Investigating Efficient Thermal Distribution in a House Room by combining Statistics with Computational Fluid Dynamics

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Received: 23 May 2024 | Revised: 10 June 2024 | Accepted: 15 June 2024

 DOI: https://doi.org/10.48084/etasr.7923

ABSTRACT

The study of energy sources is an open subject due to constraints on the current energy global production versus the current and future energy demands. From the consumption perspective, houses pull considerable energy from the electrical grid. With that being said, this paper investigates the theoretical thermal distribution of the heat in the basement of a house and measures the theoretical temperatures throughout different points at the same height by using statistics and numerical simulation. The numerical simulation, such as Computational Fluid Dynamic Analysis by COMSOL™ combined with Statistics by MiniTab™ was utilized to determine the most economical settings for the variables in the heating system evaluation. It is understood that thermal comfort for householders is achieved when the heat is evenly distributed in the room. To have a more realistic model set-up, the air flow in the room was considered as a turbulent model. The studied variables were intake airflow, positioning of the vents (intakes), airflow temperature, and external temperature. The results showed the significance of the variables. The latter were ranked from the highest to the lowest as: external temperature, airflow velocity, inlet location, and temperature input, while the highest interaction was found between the external temperature and air inlet velocity. This study comes up with a superior understanding of the system and generates an efficient setting for the variables for energy-saving purposes.

Keywords-energy saving; statistics; thermal simulation; computational fluid dynamics; heating system

I. INTRODUCTION

The modern world is striving more intensively for alternative ways to produce energy and reduce CO_2 blueprint, utilizing renewable energy forms, developing new ways to generate energy apart from fossil fuels, or researching more efficient ways to make use of or consume less energy [1-3]. As an example, energy utilization in the European Union is massive when it comes to houses, representing around 35% of the total energy expenses [4]. Consequently, the study of the efficiency of the housings' heating system is a real need. Authors in [5] conducted a thermal analysis of the impact of winds on housing. They used numerical simulation (Continuous Fluid Dynamics-CFD) to check the thermal comfort in a house with natural indoor and outdoor airflow to promote better comfort for households. Numerical simulation was also deployed to study the positioning of the houses on land on the basis of airflow. Studies conducted in Morocco [6] and South Poland [7] utilized CFD on the benefit of underfloor heating in houses and compared the calculated values with experimental measurements. The authors raised the heating system's efficiency by evaluating the heat distribution and by fine-tuning the floor heating system parameters, such as its thickness, insulation thickness and material, pipe spacing, and pipe diameter. Authors in [8] evaluated the indoor airflow velocities and temperatures using computational analysis.

Three turbulent models that could estimate very satisfactorily the flow and layered temperatures in the room were run. They concluded that the laminar flow was not as realistic as expected after comparing the results with real measurements.

Authors in [9] studied the energy consumption patterns of buildings in a district in China. They determined statistically the Energy Consumption Patterns (ECPs), forecasting heat demand, and concluded that building type as well as time are the most important variables although the latter is not sufficient for developing a precise model. With their proposed statistical model, they could save from 13.7 to 338.2 MW of energy. Authors in [10] worked on a statistical model to improve the heating system for a more cost-effective solution in compliance with the Europe Performance of Buildings Directive (EPBD). The authors collected discrepancies in the performance gap and treated them statistically to propose energy consumption calculations. In the same route, authors in [11] developed a statistical analysis of residential buildings located in Calabria. Multiple regression analysis was carried out to reach a forecasting tool to help with building refurbishments with actions focusing on minimizing heat losses throughout the outside surfaces and improving insulation.

The contribution of the current paper is the investigation of the theoretical thermal distribution in a house basement by using statistics with numerical simulation to determine the importance of the variables and their interactions in a house heating system during wintertime, aiming to determine theoretically the best setting (combination) of the thermal system variables, like the airflow (intake) blown into the basement, the intake's positioning on the ceiling, the airflow temperature, and the external temperature. Thus, a more even temperature distribution will be created in the room, providing comfort to households and indirectly saving energy.

II. MATERIALS AND METHODS

As mentioned above, a basement of a house was studied and from it, a 3D model was generated in Autodesk F360™ as shown in Figure 1. The basement was chosen for the study since it has a simple geometry where the airflow can be studied more easily and brings the first theoretical understanding of the thermal distribution in a house. Nevertheless, after this first analysis, the next step will be to expand to the other rooms in the house. Software COMSOL™ with its CFD Module was used to run the numerical simulation for heat transfer and thermal convention under turbulent conditions. COMSOL has already proven to be a powerful tool for solving heat transfer problems [12-14], fluid flows [15-16], and chemical reactions [17-18], among other engineering problems. For the statistical analysis and determination of the configuration outputs, the significance of each variable, and their interaction, software Minitab™ was utilized. The heating system employed as a reference was a Lennox model C33-18A-2-2 with a maximum pressure of 3.10 MPa (450 psi), 30.6 m^3/h (18 ft^3/m). The temperature was set by a Honeywell RTH6580WF thermostat. The basement dimensions are 4.0 m width, 6 m length, and 3.0 m height. The room has an open door to allow transit of people to the main floor and vice versa. On the left side of the door, the wall is exposed to the external space and it faces the house's backyard. The distance between the door side and the soil exposition is 1.7 m. On the back of the basement wall – left side- where a small window is seen, the external part of the wall, underneath the window is covered with soil to a height of 2.5 m.

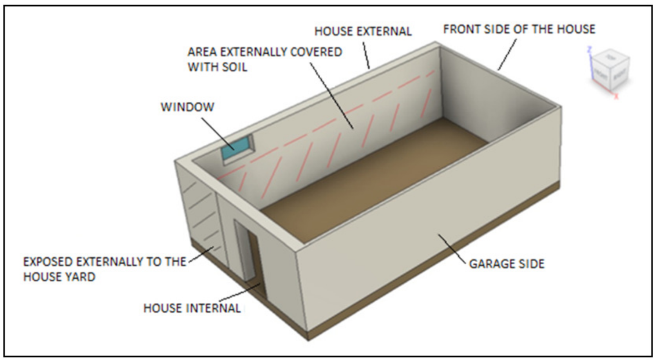

Fig. 1. Basement characteristics.

Alternatives for the positioning of the intake were disposed on a cross configuration, (see Figure 2), with changing position throughout the horizontal and vertical (X and Y axes) lines to 0% (leaning against the wall), 5%, and 10% from the wall (referencing to width and length). For the length, 5% means 0.3 m, and 10% means 0.6 m. When it comes to the width, 5% represents 0.2 m, while 10% represents 0.4 m. The intakes were rectangular with dimensions of 0.27 m and 0.10 m, maintained stable throughout all simulations. The velocity of the airflow was set up for 2.0, 2.5, and 3.0 m/s complying with [19], and the temperatures of the air intake varied from 311 K to 315 K with intervals of +1 K per simulation. The real localization of the vents [Inlet Location (Position)] was also simulated and used to evaluate the competency of the model according to the statistical equation, the distance of the inlet from the wall was 0.152 m for all vents (Intakes). The simulations used the 0.152 m position but changed the other variables.

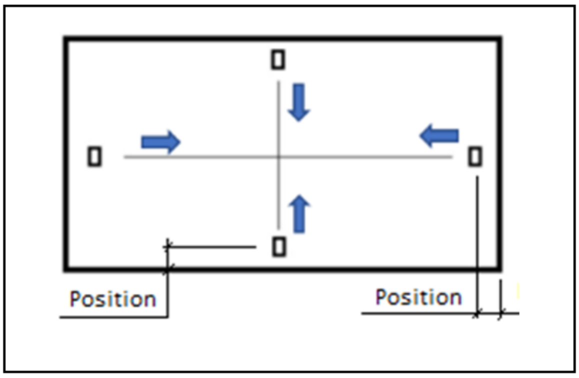

Fig. 2. Top view of the intake configurations.

In terms of external temperature, it was considered to vary from 248 K to 278 K [20] with intervals of 5 K per numerical simulation. The measurement points, from which the temperatures were taken from the numerical simulation are according to Figure 2. For the numerical simulation, the software COMSOL Multiphysics was deployed.

A. Heat Transfer in Solids and Fluids

For the energy equation, the following equation was used:

$$\rho C_p u.\nabla T + \nabla.q = 0 \quad (1)$$

where $q = -k\nabla T$, ρ is the density, C_p is the specific heat, u is the velocity, and T is the temperature. More details about the terms of (1) can be found in [27].

B. Turbulent Flow

Airflow was considered a turbulent condition [8], which is governed by (2):

$$\rho(u.\nabla)u = \nabla.[-pl + K] + F \quad (2)$$

$$\nabla.(\rho u) = 0 \quad (3)$$

where u is the same velocity in (1), and p is the pressure. More details about the terms of (2) and (3) can be found in [28].

C. Statistical Analysis

For the statistical analysis, the software Minitab™ was used. To validate the results for the average temperature in the room, the K-fold method, with K = 10, multivariable linear regression was assessed. After the statistical modeling, the room temperature was optimized by fine-tuning the variables in the system with MiniTab™. Statistics was chosen for the study since it is a powerful tool for effectively evaluating variables in the sense of identifying the logic of the behavior of each variable in it. On top of that, it provides "hard facts" for determining the significance and interaction of each variable. In comparison with other works, the current paper provides enough data to reach a more accurate conclusion.

III. RESULTS

An exploratory analysis was performed by changing the following control variables: External Temperature (T_{ext}), Temperature Input (T_{hot}), Airflow Velocity (U_0), and Inlet Location (Position in % = $p_{\%}$), as seen in Table I. A total of 308 experiments (N) were conducted in MiniTab™ with the independent variables being within the range illustrated in Table I. For the statistical analysis carried out in this work, 5 monitoring points (X-Y) were verified (coordinates in m): A(3;2), B(1.5;1), C(4.5;1), D(4.5;3), and E(1.5;3). All points were at a height of 1.25 m from the basement floor.

TABLE I. STATISTICS.

Variable	Average	STDev	Minimum	Maximum
T_{ext} [K]	263.00	10.02	248.00	278.00
T_{hot} [K]	313.00	1.43	311.00	315.00
U_0 [m/s]	2.5114	0.4064	2.0000	3.0000
$p_{\%}$	4.886	4.064	0.000	10.000

STDev: standard deviation.

From the K-fold validation method with K = 10, multivariable linear regression was assessed for the average temperature in the room, depending on the independent variables in Table I. The best result was obtained by (4) (where T_M is the average temperature in K, for points A, B, C, D, and E), as disclosed by the variance analysis demonstrated in Table II and Figure 3.

$$T_M = -6.77 + 0.61392T_{ext} + 0.3866T_{hot} + 4.78U_0 + 2.0941p_{\%} - 0.9444U_0^2 + 0.010214p_{\%}^2 - 0.081847T_{ext}U_0 - 0.006678T_{ext}p_{\%} + 0.08245T_{hot}U_0 - 0.04112U_0p_{\%} \quad (4)$$

TABLE II. ANALYSIS OF THE VARIANCE MODEL CONFORMING TO (4)

Source	GL	SQ (Aj.)	QM (Aj.)	F-value	p-value
Regression	10	6133.02	613.30	194614.79	0
T_{ext} [K]	1	4348.36	4348.36	1379834.22	0
T_{hot} [K]	1	221.84	221.84	70396.44	0
U_0 [m/s]	1	856.04	856.04	271641.78	0
$p_{\%}$ [%]	1	563.83	563.83	178915.63	0
U_0^2 [m²/s²]	1	3.85	3.85	1221.97	0
$p_{\%}^2$	1	4.50	4.50	1429.38	0
$T_{ext}U_0$ [K·m/s]	1	33.93	33.93	10766.28	0
$T_{ext}p_{\%}$ [K]	1	22.59	22.59	7167.28	0
$T_{hot}U_0$ [K·m/s]	1	0.71	0.71	226.50	0
$U_0p_{\%}$ [m/s]	1	1.40	1.40	442.96	0
Error	297	0.94	0.00		
Total	307	6133.95			

GL: degrees of freedom; SQ (Aj.): sum squared; QM (Aj.): medium sum squared; F-value: F distribution value.

When looking at the data, it is observed that all studied variables are independent. Moreover, there are relevant second-order interactions among the variables. With that being said, the variance analysis reveals that the most significant variable that influences the temperature in the room is the External Temperature (T_{ext}), followed by the Airflow velocity (U_0), the Inlet Location ($p_{\%}$), and lastly Temperature Input (T_{hot}). In the study of the residue of the model by (4), deviation of normality was not observed since the p-value resulting was higher than 0.15, as depicted in Figure 4.

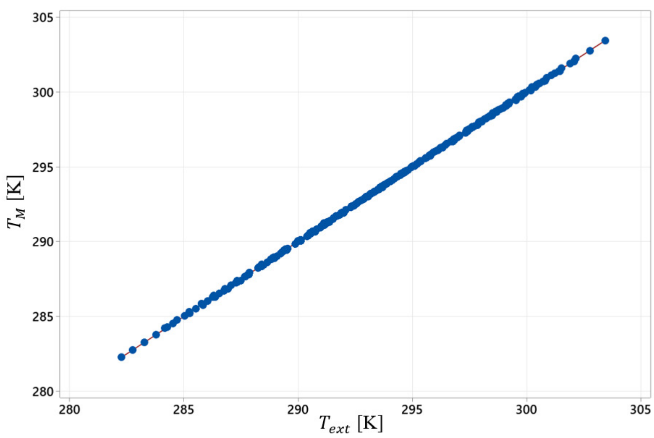

Fig. 3. Fitting of the experimental data to the model conforming to (4).

The data fitting to (4) is summarized in Table III. The data fit very well the linear curve, which highlights the high power of extrapolation of the model demonstrated by the high value of R^2 (0.9998) from the 10-fold validation. It should be noted that the regression model uses only 10 degrees of freedom, whereas the data bank utilized 308 degrees of freedom. Therefore, by making use of a few terms in (4), it was possible to demonstrate satisfactorily the variation of the average temperature in the room within the ranges described in Table I. Figure 5 shows the quality of fitting.

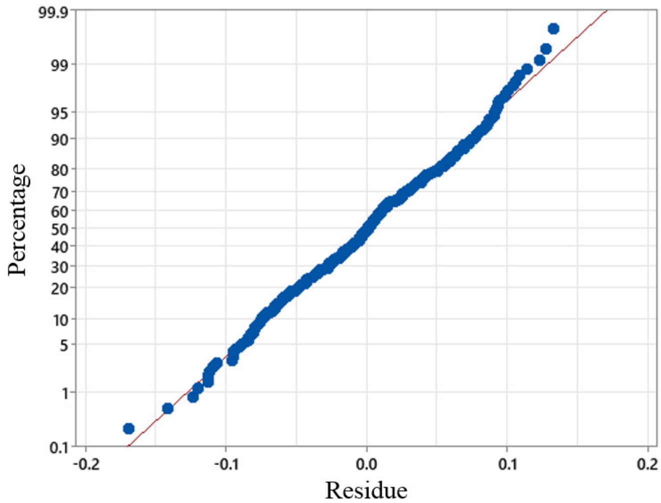

Fig. 4. Normality test for the residue of the model conforming to (4).

TABLE III. SUMMARY OF THE QUALITY OF FITTING OF THE MODEL CONFORMING TO (4).

S	R^2	R^2(aj)	R^2(pred)	10-fold S	10-fold R^2
0.0561370	99.98%	99.98%	99.98%	0.0578297	99.98%

S: sum square; R^2: R square; R^2 (aj): R^2 adjusted; 10-fold S: sum squared of the validation process 10 folds; 10-fold R^2: R^2 of the 10-fold validation process.

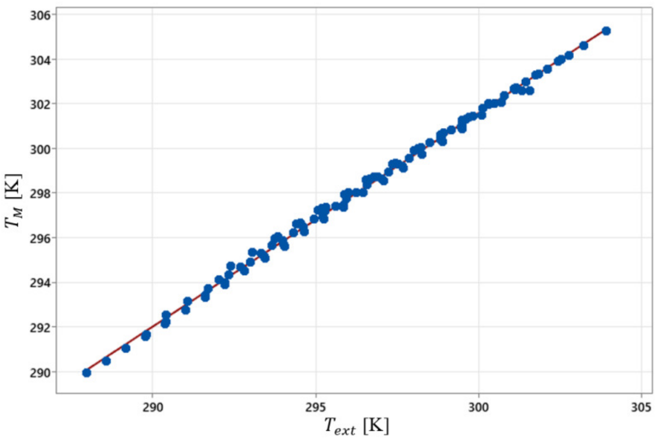

Fig. 5. Fitting the experimental points to the model conforming to (4). Generalization test.

To evaluate the competence of the model presented in (4) to predict the average temperature in the room, the real variable "Inlet Location (Position)" was maintained at 0.152 m (see in Figure 6 the temperature distribution for this case) but still with changes in the other variables within the range predetermined in Table I. The results from the model generalization can be seen in Figure 5. The capability of the model presented in (4) to predict the average temperature of the room is clear.

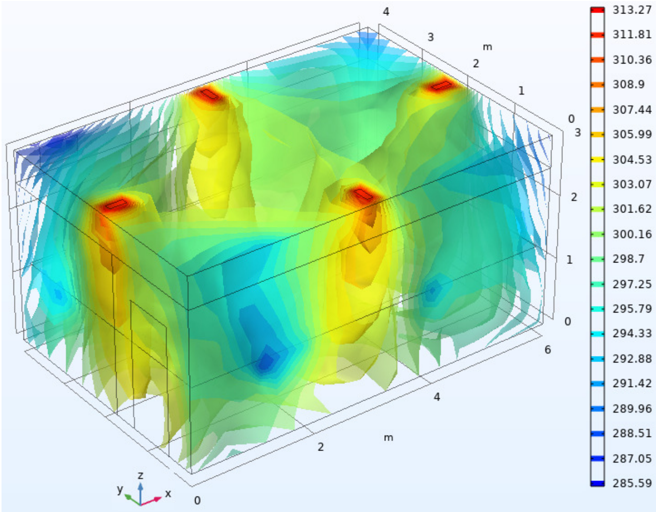

Fig. 6. 3D temperature distribution [K] close to the real conditions (U_0 = 3 m/s; T_{hot} = 314 K; T_{ext} = 278 K).

$$STDev = 0.814 - 0.011714T_{ext} + 0.009074T_{hot} - 0.109U_0 + 0.1775p_{\%} - 0.0064U_0^2 + 0.001986p_{\%}^2 + 0.000377T_{ext}U_0 - 0.001577T_{ext}p_{\%} + 0.001091T_{hot}p_{\%} - 0.1273U_0p_{\%} + 0.000358T_{ext}U_0p_{\%} + 0.00567U_0^2p_{\%} - 0.001372U_0p_{\%}^2 \quad (5)$$

TABLE IV. ANALYSIS OF THE MODEL VARIANCE CONFORMING TO (4)

Source	GL	SQ (Aj.)	QM (Aj.)	F-value	p-value
Regression	13	16.8278	1.29444	6019.22	0.000
T_{ext} [K]	1	6.0999	6.09993	28364.92	0.000
T_{hot} [K]	1	0.1306	0.13065	607.51	0.000
U_0 [m/s]	1	0.1678	0.16777	780.13	0.000
$p_{\%}$	1	3.1615	3.16154	14701.29	0.000
U_0^2 [m²/s²]	1	0.0020	0.00197	9.14	0.003
$p_{\%}^2$	1	0.0919	0.09190	427.34	0.000
$T_{ext}U_0$ [K·m/s]	1	0.0229	0.02286	106.32	0.000
$T_{ext}p_{\%}$ [K]	1	0.2329	0.23292	1083.09	0.000
$T_{hot}p_{\%}$ [K]	1	0.0125	0.01250	58.14	0.000
$U_0p_{\%}$ [m/s]	1	0.2695	0.26946	1252.98	0.000
$T_{ext}U_0p_{\%}$ [K·m/s]	1	0.0106	0.01059	49.23	0.000
$U_0^2p_{\%}$ [m²/s²]	1	0.0023	0.00230	10.69	0.001
$U_0p_{\%}^2$ [m/s]	1	0.0134	0.01345	62.52	0.000
Error	294	0.0632	0.00022		
Total	307	16.8910			

GL: degrees of freedom; SQ (Aj.): sum squared; QM (Aj.): medium sum squared; F-value: F distribution value.

By the evaluation of models in (4) and (5) it is possible to generate boundary graphs for the average temperature (T_M) and standard deviation ($STDev$), identifying operational regions of the control variables, in a way that T_M and $STDev$ satisfy certain conditions. So, the white region of Figures 7–11 indicates the acceptable ranges for T_{ext} and T_{hot} to fixed values for U_0 and $p_{\%}$. Thus, a small standard deviation for the temperature variation until 0.8 K was considered as acceptable along with and temperature within 293 and 298 K, to the fixed conditions U_0 = 2.5 m/s and $p_{\%}$ = 5. Figure 7 exhibits the admissible region to these conditions (white color in the graph).

TABLE V. THE SUMMARY OF THE QUALITY OF FITTING OF THE MODEL CONFORMING TO (5)

S	R^2	R^2(aj)	R^2(pred)	10-folds S	10-folds R^2
0.0146647	99.63%	99.61%	99.59%	0.0151341	99.58%

S: sum square; R^2: R square; R^2 (aj): R^2 adjusted; 10-fold S: sum squared of the10 fold validation process; 10-fold R^2: R^2 of the 10-fold validation process

It is noticeable in Figure 7–11 that it is not possible to find values for the operational variables that comply with the necessary range for T_M and $STDev$ when the external temperature is less than 260 K.

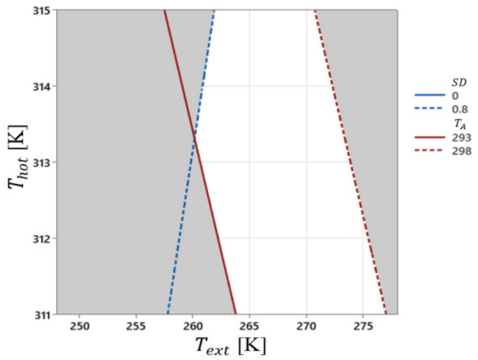

Fig. 7. Boundary graph for T_M and $STDev$ as functions of the experimental conditions, with $U_0 = 2.5$ m/s and $p_{\%} = 5\%$.

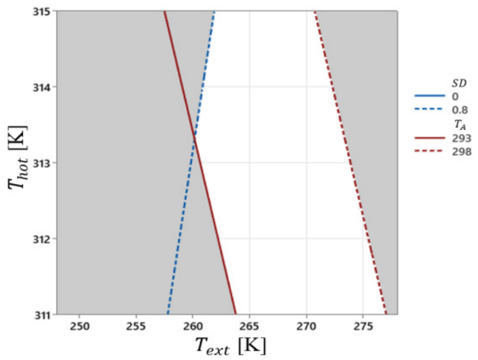

Fig. 8. Boundary graph for T_M and $STDev$ as functions of the experimental conditions, with $U_0 = 3$ m/s and $p_{\%} = 0$ %.

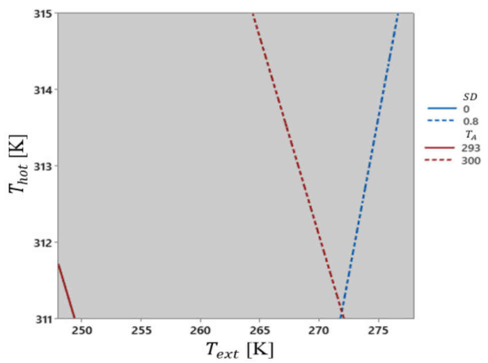

Fig. 9. Boundary graph for T_M and $STDev$ as functions of the experimental conditions, with $U_0 = 2.5$ m/s and $p_{\%} = 15.2$ %.

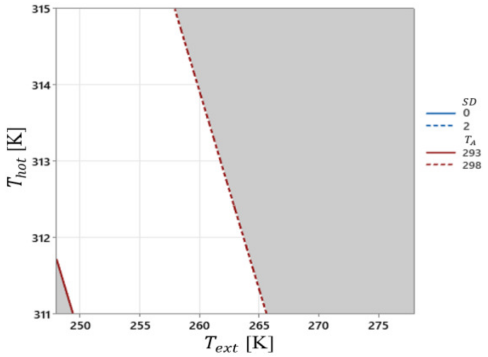

Fig. 10. Boundary graph for T_M (293 – 298 K) and $STDev$ as functions of the experimental conditions, with $U_0 = 2.5$ m/s and $p_{\%} = 15.2$ %.

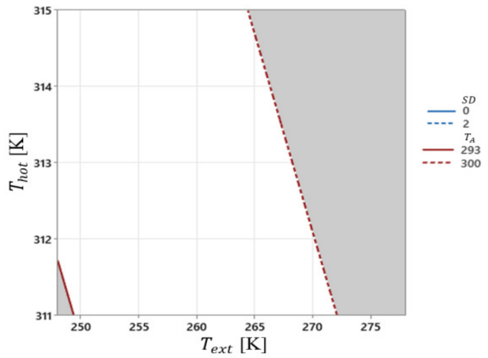

Fig. 11. Boundary graph for T_M (293 – 300 K) and $STDev$ as functions of the experimental conditions, with $U_0 = 2.5$ m/s and $p_{\%} = 15.2\%$.

Figure 8 demonstrates that, when changing U_0 to 3 m/s and $p_{\%}$ to 0, it is possible to reach a region that complies with the previous specifications for T_M and $STDev$ in the white region. For a fixed value of 0.152 m as a real value (Figure 8), it is clear that no one of the experimental conditions can reach the specified conditions for T_M and $STDev$. Still, Figure 9 conveys that whether or not there is an increase in the range for $STDev$ up to 2 K, under the real condition $p_{\%}$, the conditions for T_A and $STDev$ are reachable, even for very low values of T_{ext}, close to 250 K. Figure 10 reveals that with the real position $p_{\%}$ is likely to achieve a region with a higher average temperature variation in the room.

IV. DISCUSSION AND CONCLUSION

Throughout the review of the state-of-the-art research on computational fluid dynamics and statistics, it was possible to find papers that study thermal distributions with numerical calculations and statistics, both aiming for energy saving. This paper, on the other hand, combined both methods for the same purpose. With the utilized methods, it was possible to determine the theoretical combination of the thermal system variables for a basement room, like the airflow (intake) blown into the basement, the intake's positioning on the ceiling, the airflow temperature, and the external temperature. As an output of the variable's studies, it was considered an evenly average temperature and a narrow standard deviation. By using this approach, it was possible to establish an ideal setting when it comes to energy saving. The numerical simulation with the statistics ended up showing the significance of the variables that impact to an even temperature distribution in the room. The variables ranging from the highest to the lowest are: External Temperature (T_{ext}), followed by Airflow velocity (U_0), Inlet Location ($p_{\%}$), and Temperature Input (T_{hot}). The highest interaction was found between the external temperature and the air inlet velocity. As a secondary contribution, this paper demonstrates the power of numerical simulations and statistics mainly when they are used complementary. They can provide a deeper understanding of complex systems with multiple variables, which matches very well with the study of energy savings in houses. The expectation is to have this work replicated in different situations for a better understanding of a heating system that might involve computational fluid dynamics and statistics applied with the aim to increase the energy savings.

ACKNOWLEDGMENT

The authors acknowledge the financial support of the Higher Education Personnel (CAPES) on this research.

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