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Fluid Dynamics Analysis and Fire Evacuation through Computer Simulation: A Case Study

Cynthia Jordão de Oliveira Santos[a]*, Victor de Sá Alencar e Moraes[b], Bianca M. Vasconcelos[c]

[a,b,c]*Polytechnic School of the University of Pernambuco (POLI/UPE), Benfica Street, 455 - Madalena, Recife – PE, 50720-001, Brazil*

[a]*Email: cjos_pec@poli.br,* [b]*Email: vsam_pec@poli.br,* [c]*Email: bianca.vasconcelos@upe.br*

Abstract

Accidents caused by fires are harmful to both property and human life, causing most of the events to result in disasters. As an aid method for fire and panic protection and combat projects, fluid dynamics and building abandonment simulation software can be used, which can suggest re-dimensioning of accesses and active and passive protection systems, to mitigate structural damage and improve protection for users. In this context, the present research aimed to simulate the propagation of smoke and the abandonment of the Occupational Safety and Hygiene Laboratory (LSHT), using the PyroSim software, related to fluid dynamics analysis, and Pathfinder, related to evacuation dynamics. To this end, the research followed the following steps: literature review; 3D modeling of the LSHT, as well as the insertion of the materials present in the building, firing configurations, and then fire simulation through PyroSim; finally, the simulation of the evacuation of the occupants through the Pathfinder highest rate of thermal heat transfer through radiation. Regarding the results of computer program; and data analysis. The results show that during the 600s simulation, the smoke spread through all environments of the LSHT, reaching a temperature of 240.04ºC at the end of the simulation, with the evacuation simulator, it was verified that the individuals vacated the environments in only 36.5s. Regarding the results of the evacuation simulator, it was found that the individuals vacated the environments only 36.5s. Within the abandonment time, they have not reached levels that could compromise the survival of the occupants.

Keywords: Fire protection; PyroSim; Pathfinder; Occupational safety and health.

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* Corresponding author.

1. Introduction

Events generated by disasters bring disruption and destruction to property, as well as accidents that can be fatal for people present at the site of the fire. Thus, to avoid or minimize these eventualities, it is necessary to identify the risks and offer control measures [17].

The occurrence of accidents is recurrent in urbanized areas, bringing several damages not only to the architectural heritage but also physical and psychological to the users of the place. In this sense, it is fundamental that buildings are evaluated to minimize risks [21]. Disasters, however, may occur during the attempt to evacuate the population present on sites, such as trampling and blocking passages due to excessive smoke and deteriorated materials. For this reason, it is essential the dimensioning accesses, corridors, stairs, and door openings, so that users can exit the environment safely [12].

Nevertheless, the prevention of accidents in buildings happens from the identification of risks and the elaboration of the firefighting project. Actions of preventive nature are, therefore, responsible for specifying the dimensioning requirements of circulations, firefighting equipment, definition of rescue and evacuation sites, and firefighting methods [5].

Therefore, windows, doors, and open stairways should be evaluated and sized, since the supply of oxygen by natural ventilation is also one of the factors that can determine the spread of fire throughout the building, the occurrence of fire growth and generalized burning, which is called flashover [14].

Thus, the search for prevention and minimization of events generated by disasters aims to obtain contributing factors to reduce the risk of fire [5]. In this perspective, the most appropriate means for this goal is the project of protection and fire and panic fighting, duly prepared by a qualified professional.

This intervention, therefore, is recommended by architecture and engineering professionals to be used to establish appropriate protection measures against the occurrence of accidents in buildings [13]

Regarding the proposal and development of the designs, the designers must analyze the constructive materials and suggest the elements that contain the lowest level of inflammability, so that, in this way, the fire is not fed with combustible substances, thus reducing its burning time [4].

About the evaluation of safety conditions against fires and explosions, two types of approaches can be used: the first follows the parameters established by legislation, while the second, based on performance, analyzes, qualitatively and quantitatively, the measures that should be adopted [11]. Thus, in establishing control measures, it is necessary to conduct studies of the building according to its typology and use, to then launch a proposal for a project of fire and panic prevention and combat, which must follow the current laws [19].

It is the norms and legislations that determine the parameters, being the due knowledge and compliance fundamental for fire protection. However, along with the laws, there may be the application of the method, which using computer technology will enable the evaluation of the real picture of the building. Another aspect to be considered refers to the materials used for the construction of each type of building, it is worth noting that, since there are fire resistant elements and other flammable elements that enhance the spread of flame and fire propagation. In the case of concrete structures, the fire is dis- sipated utilizing heat transfer, notably through surfaces caused by radiation, reaching the structure which, in turn, undergoes chemical changes; from these, pathologies are produced in the concrete, presented by cracking and chipping that cause its explosion [15].

The influence of construction elements on the propagation and behavior of fire is well known. Thus, the components that contain inflammable substances (generating fire growth) and products that are insulating (protecting the building from the flame spread), perform investigative studies to the expo sure of materials and structures to fire, which should be considered during fire simulation [11].

Certainly, the exposure of materials to high temperatures by fire generates deformities in the building materials. This action on the building components occurs from 100º C, leading to burning, rupture, and complete collapse of the building [23]. Therefore, it is of utmost importance an adequate specification of the materials, opening for the exit of gases and the physical arrangement, as well as the location of accesses as points for the escape, an indispensable means to avoid human losses. With technological advances, the help provided by software makes it possible to conduct studies on heat dissipation and the phenomenon of flame spread, seeking to solve the concentration of shock waves [7].

Thus, even in the face of the specificities, also technological, the existence of materials with innovative solutions, about the appropriate behavior for resistance and exposure to fire, can be implemented as interventions to nonflammable and fire-resistant components, to generate less damage to the building and, therefore, increase the time for the evacuation of people [16].

The transformation of processes assists in organizational development, which provides the labor market with changes by presenting benefits to the production method of companies, through software with intelligent systems and innovative technologies [19]. In this way, through the study of constructions in computational modeling, employing technological tools with dynamic concepts, it becomes possible to predict, from the beginning of the fire, the propagation temperature, the environments that will be affected and even complete spread in the building [20].

It is important to point out that among the places where fires and explosions occur, those that occur in urban areas are the ones that account for the largest amounts of human losses. Thus, it is necessary to implement preventive and protective measures for the lives of users in other buildings [6].

The objective was to simulate the fluid dynamics of fire and evacuation in a sector of a public building using PyroSim and Pathfinder software, to detect inconsistencies in the firefighting system. The specific objectives were as follows: to simulate a fire in the PyroSim software; to simulate the abandonment of the building in the Pathfinder software; to examine the results and treat the data, and to analyze the inconsistencies.

2. Fire data

According to the National Secretariat of Public Safety of the Ministry of Justice, Brazil is considered one of the countries with the highest number of fire related fatalities. The data inform that an average of 267,000 fires occurs annually, with about 700 occurrences in a single day, with about 1,000 people dying within a year [2].

Instituto Sprinkler Brasil states, however, that in Brazil there is no official information about the occurrences of fires; it is estimated that the cases disclosed represent around three portents of the casualties between the periods from 2012 to 2020 (except for the year 2016) [10]. This Institute is a private entity that aims to point out the causes of fires that could be avoided with the use of sprinkler systems. In turn, although the ISB makes fire data available, there is no balance of those that affect residences. Thus, it only accounts for structural fires in warehouses; commercial (such as stores, shopping malls, supermarkets); industrial; public and educational companies; health services (such as hospitals, posts, and clinics); places where the public congregates, and accommodation services. In this set, the buildings could get the claims contained with the presence of an effective fire safety system [10].

Also, according to the Institute, the causes of fires that could be prevented with sprinkler systems, between the years 2012 and 2020 (no data for the year 2016), had the highest occurrences in the state and Sao Paulo, as shown in Figure 1, which totaled 1,508 events. The second state with the highest rate in recent years is Santa Catarina, with 859 cases, followed by the state of Minas Gerais, with 736 events [7]. The following image (Figure 1) explains the six states with the highest rates of fire occurrences.

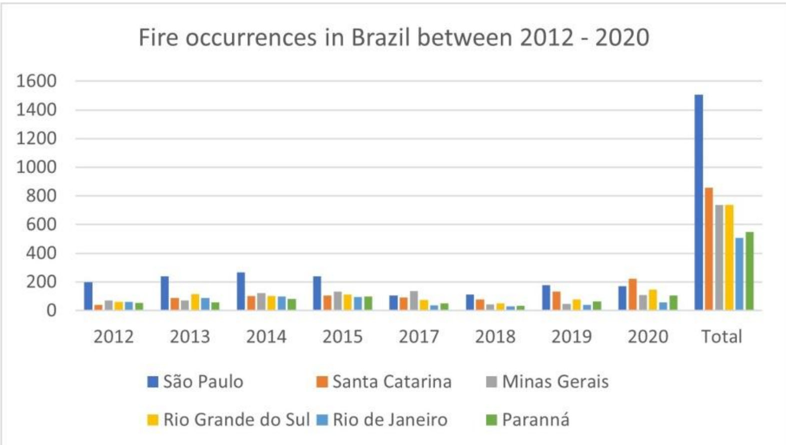

Figure 1: Graph of fire occurrences in Brazil between 2012 -2020.

Source: ISB (2021) adapted by the authors.

2.1. Fluid dynamics concepts

For the interpretation of the results presented by the fire dynamics experiment, in this scenario, computer simulation, it is necessary to learn the basic principles of fluid dynamics, such as the emergence of the initial ignition of the fire, types of heat transfer, and fire phases.

Fire arises from a combined point between the presence of ignition, oxygen, and heat; it is from the union of these three elements that its production is provided. The flame, in turn, happens when the burning material reaches its critical temperature, arriving in the process of inflammation [9].

To maintain itself, fueling the presence of oxygen by producing heat by which through combustion can cause the union of substances and materials, changing them. This phenomenon is titled by the literature the fire triangle since the existence of these three elements is indispensable.

Thus, for the fire to remain stable, sufficient combustible material and thermal energy are needed to maintain the burning. The temperature increase happens when the kinetic energy released gets the speed of action of the particles, speed equal to the acceleration that is produced; such temperature will depend on the methods of heat transfer, being they conduction, convection, and radiation [24].

Heat transfer phenomena are divided into three types. Conduction is the transfer of heat flow from the contact of molecules on solid surfaces; convection happens in the heat transport between fluids or from fluid materials to a solid body, and radiation, through electromagnetic waves [3].

It is possible to predict, probabilistically and sensitively, the duration and intensity of the fire from the dimensioning and survey of flammable or resistant materials involved in the accident. Therefore, it is of utmost importance the knowledge of the fire phases to relate them to the temperature/time in which the building is consumed by fire or collapses [18].

Based on this perspective, the fire phases are characterized as follows: initial phase; growth phase; unleashing phase; and, finally, the decay phase, respectively [1].

3. Methodology

In the first moment, bibliographical research was carried out in databases, using the search words:” fire”,” design”,” protection”, with the Booleans “AND” and “OR” between the advanced search bars. We also considered monographs, dissertations, and theses, identified through the Google Scholar academic platform.

With a descriptive and experimental methodology, the object of study was limited to the Occupational Health and Safety Laboratory (LSHT) located in a building of the Polytechnic School of the University of Pernambuco, through an architectural project in DWG format, using the PyroSim and Pathfinder software. Finally, based on the data treatment, the dissemination and viscosity of the smoke, the predominant type of heat transfer, the temperatures in each environment, the gases released, and the evacuation time of the occupants were analyzed.

3.1. Construction of references

The Fire Dynamics Simulator (FDS) is a simulator of flame propagation in the event of an accident, used in studies about the building concerning fire protection and firefighting. One of the software that uses the FDS model for fluid dynamic analysis is PyroSim, a program developed in the United States by Thunderhead

Engineering Consultants, in which 2D or 3D projects are inserted to simulate fire on site. From this, the best solutions are tested in its computational mesh, to avoid fire propagation and establish escape routes.

The study comprised the following simulation steps based on the PyroSim computer program:

Importing the project in DWG into PyroSim (pilot study). 2. Implementation of the mesh (MESH) and its configuration. At first, the mesh was added with the following dimensions: initial X 0,0m; final X 14,00m (length); initial Y 0,0m; final Y 12,00m (width); initial Z 0,0; final Z 3,00m (height); and with the size between cells of 0,1m (0,1 x 0,1 x 0,1), determining its resolution, which was defined as moderate. The smaller the cell size, the more accurate the simulation results will be. Thus, the number of cells contained in each of the directions is 140 in X, 120 in Y, and 30 in Z, with a total of 504,000 cells. To obtain the proper calculation of the mesh resolution it is necessary to apply a compatible Heat Release Rate (HFR), for this case the value 1.110kW. 3. Three-dimensional modeling and addition of the obstructions. 4. Characterization of the materials. 5. Surface configuration. 6. Insertion of openings and ventilation. 7. Addition of the vent flame with the 1111,8 kW/m². 8. Placement of the firing reaction. The reaction chosen for the simulation is PMMA (Poly Methyl Methacrylate). It was tested to insert another type of reaction not belonging to its library; however, the results were not presented correctly, generating a simulation error. Therefore, among the available reactions, the chosen one was PMMA (Poly Methyl Methacrylate), since it is a polymer that is close to the rigid plastic material of the small electric appliances that constitute LSHT. 9. Insertion of thermocouples in all doors at 2.00m from the floor and only one at 0.40m near the vent flame. The Thermocouples were added from the Device command, in the access openings, that is, totaling seven temperature sensors at 2.00m from the floor. In addition to these described, a thermocouple was added near the Vent flame at 0.40m from the floor to check the temperature emitted by the burner. 10. Addition of 2D Temperature and Visibility Slices. The slices show the temperature in colors, red for high temperatures, green for intermediate temperatures, and blue for the usual environment. Thus, three temperature slices were placed in X and one in Y near the vent flame, (aiming to visualize the temperature in all environments in both axes) totaling four temperature slices. Furthermore, three visibility slices were inserted in Y, to visualize the viscosity of the soot produced by the flame. 11. Setting the simulation parameters to 600s. For this simulation run time. The program ran the settings for approximately 20h. 12. Generation of the results in Smokeview.

3.2. Pathfinder

For the simulation of the evacuation of people, the Pathfinder program was used, which, like PyroSim, belongs to the Thunderhead software company. In this research, the purpose of PyroSim was to model the dynamics of fires in buildings, while Pathfinder had the duty of modeling emergency evacuation.

From the PyroSim modeling, and after the simulation of the smoke dynamics displayed in Smokeview, the 3D modeling is inserted into Pathfinder. With this, the steps for the evacuation configurations of people in the LSHT were performed. To perform the simulation, the following tasks were performed:

Selection of the environments. 2. Naming the environments. 3. Configuration of the openings. 4. Configuration of the general output. 5. Insertion of evacuation polygons. 6. Deployment of forty geometries to simulate individuals leaving the environments. 7. Change of geometries for people. 8. Configuration of the individuals' profiles. 9. Running the simulation.

4. Results

The Safety and Occupational Hygiene Laboratory (LSHT) is in the Polytechnic School of the University of Pernambuco (POLI/UPE). The Safety Laboratory is composed of the following environments: teachers' room, student researchers' room, pantry, meeting/guidance room, amphitheater, and library, as can be seen in Figure 2.

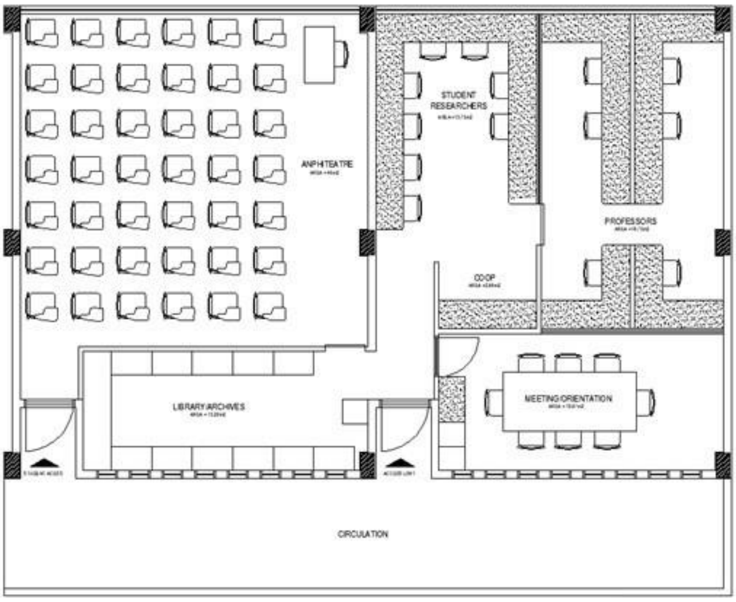

Figure 2: Floor plan - LSHT.

4.1. PyroSim simulation

With the knowledge of the environments and the study of the floor plan, the project that was previously in DWG format was imported to the PyroSim software. Afterward, it was transformed from 2 Dimensions to 3 Dimensions, with the addition of the walls, openings (doors and windows), and furniture. The walls are modeled from the Obstruction (OBST) command, the doors, and windows from the HOLE command.

Next, the constituent materials and coatings of the objects and materials were added, essential for determining the combustible elements, burning time, and temperature. In this context, the burner was also added (recognized in the program as Vent flame and named in its description as burner vent), which was inserted in its surface the Heat Release Rate Per Unit Area - HRRPUA of 1111,8 kW/m².

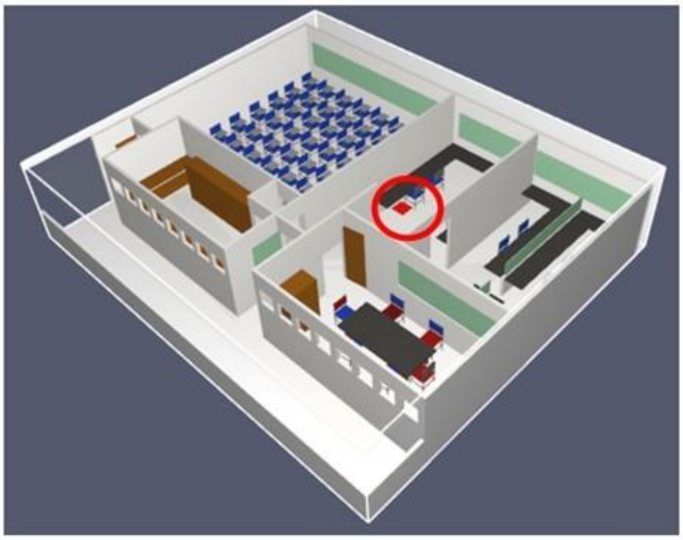

Figure 3: 3D Model - LSHT.

The place chosen for the simulation of the fire dynamics includes computer stabilizers, which would simulate a case of short circuit in one of these types of equipment. Such a burner can be identified in Figure 3, with a red squarelocated in the researcher's room.

The simulation results according to the Slices, three in X and one in Y, showed that the temperature in the room where the fire started reached 170°C (Figure 3). The bar next to it points out the temperature degrees according to the colors shown. Unlike the temperature slices, the visibility slices have the highest soot manufacturing index in blue, and the lowest soot manufacturing index in the red. Figure 4 also shows the recording of the simulation at 300 seconds and 600 seconds.

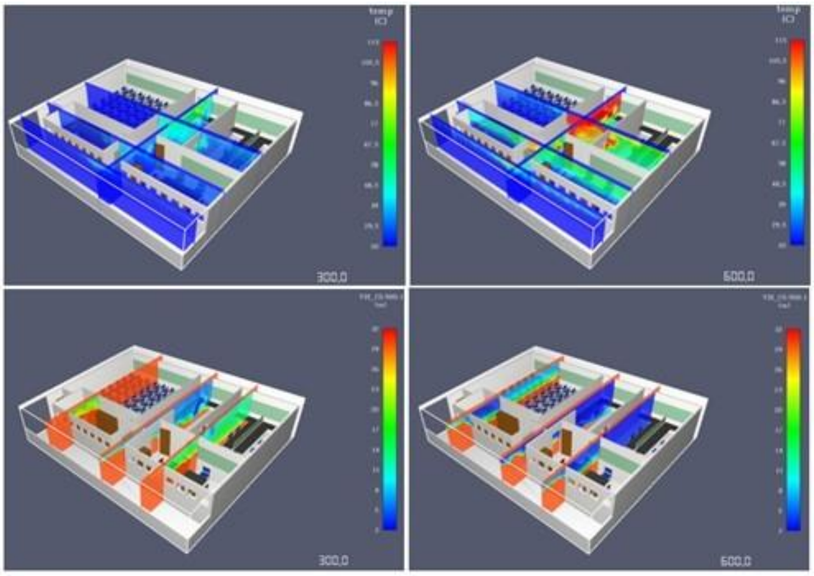

Figure 4: Temperature and visibility slices.

As far as fire and smoke are concerned, it can be noticed that the fire starts, and the smoke takes the environment where the burner is located (the researchers' room), extending to the pantry, and then, in the 20s, starts to invade the teachers' room. In the place where the fire starts, the temperature rises near the ceiling, because the cold air molecules have a higher density than the hot air particles. Therefore, the highest temperature is located near the ceiling of the building.

At 100 seconds of simulation, besides the researcher's room where the fire started, it is noticeable that the smoke has taken over the professors' room, along with the meeting room and the library, starting to invade the classroom (amphitheater). In the 210 seconds of simulation, it is noticeable that the smoke density increases, and consequently the production of toxic and flammable substances contained in the smoke increases.

Therefore, the complete dissemination of the smoke through the environments of the laboratory takes place at 600 seconds of simulation, that is, in 10 minutes, in which the environments studied would already be taken by the smoke in a case of fire. However, pyrolysis does not occur within this period, because the low fire load in the environment has a maximum smoke temperature of 115C, which is enough to kill a person (Figure 5).

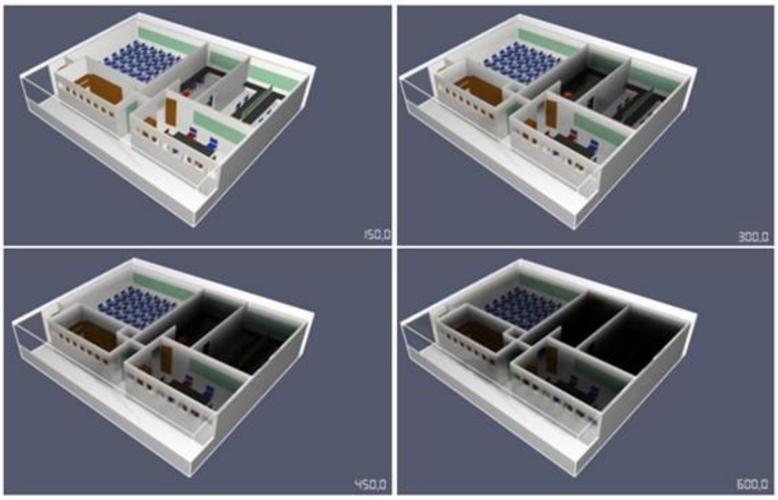

Figure 5: Fire simulation in PyroSim.

4.1.1. Heat Release Rate

In addition to simulation, the PyroSim software guarantees the execution of statistical graphics, from the data provided. Fig. 6 presents the Heat Release Rate, which represents the amount of heat released during a fire and defines the dimension of the accident, having its magnitude in combustion demonstrated in HRR, expressing in turn, the oscillation of the heat release rate concerning the determined time for simulation, in this case, 600 seconds, which had 250kW, as can be seen below in Figure 6.

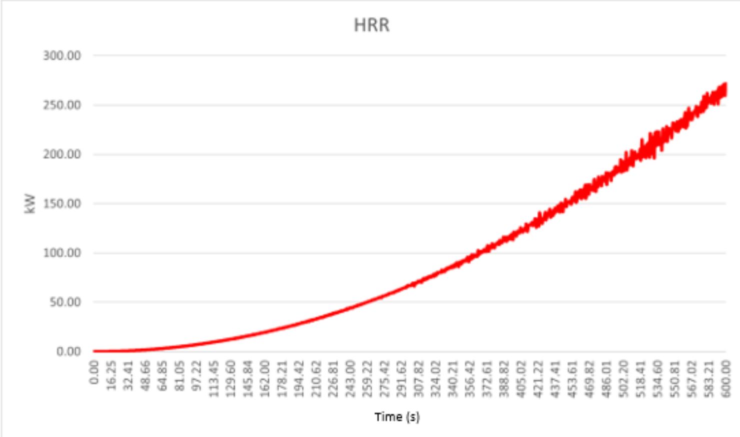

Figure 6: Heat Release Rate.

4.1.2. Conduction, convection, and radiation

It was found that the heat transfer by conduction is due to the direct contact of the flame with the floor, wall, marble countertop, and the chair that are close to the burner. The results of the transfer power (kW) about the simulation time (600s) were 70 kW.

In the case of convection heat transfer, the graph Q CONV displays the results of convection with the emitted power of 60 to 80 kW in the 600 seconds of stimulation, whereas in radiation, the heat energy is transmitted by magnetic waves, enabling its transfer in a vacuum. That is, the heat source located in the researchers' room radiates to the other environments. Fig. 7 shows the results of this type of heat transfer, obtaining the value of 120 kW in 600s of simulation.

It is possible to identify that radiation (heat dissemination through electromagnetic waves) obtained the highest rate of heat transmission to conduction (transmission through direct contact with the heat source) and convection (transfer through smoke containing high temperature). The values in the negative format presented in the heat transfer graphs mean that the energy transmission happens when the released heat is absorbed, occurring, therefore, from the agitation of the high temperature atoms and molecules propagating to the lower temperature atoms and molecules.

From the analysis of the graphs, having as the X the stipulated simulation time, in this case, 600s, and the Y, the value relative to the transfer in kilowatts, the greatest oscillation in the curve of the diagrams occurs during radiation, where the highest rate of thermal energy is generated with the value relative to the heat transfer of 120 kW.

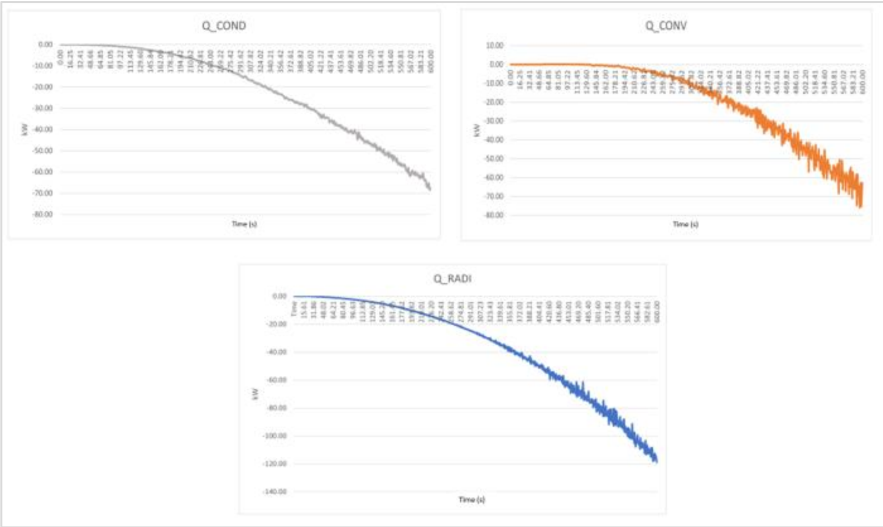

Figure 7: Conduction, convection, radiation, and comparative rates.

4.1.3. Temperature of the environments

The thermocouples were inserted in the access openings (doors to the teacher's lounge, meeting room, library, entrance hall to the LSHT, amphitheater and at the beginning of the hallway), 2.00m from the floor, and one near the Vent flame 0.40m from the floor, totaling eight thermocouples. Figure 8 shows the location of the thermocouples.

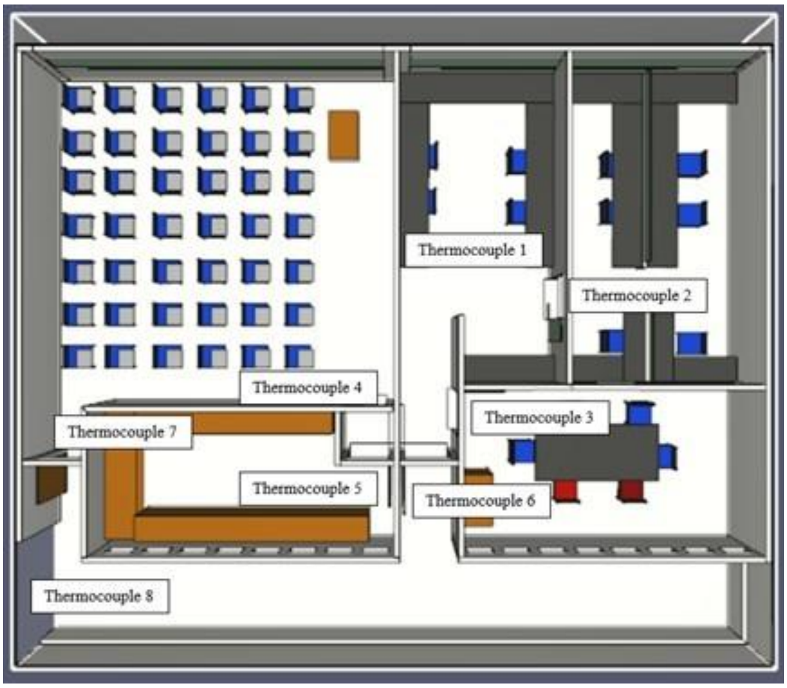

Figure 8: Thermocouple locations.

The result of the thermocouple 1 located in the researcher's room near the burner indicated the temperature oscillation in the environment, reaching 500.35ºC in 588.02s. Thermocouple 2 located at the access door to the teachers' room detected the temperature increase at 90.07s of simulation. After that, the temperature was increasing, reaching 128.55ºC in 585.01 seconds of simulation. Temperature sensor 03 located at the access to the meeting room shows a temperature variation between 90º and 117ºC starting at 555 seconds. And continues to oscillate until the end of the simulation at 600 seconds.

Thermocouple 04 is located at the access door to the amphitheater. At this location, the sensor detected the oscillation between the following temperatures, 66.92ºC to 72.98ºC at 540s. The fifth temperature sensor is located at the entrance to the library, which in turn, detected the highest temperature at the location of 102.02ºC at 600 seconds of simulation.

However, in the sixth thermocouple, located in the main access of the LSHT, there was a temperature peak at 585.01 seconds, with 114ºC. In thermocouple 07, positioned in the hallway access door to the amphitheater, the highest temperature found was 26.59ºC at 583.21 seconds of simulation. Finally, thermocouple 08, located in the hallway outsidehe LSHT, had a low temperature variation, ranging from 20ºC to 21.40ºC. Figure 9 graphically illustrates the temperatures cited.

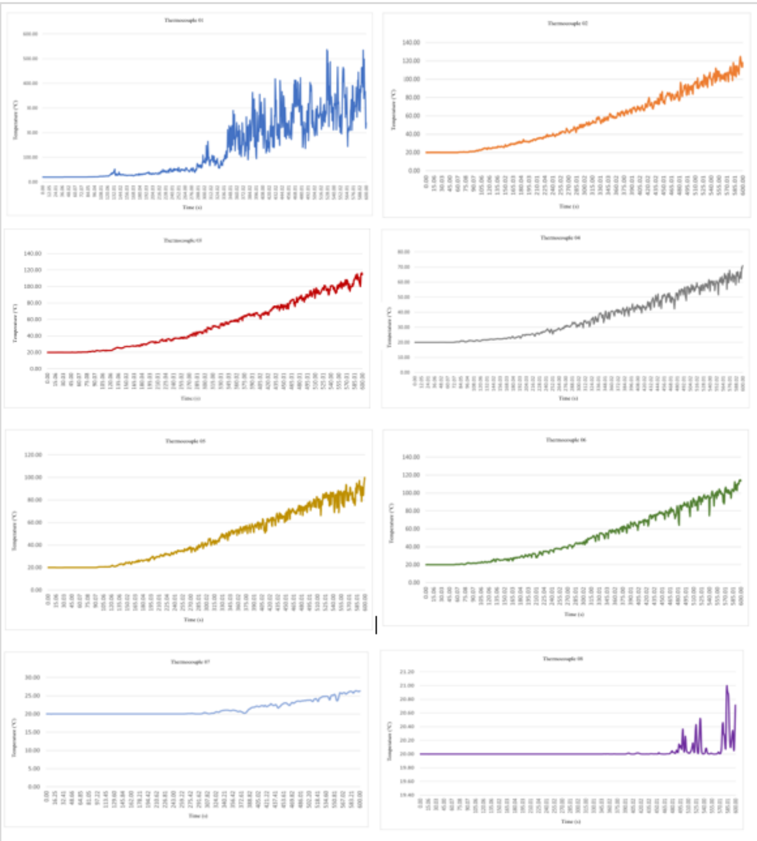

Figure 9: Thermocouples results.

According to the data and diagrams with temperature information, the environment with the highest temperature concentration is the investigators' room, where, in the simulation, the fire started.

4.2. Pathfinder simulation

At first, the 3D model worked on in PyroSim was imported and inserted into the abandonment simulation software. For this, it was assumed that the LSHT, at the time of evacuation, contained 40 occupants, this being the average number of people in normal operation, considering an adult walking speed of approximately 1.6m/s.

The diagrams show the number of occupants concerning their exit time. Thus, it becomes possible to identify that the first individual evacuated the environments in 4s of simulation, while the last occupant left in 36.5s (this information can be identified in the graph with the line in purple). Also, when reading the graph, all 40 occupants left the LSHT at 36.5s (shown with the green line).

The second graph provided by the software reflects the evacuation results, specifying the seconds in which the environment was left to the number of occupants present in the place, being then possible to identify which area has the highest abandonment potential, being the following departments: researchers' room, library, teachers' room, meeting room, amphitheater, and the access corridor. This executed relation refers to the abandonment from one environment to the other, which leads to the understanding that the last space to be evacuated is the access corridor since all occupants pass through it now of abandonment (Figure 10).

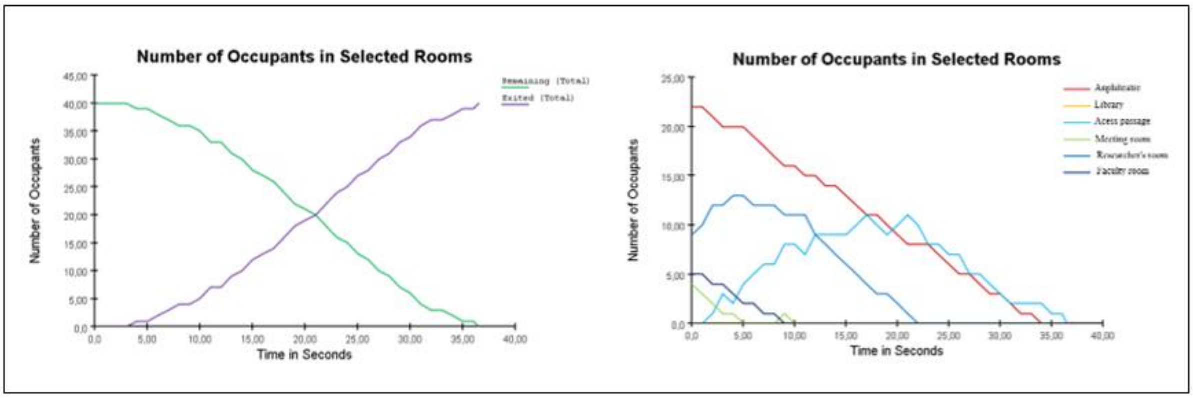

Figure 10: Number of Occupants in select rooms.

5. Conclusions

Simulations were developed by computer programs, first in the PyroSim software, and later, in Pathfinder.

Regarding the simulation of the smoke propagation, utilizing PyroSim, we have the following results:

- The environment where the fire started was taken by the smoke produced by the flame, and, during the simulation time, it was observed the temperature growth, reaching the peak of 754.64ºC in 201.31s, thus being the region most affected by the accident.

- The fire reached the growth phase, being the stage in which the fire starts the process of spreading to other environments.

- The highest heat transfer rate was emitted by radiation, reaching at its highest point 142 kW, compared to conduction and convection, which reached 70 and 80 kW, respectively.

- All environments of the LSHT were dominated by smoke within 480.08 seconds.

Regarding the results exposed in the abandonment simulation, using the Pathfinder software, we have the following results:

- The first environment to be evacuated was the amphitheater, with the

exit of the first individual in 4.0 seconds of evacuation, and according to the PyroSim results, it is identified that it is the region with the lowest temperature, so it can be considered as the environment with the highest abandonment potential.

- The total abandonment of occupants occurred in 36.5 seconds. Regarding the PyroSim simulation, in 36.5 seconds, the smoke starts the dissipation process in the researchers' room, expanding to the other environments. The temperature in the first environment mentioned within this simulation time has not changed significantly, being 20.05 ºC.

- Because of the above, it is noted that the temperatures reached at the end of the evacuation simulation in LSHT (36.5s) do not reach levels that could compromise the survival of teachers and students.

Finally, it is known that two types of techniques can be applied with the purpose of establishing the measures for protection and firefighting, the first is the project using the prescriptive mode (based on the laws, standards, and codes) and the second is the method based on performance (this, besides being based according to the parameters of the norms, aims to test how the building would behave in a possible case of fire). To this end, technological means can be used with the use of computer programs, which was the case in this study. Thus, the results show the relevance of simulation studies. The software allows us to verify the performance of buildings in case of accidents, and, based on the acquired data, to recommend the ideal methods for signaling exits, dimensioning corridors, stairs, accesses, and fire extinguishing systems.

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