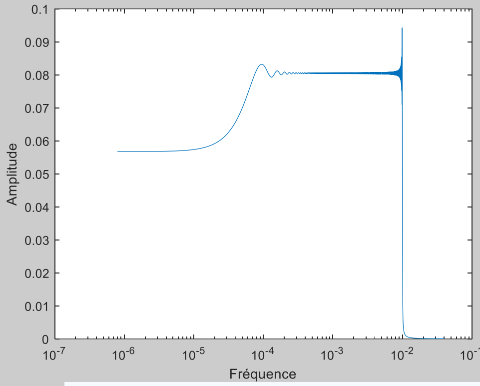

Fig10: CosFB signal spectrum used in identification

C. .Cosinus à fréquence variable sur multi expériences :

The cosine signal with variable frequency on multi experiments has the same characteristics as the variable frequency cosine signal. Instead of using the entire heat exchanger operating frequency range ([10^{-7},10^{-2}]), we opted for dividing this signal over four frequency intervals ([10^{-7},10^{-5}], [10^{-6},10^{-4}], [10^{-5},10^{-3}], [10^{-4},10^{-2}]). The part of the signal in the interval [10^{-5},10^{-3}] Hz is shown in figure 15.

This method saves us a lot of time for the simulation on COMSOL, the 60 hours (CosFB input) or 34 hours (SPAB input) usually required for simulating the system's dynamic behavior can be reduced to 30 minutes for each frequency interval.

Therefore, the simulation the exchanger's dynamic behavior can be performed within its operating frequency range in 2 hours, thus saving more than 30 hours of simulation. Moreover, the hard drive data capacity from tens of gigabytes to hundreds of megabytes can be reduced.

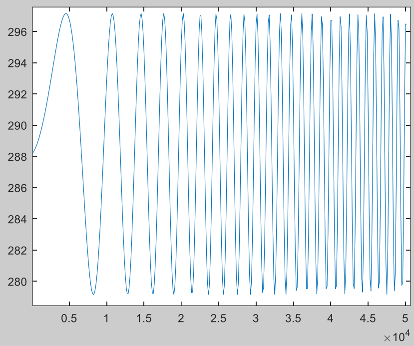

Fig11: variable frequency cosine signal on multi experiment (frequency interval [10^{-5},10^{-3}] Hz)

The signal spectrumshown in figure 10 is presented on the following figure.

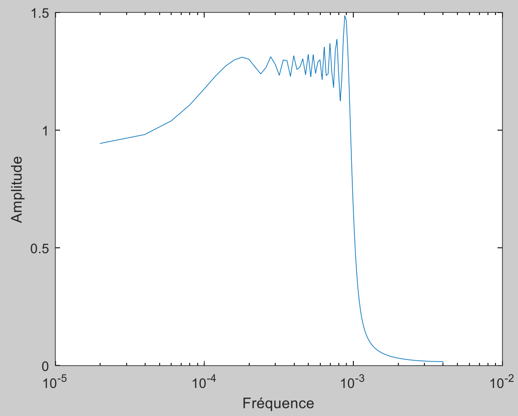

Fig12: spectrum of the cosine signal at variable frequency over multi intervals, used in the identification (frequency interval [10-5,10-3] Hz)

VI. Comparaison of the signal generated by COMSOL and the identified transfer function response:

In order to compare the data generated by COMSOL and the identified transfer functions' response we used the following equation to determine the error.

We then calculated the mean value and the interval containing 95% of the errors (extreme values are removed) from these data.

$$error = \frac{(transfer\ function\ response - data\ generated\ by\ COMSOL)}{data\ generated\ by\ COMSOL} \tag{8}$$

A. .Heat Exchanger Model Application

We launched two different system simulations: two scenario of simulation have been done

In the first simulation, we varied the inlet temperature (Tin) and kept the environment temperature (Tenv) constant. Subsequently, we identified the transfer functions of the blown temperature (Tf) and the transmitted flux (Qt) as a function of the absorbed flux (Qa)

In the first simulation we modified the inlet temperature (T_{in}) and maintained the environment temperature (T_{env}). Then, the transfer functions of the blown temperature (T_f) and that of the transmitted flow (Q_t) were identified as a function of the absorbed flux (Q_a).

In the second simulation, we varied the environment temperature and kept the inlet temperature constant. Subsequently, we identified the transfer functions of the blown temperature (Tf) and the transmitted flow (Qt) as a function of the environment temperature (Tenv).

In the second simulation we modified the environment temperature and kept the inlet temperature constant. Subsequently the blown temperature (T_f) and transmitted flow 's (Q_t) transfer functions were identified based on the temperature of the environment (T_{env}).

B. Earnings Calculation :

The static gain of the transfer function of the blown temperature as a function of Tenv (H2) and the transmitted flux as a function of Qa (H3) is equal to 1.

The static gain of the blown temperature's transfer function as a function of T_{env} (H_2) and the transmitted flow as a function of Q_a (H_3) is equal to 1.
In an established regime when both Q_a and T_{env} are constants the following equation should be considered :

$$T_f = K_1 \times Q_a + K_2 \times T_{env} \tag{9}$$

Where K_2 equal to 1 , the following expression should be taken:

$$K_1 = \frac{(T_f - T_{env})}{Q_a} \tag{10}$$

$$K_1 = \frac{(T_f - T_{env})}{Q_a}$$

$$K_1 = \frac{(292.08 - 298.15)}{-43.938}$$

hence $K_1 = 0.1381$

$$Q_t = K_3 \times Q_a + K_4 \times T_{env} \tag{11}$$

Where K_3 equal to 1 so:

$$K_4 = \frac{(Q_a - Q_t)}{T_{env}} \tag{12}$$

$$K_4 = \frac{(Q_a - Q_t)}{T_{env}}$$

$$K_4 = \frac{(-43.938 - (-21.974))}{298.15}$$

$$K_4 = -0.0737$$

TABLE I. TRANSFER FUNCTIONS GAIN

	Q_a	T_{env}
T_f	0.1381	1
Q_t	1	−0.0737

1) *Identification of the blown temperature's transfer function based on the absorbed flux (H_1):*

In order to identify the transfer functions of the blown temperature (Tf) as a function of Qa, we launched a simulation by varying Tin with the three types of while keeping Tenv constant. Subsequently we calculated the system response generated only by the Qa input .

In order to identify the blown temperature (T_f)'s transfer functions based on Q_a, we launched a simulation by varying T_{in} with the three types of input (SPAB, cosine at variable frequency and cosine at variable frequency on multi experiments) while keeping T_{env} constant. Then we calculated the response of the system uniquely generated by Q_a input.

$$T_f = H_1(Q_a) + H_2(T_{env}) \tag{13}$$

$$H_1(Q_a) = T_f - H_2(T_{env})$$

We have T_{env} = constant and H_2 gain = 1 so

$$H_1(Q_a) = T_f - T_{env} \tag{14}$$

After that, an algorithm to identify the transfer function of a pole shape and 0 zeros up to 5 poles and 5 zeros has been

Manuscript 334 submitted to 2023 9th International Conference on Control, Decision and Information Technologies (CoDIT). Received February 28, 2023.

developed. After the identification, the results have been filtered in order to keep the transfer functions with a maximum value of the error's absolute value lower than 20% (|error|<20%).

The next step is to select the transfer function with the minimum error value, poles and real negative zeros.

For the SPAB input and variable frequency cosine, we weren't able to find transfer functions with an error lower than 20%.

For the input variable frequency cosine on multiple experiments, we identified only two transfer functions with an error lower than 20% as shon on figure 12..

Test N°	1	2
Pole number	2	3
Zero number	2	2

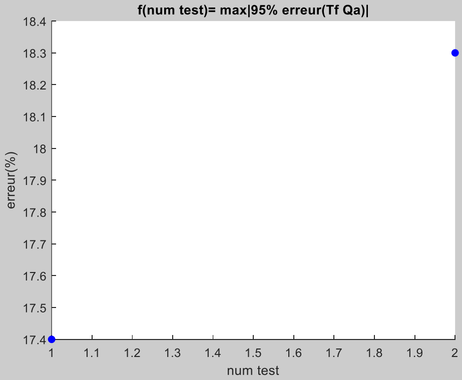

Fig 13 : range of blown temperature (T_f) identification result points based on absorbed flux (Q_a)

The two identified transfer functions have real negative poles and zeros. The transfer function with two poles and two zeros has a minimal error value 17.4 %, that's why we kept this transfer function to build the substitution model as follows.

$$H_1 = \frac{0.050511\times(s+0.002196)\times(s+2.976\times10^{-5})}{(s+0.00178)\times(s+1.342\times10^{-5})} \quad (15)$$

2) Identification of the blown temperature's transfer function based on the environment function (H_2) :

In order to identify blown temperature's transfer functions based on T_{env} :

First, we launched a simulation with T_{env} variable (variable frequency cosine input on multi experiment) and T_{in} constant. Second, we calculated the the response of the system generated uniquely with T_{env}. Since T_f varies based on T_{env} et Q_a varies based on T_f, we're not able to maintain maintenir Q_a constant for H_2 identification. That's why we used the previously identified transfer function(H_1) to calculate the response of the system generated by T_{env} follows.

$$T_f = H_1(Q_a) + H_2(T_{env}) \quad (16)$$
$$H_2(T_{env}) = T_f - H_1(Q_a)$$

Next we followed the same steps we used for H_1 identification to identify H_2 transfer function and filter the results.

Figure 13 represents the obtained results:

- The blue dots represent the transfer functions with real negative poles and zeros
- The red dots represent the transfer functions with complex poles or zeros.
- The green dots represent the transfer functions with real positive poles or zeros

TABLE II. POLE AND ZERO NUMBER

Test N°	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Pole number	1	1	2	2	2	3	3	3	3	4	4	4	4	4
Zero number	0	1	0	1	2	0	1	2	3	0	1	2	3	4

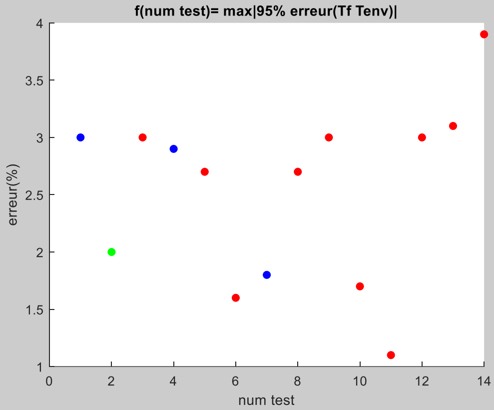

Fig14: Dot figure of the results of the identification of the blown temperature (T_f) according to the environment temperature (T_{env})

We have identified 14 transfer functions with an error margin less than 20%. Among them, there are 10 transfer functions with complex poles or zeros, one transfer function with positive real poles or zeros, and 3 transfer functions with negative real poles or zeros. The transfer function identified in the 7th test has a minimal error value. While this transfer function has a pole at high frequency, we have kept the transfer function of the fourth test to build the model of substitution. The transfer function identified in the fourth test has 2 poles and a zero as descried by the flowing expression.

$$H_2 = \frac{0.00066321\times(s+1.295\times10^{-5})}{(s+0.0006675)\times(s+1.287\times10^{-5})} \quad (17)$$

3) Identification of the transfer function of the transmitted flux as a function of the absorbed flux (H3) and the transmitted flux as a function of the environmental temperature (H4) :

In order to identify the transfer functions H_3 and H_4 we have taken the same steps followed to indentify H_1 and H_2 (identification tests and sifting through the results).

We have obtained results only of the simulations done with cosine entries at variable frequency.

Figure 13represents the results of the identification of H_3

TABLE III. TEST

N° of test	1	2	3	4	5	6	7	8	9	10	11	12	13
Number of poles	1	1	2	2	3	3	3	3	4	4	4	4	4
Nombers of zeros	0	1	0	2	0	1	2	3	0	1	2	3	4

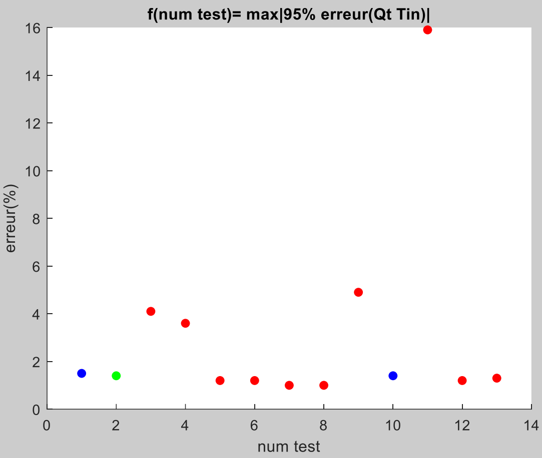

Fig15: Dot figure of the results of the identification of the transmitted flux (Q_t) according to the absorbed flux (Q_a),

We have identified 13 transfer functions with an error inferior to 20%. Among these transfer functions, there are 10 functions with complex poles or zeros, one transfer function with positive real poles or zeros [..], and two functions with negative real poles or zeros.

The transfer function identified in the tenth test has the value of minimal error, so we have kept it to build the substitution model. The transfer function identified in the tenth test has 4 poles and a zero.

$$H_3 = \frac{4.4279 \times 10^{-13} \times (s + 6.162 \times 10^{-6})}{(s + 0.000339) \times (s + 0.0001302) \times (s + 1.125 \times 10^{-5}) \times (s + 5.497 \times 10^{-6})} \tag{18}$$

As for the transfer function of the flow transmitted by the environment's temperature, we have only identified transfer functions with an error superior to 100%.

VII. Conclusion

All the parameters of the transfer functions (transmitted flow vs. inlet temperature, blown flow vs. inlet temperature, transmitted flow vs. ambient temperature, blown flow vs. ambient temperature) are variable as a function of velocity, which complicates the simulation of the dynamic behaviour of the heat exchanger with the first substitution model

References

[1] J. Romaní, A. de Gracia, et L. F. Cabeza, « Simulation and control of thermally activated building systems (TABS) », *Energy Build.*, vol. 127, p. 22-42, sept. 2016.

[2] A. Li, Y. Sun, et X. Xu, « Development of a simplified resistance and capacitance (RC)-network model for pipe-embedded concrete radiant floors », *Energy Build.*, vol. 150, p. 353-375, sept. 2017.

[3] Chung, W.J.; Park, S.H. Utilization of Thermally Activated Building System with Horizontal Ground Heat Exchanger Considering the Weather Conditions. *Energies* **2021**, *14*, 7927.

[4] Dharmasastha, K.; Samuel, D.L.; Nagendra, S.S.; Maiya, M. Experimental investigation of thermally activated glass fibre reinforced gypsum roof. *Energy Build.* **2020**, *228*, 110424

[5] Heidenthaler, D.; Leeb, M.; Schnabel, T.; Huber, H. Comparative analysis of thermally activated building systems in wooden and concrete structures regarding functionality and energy storage on a simulation-based approach. *Energy* **2021**, *233*, 121138.

[6] Romaní, J.; Cabeza, L.F.; de Gracía, A. Development and experimental validation of a transient 2D numeric model for radiant walls. *Renew. Energy* **2018**, *115*, 859–870.

[7] Krzaczek, M.; Florczuk, J.; Tejchman, J. Improved energy management technique in pipe-embedded wall heating/cooling system in residential buildings. *Appl. Energy* **2019**, *254*, 113711.

[8] Delgado, M.G.; Ramos, J.S.; Domínguez, S.; Ríos, J.A.T.; Cabeza, L.F. Building thermal storage technology: Compensating renewable energy fluctuations. *J. Energy Storage* **2020**, *27*, 101147.

[9] Kalús, D.; Gašparík, J.; Janík, P.; Kubica, M.; Šťastný, P. Innovative Building Technology Implemented into Facades with Active Thermal Protection. *Sustainability* **2021**, *13*, 4438.

[10] Ruiz-Pardo, Á.; Rodríguez Jara, E.Á.; Conde García, M.; Ríos, J.A.T. Influence of Wood Properties and Building Construction on Energy Demand, Thermal Comfort and Start-Up Lag Time of Radiant Floor Heating Systems. *Appl. Sci.* **2022**, *12*, 2335.

[11] DG, L.S.; Nagendra, S.S.; Maiya, M. Feasibility analysis of passive thermally activated building system for various climatic regions in India. *Energy Build.* **2017**, *155*, 352–363.

[12] Leo Samuel, D.; Shiva Nagendra, S.; Maiya, M. An analysis of operating parameters in the cooling tower-based thermally activated building system. *Indoor Built Environ.* **2018**, *27*, 1175–1186.

[13] Montenegro López, F.J.; Hongn, M.E. Estudio computacional de un sistema de acumulación estructural orientado a refrescamiento bioclimático: Primeros resultados. *Av. Energías Renov. Medio Ambiente* **2020**, *24*, 51–61.

Manuscript 334 submitted to 2023 9th International Conference on Control, Decision and Information Technologies (CoDIT). Received February 28, 2023.