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Understanding Thermal Comfort Impact and Air Movement Around Open Stairs Through the Use of CFD Modeling

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Understanding Thermal Comfort Impact and Air Movement Around Open Stairs Through the Use of CFD Modeling

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Abstract

The air exchange between two floors of a building has an impact on thermal comfort. The present research attempts to quantify this impact and identify the contributing factors disrupting the thermal comfort on and around stairs. Various heating and cooling scenarios were analyzed, using CFD modeling, in a simple two-story building separated by a single staircase. The research examines a single building layout with a fixed inlet and outlet configuration. In addition, the study investigated the short-term impact on thermal comfort. As a result, the duration of the simulations varies from two and half minutes to ten minutes, consistent with the typical cycling of unitary air-conditioning equipment. The main parameters of interest were the air temperature, air velocity, and the thermal comfort parameter Predicted Mean Vote (PMV). In both cooling and heating scenarios, the influence of the upper room and staircase had a negative impact on both the thermal comfort and energy usage in the building. The largest impact was seen during the heating scenario simulations. During the ten-minute heating simulations, the main area of the building saw a 2.12-2.79 °C drop in air temperature, along with PMV values of below -1.7.

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1. INTRODUCTION

Stairs are a common and important part of buildings, especially concerning the exchange of air. The ability to effectively heat or cool a zone in a building is the goal for HVAC systems. The heating and cooling loads in a zone play a huge part in the design of the HVAC system. Common load considerations are people, outdoor climate, equipment, lighting, and infiltration/exfiltration. However, the exchange of air between two floors in a building, or two zones, is not commonly considered. The exchange rate between zones is of course considered, but it is difficult to know how much effect this exchange has on system effectiveness, cost, and thermal comfort. The air exchange between stories, or floors, of a building has been a topic of interest for past research, specifically the spread of smoke through a stairwell [1,2,3,4]. However, to the author's knowledge, no research has been conducted to specifically identify the impact of an open staircase on the thermal comfort of occupants in a building. So, the quantity of air, air temperature, and rate of air exchange are characteristics under investigation. If the exchange of air can be quantified given certain known information, such as temperature difference, the impact of this air exchange on the thermal loads in a zone can be quantified. Once the impact is known, and if the impact is significant, certain changes in the zone could be made to benefit the cost, HVAC system load, and occupant thermal comfort. Ultimately, the goal is to add knowledge to the field of HVAC to improve the thermal comfort of people in the building. Through the use of computational fluid dynamics (CFD) simulations, the research purpose, described in this thesis, was to investigate the impact of air exchange between flows connected by a stairwell, specifically, the impact on the thermal comfort in the building.

2. BACKGROUND

Buoyancy-driven air exchange between two floors through a stairwell has been researched as described in detail below. However, a study has not been conducted that focuses on the impact of these stairways/stairwells on thermal comfort. Since the 1970s, the basis of thermal comfort has depended on Predicted Mean Vote (PMV) [5]. PMV has a scale from negative three to three, where zero is the target value. As shown in Table 1 below, the negative values indicate the area is too cold, and the positive values above zero indicate the area is too warm. The ISO standard concerned with the indoor environment is BS EN ISO 7730 and ASHRAE 55. These standards essentially provide means to calculate PMV and PPD (Predicted Percent Dissatisfied) indices [5]. The PPD ranges from 5% to 100%, where a value of under 10% is ideal. The main goal of these two indices is to quantify with a single value the predicted thermal comfort in a building.

Table 1. Predicted Mean Vote (PMV) values and the corresponding sensation by the occupant.

Value	Sensation
-3	Cold
-2	Cool
-1	Slightly Cool
0	Neutral
1	Slightly Warm
2	Warm
3	Hot

Six primary factors determine the thermal comfort parameters:

1. Metabolic Rate (Activity Level)
2. Clothing Insulation
3. Air Temperature
4. Radiant Temperature

5. Air Speed
6. Humidity

Table 2 below shows the various categories identifying the comfort level in the building. The lower category 1 is in the most ideal setting, whereas category four is edging on becoming uncomfortable. The PPD that correlates to the acceptable limits of PMV from category one to three is 6%, 10%, and 20%. The optimum indoor temperature, according to ASHRAE is between 23.89 to 25 °C [5]. In addition, ASHRAE standard 55 has a PMV suggested limit of -0.5 to 0.5 [6]. In addition, no occupied point should have a PPD value of over 20%. Although it is very difficult to please every person in a building, the main goal of thermal comfort parameters is to mitigate thermal discomfort in a building.

Table 2. Suggested applicability of categories and their corresponding temperature and PMV range [1].

Category	Explanation	Suggested Acceptable Range (K)	Suggested Acceptable Limits (PMV)
1	High level of expectation only used for spaces occupied by sensitive and fragile persons	± 2	± 0.2
2	Normal Expectation for new buildings and renovations	± 3	± 0.5
3	A moderate expectation used for existing buildings	± 4	± 0.7
4	Values outside the criteria above	> 4	> 0.7

The earliest journal article published concerning the flow of air through a stairwell the author could find was published in 1986 by Reynolds [7]. The paper attempts to develop a simple analytical model for the flow processes within stairwells and suggests the formula structure that should be introduced into a computer model to realistically capture the flows of mass and energy between the several floors of a building. Reynolds showed that it is possible to relate the results of a smaller, scaled model to the full-scale model and concluded that for the simplest case of flow in a stairwell, the main aspects of the flow are determined by the relationships between the Grashof number, Froude number, Reynolds number, and the ratio of energy flux [7].

Another early publisher on this topic was Riffat, with his paper on heat and mass transfer between two floors of a house [8]. Riffat was not concerned with the air flow through a stairwell, but rather the air exchange within a building through a doorway connecting an upper and lower floor. Riffat concluded that the mass flow rate and coefficient of discharge for the doorway were functions of the temperature difference between the upper and lower floors of the house. The mass flow rate between the two floors was found to increase significantly with increasing temperature difference in the house [8]. The mass flow rate between the two floors was found to increase significantly with increasing temperature differences [8]. Additional work that followed closely behind was a study of the natural convection through a stairwell by Ergin [9]. The paper describes an experiment using a lower and upper room connected by a stairwell to identify the effect of outlet size on air exchange. Changes in the outlet size were shown to have significant impacts on the buoyancy-driven flow through the stairwell. However, the overall flow patterns remained the same. Increasing the outlet size resulted in the reduction of the average temperature in the stairwell and the flow temperatures through the stairwell [9].

The first paper published incorporating computational fluid dynamics (CFD) on this topic was done in 1989 by Peppes [10]. The paper covers the measurement and CFD modeling of buoyancy-driven air flow through a residential building stairwell. This study used the RNG k-epsilon turbulence model in the CFD simulations due to the model's ability to be valid for a very-wide range of flow types including both high and low Reynolds numbers [10]. Using the two opening sizes in the experiment, the coefficient of discharge appeared to only be dependent on the average temperature difference between the two floors, not the opening size. Like Riffat above, the coefficient of discharge was found to decrease as the temperature difference increased. Peppes, along with Riffat, attributes this relationship to the interfacial mixing between the warm and cool air [10]. The volumetric, heat, and mass flow rates through the opening did appear to be a function of both the average temperature difference and the opening size [10].

The work most closely related to the present work was done by Dehghan in 2011 [11]. The paper presents a numerical study of buoyancy-driven flow in an experimental half-scale model of a two-floor building. The model consists of an upper and lower zone with a stairway connecting the two floors, with no inlet or outlet, forming a closed system. The flow was driven by a single heat source placed on the lower floor [11]. The CFD modeling incorporated k-epsilon and LES models to find which agreed more with experimental results. Dehghan concluded that results obtained using LES were more realistic, but the results obtained using the k–epsilon model still produced the main overall features and predicted the correct order of magnitudes [7].

There have been a few papers published that study the thermal comfort within a building. Most of the papers the author came across were attempting to maximize the energy savings in a building while maintaining thermal comfort[8,9,10]. A study conducted by Hirose in 2021 researched occupants' thermal sensations in a cross-ventilated building model using large-eddy simulations [15]. The study attempted to generate natural ventilation design guidelines for buildings while tracking the PMV and PPD of occupants [15]. Hirose found that an ideal ventilation design usually is not an ideal building design for heat mitigation and thermal comfort [15].

Another study surrounding thermal comfort was done by Humphreys in 2002 [12]. The paper explored the discrepancy between the PMV measurement and the actual vote of the occupants; then, the paper explores the effect of climate and the scope for improving PMV [16]. Humphreys concluded that the direction of the overall bias in PMV overestimates the mean subjective warmth of occupants in warm environments, which can lead to unnecessary cooling and energy use [16].

3. METHODOLOGY

To begin the CFD simulations, with very simple layouts, a simplistic two-story building layout was created using the program SolidWorks [17]. Afterward, the design was imported into the cloud based CFD software SimScale, to perform CFD simulations. SimScale is cloud-based computer software that allows computational fluid dynamics, finite element analysis, and thermal simulations [18]. Within the SimScale platform, the program has the option to simulate HVAC-specific scenarios using the programs' CFD solver [18]. The SimScale building layout is shown below in Figures 1 and 2. The building consisted of a small upper room in the top left corner of the building, connected to the lower main area by a single staircase. The doorway had dimensions of 3.048 meters tall and 0.838 meters wide. The staircase had the standard dimensions of 0.914 meters wide, 0.253 meters deep, and 0.17 meters steep. The upper room dimensions were 4.26 meters by 3.66 meters by 3.048 meters, with no obstacles in the room. Similarly, the main area had dimensions of 7.01 meters by 9.14 meters by 6.10 meters without any obstacles or any chances for disruptions of flow.

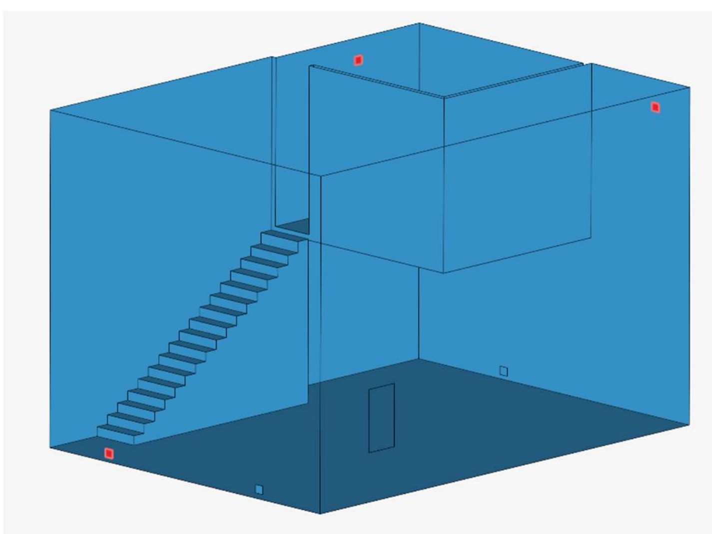

Figure 1. The simplistic building layout is shown without the roof and two exterior walls, with the inlets, highlighted in red.

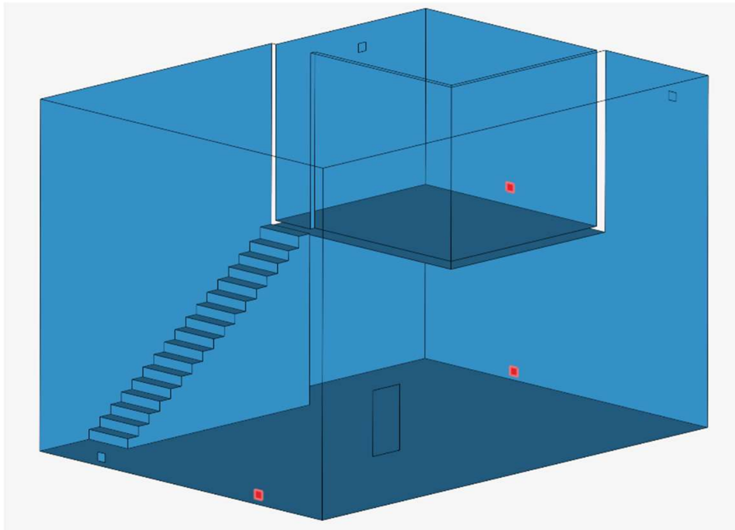

Figure 2. The room walls are faded to allow the viewer a point of view of the upper room, with the outlets highlighted in red.

The upper room had a single inlet and outlet, both sized 0.13 meters by 0.15 meters. The inlet was placed in the top-center of the left wall, as shown in Figure 1. The inlet had a constant volumetric flow rate of 0.5 cubic meters per second. For a heating scenario, the inlet air was 32.2 °C, and for a cooling scenario, the inlet air was 12.8 °C. The room air outlet was placed near the bottom of the center-back wall, as shown in Figure 2. The main area began with a single inlet and outlet of the same dimensions, inlet flow rate, and inlet temperatures. The inlet was placed on the wall facing the staircase bottom, 0.08 meters to the right from the staircase, shown in Figure 1. The outlet was on the opposite wall of the inlet, under the upper room, and off-center to the left, shown in Figure 2. This outlet placement was selected due to suspected stagnant air in this area. The exterior walls of the house were an external wall heat flux boundary condition, with derived heat flux. The exterior walls had a U-value of 0.25 $W/m^2.K$, with an outdoor temperature of 4.44 °C for heating scenarios, and an outdoor temp of 37.8 °C for cooling. The ceiling had the same boundary condition type as the main walls, with a higher U-value of 0.4

W/m^2.K, with all other surfaces in the building set to a simple wall with no-slip boundary condition.

Multiple k-omega shear stress transport (SST) simulations were conducted to ensure a proper setup of the model, convergence, and interpretation of the results. The simulation was considered to reach convergence if the residuals were lower than 1E-3 and the other convergence plots flat-lined. The simulations used a fine mesh with a mesh cell count of 2.3 million cells and 1.2 million nodes. After combing through the various simulation results, it was obvious the inlet flow rates required correcting due to the indoor temperature not reaching the target temperature of 21.1 °C in cooling and 20 °C in heating. The flow rate in the upper room seemed too high in both heating and cooling scenarios, as the room was too warm in heating and too cold in cooling. A similar issue was seen with the inlet in the lower area, except the inlet required an increase in flow rate, since the temperatures were too cold in heating scenarios and too warm in cooling scenarios.

3.1 Heat Transfer Calculations

To ensure the target indoor temperatures were met, a few calculations were made to find the required inlet flow rates. First, the heat transfer through the walls and ceiling was calculated using the assumed U-values, wall areas, and temperature difference with the outdoor temperature. The equation used to find the heat transfer through the walls and ceiling is shown below in Eq 1. Using "Principles of HVAC 8th Ed", the equation shown by Eq 2., was used to calculate the sensible heat gain of the inlet air [19]:

$$q = U * A * \Delta T \qquad \text{(Eq. 1)}$$

$$q = 1.23 * \dot{V} * \Delta T \qquad \text{(Eq. 2)}$$

where

U = U-Value of wall in $W/m^2 * K$

A = wall area in square meters

$\dot{V}$ = volumetric flow rate in liters per second

ΔT = temperature difference in Kelvin

Below are tables displaying the areas, U-values, and calculated heat transfer through the walls and ceilings. The heat transfer in the room and main area were calculated separately to find the required inlet flow rates for each area.

Table 3. The calculated heat transfer through the building with the used areas and U-values.

Boundary	Scenario	U-Value ($W/m^2 * K$)	Area (m^2)	Heat Transfer (W)
Room Walls	Heating	0.4	24.16	-146.43
-	Cooling	-	-	161.80
Room Ceiling	Heating	0.25	15.61	-59.14
-	Cooling	-	-	65.34
Main Area Walls	Heating	0.4	170.26	-1031.78
-	Cooling	-	-	1140.06
Main Area Ceiling	Heating	0.25	50.65	-191.84
-	Cooling	-	-	211.97

The overall heat transfer through the room in the cooling and heating scenarios are, respectfully, 227 Watts and -206 Watts. The overall heat transfer through the main area for cooling and heating is 1352 Watts and -1224 Watts. The negative values indicate the heat leaving the building in heating scenarios, and the positive values indicate heat entering the building in a cooling scenario. These values were used to find the inlet flow rates for the room and main area separately. Below in Table 4, the calculated inlet flow rates are displayed.

Table 4. The calculated inlet volumetric flow rates for the inlets in each scenario.

Domain	Scenario	Inlet Flow Rate (m^3/s)
Room	Cooling	0.022
-	Heating	0.014
Main Area	Cooling	0.13
-	Heating	0.084

To reaffirm the calculated heat gain and loss, shown in Table 4 above, a model in Revit was created, shown in Figure 3. The model had the exact dimensions and properties as the Solidworks model. Utilizing Revit's HVAC analysis feature, the model's cooling and heating loads were calculated for four different locations [20]:

- Bentonville, Arkansas
- Orlando, Florida
- Las Vegas, Nevada
- Grand Rapid, Michigan

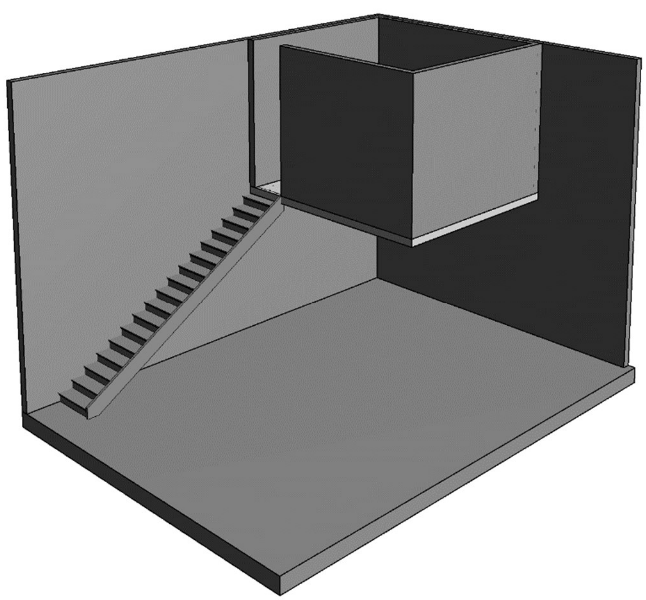

Figure 3. The building model created in Autodesk Revit used to calculate heating and cooling loads.

Each of the values calculated were similar to the previously calculated values, which provided reassurance on the accuracy of the calculated heating and cooling loads. The Revit calculated values are shown below in Tables 5 and 6.

Table 5. Calculated cooling loads for the building in four different cities using Autodesk Revit.

Destination	Upper Room Walls (W)	Upper Room Roof (W)	Main Area Walls (W)	Main Area Roof (W)
Bentonville, AR	187	40	2,007	95
Orlando, FL	162	41	1,623	91
Las Vegas, NV	227	57	2,121	137
Grand Rapids, MI	155	28	75	1,598

Table 6. Calculated heating loads for the building in four different cities using Autodesk Revit.

Destination	Upper Room Walls (W)	Upper Room Roof (W)	Main Area Walls (W)	Main Area Roof (W)
Bentonville, AR	-334	-112	-2,421	-286
Orlando, FL	-177	-63	-1,285	-161
Las Vegas, NV	-78	-218	-1,583	-199
Grand Rapids, MI	-372	-122	-2,699	-313

3.2 Refining the Model

After calculating the required inlet flow rates, the model required changes to the inlets and outlets in the main area. The refined model had the inlet size increased from 0.13 meters by 0.15 meters to 0.15 meters by 0.18 meters to allow for the increased flow rate without dramatically increasing the throw. In addition, there was another inlet and outlet added in the main area to allow for the increased inlet air demand. The second inlet was placed in the top, back-right, corner of the building, 5.49 meters high. This position was chosen to excite air movement in the top region of the building and prevent air stagnation. The second outlet was placed on the same wall as the original inlet, 1.8 meters over to the right. After the additions to the model, the room still had a single inlet and outlet. The main area now contained two inlets and two outlets, with an inlet and outlet on each of the front and back walls.

To verify the effectiveness of the new building layout, more simulations were conducted with a finer mesh quality. The new mesh contains 2.8 million mesh cells and 1.5 million nodes. Within the boundary conditions, a heat transfer coefficient was added to the exterior walls. In a heating scenario, the heat transfer coefficient had a value of 34 $W/m^2.K$. In a cooling scenario, the heat transfer coefficient had a value of 22.7 $W/m^2.K$. The simulations ran until the residuals were under 1E-3 and the other normalized convergence plots steadied to a flat line. The cooling scenario had a steady-state temperature of 21.4 °C, and the heating scenario had a steady-state temperature of around 20.6 °C. Although the steady-state temperature of the building in the heating scenario was over the target temperature, the result was deemed acceptable.

3.3 Transient Simulations

Now that the building layout and simulation set-up achieved the target steady-state conditions, the focus moved towards the thermal comfort parameters, and how they change when the inlets cycle off. Specifically, how the air exchange between the room and main area, through the doorway and down the stairs, affects thermal comfort. The simulation set-up moves from a steady-state to a transient k-omega SST simulation to account for the inlets cycling off after a certain amount of time. The simulation setup started with the entire building flow region set to a temperature of 20.6 °C in heating and 21.4 °C in cooling. The initial flow region temperatures were chosen to simulate the last seconds of the inlets being on and reaching the desired set-point temperature. The wall boundary conditions were kept the same as the steady-state simulations explained above. The inlet boundary conditions were made to cycle off after a certain amount of time, to simulate the AC system reaching the set-point temperature.

Next, the simulations ran for 100 seconds and 250 seconds, with the inlets cycling off after 25 seconds, for both heating and cooling scenarios. In addition, a 100-second simulation, for both heating and cooling scenarios, ran with the main inlets cycling off after 25 seconds and the room inlet staying on. Plus, a 100-second simulation ran with the room inlet cycling off after 25 seconds and the main inlets staying on. Due to the nature of the transient simulation set-up, the inlet flow rates were increased to ensure convergence, and at the same time, not allow the Courant number to reach a value larger than one. The room inlet flow rate was increased to 0.025 cubic meters per second for both heating and cooling in the room. The inlet flow rate for the main inlets was changed to 0.066 cubic meters per second for both scenarios. Although in some cases the flow rates are higher than what is required, the effect on the temperature and thermal comfort is assumed to be minimal due to the short time the inlet is cycled on.

Furthermore, various scenarios were simulated for when both the inlets are cycled off. The upper room had a starting temperature of 24 °C and the main area had a starting temperature of 20 °C in both heating and cooling conditions. Next, the upper room had an initial temperature of 20 °C and the main area had a temperature of 24 °C in both heating and cooling conditions. Then, with all the inlets cycled off after one second, the main area had an initial temperature of 24.5 °C, with the room having initial temperatures of 26 °C and 30 °C. The conditions were set to a cooling scenario to simulate a less-used upper room of a building having a set-point temperature higher than the main area to save energy. Tables 6 and 7 below show all the simulations taken into consideration throughout this paper. The simulations are separated into cooling and heating scenarios, with the inlet cycling, simulation length, and temperature difference shown.

The simulations considering the thermal comfort parameters varied slightly from the above-described simulations. The simulations of 150 seconds, 360 seconds, 400 seconds, and 600 seconds had an initial temperature of 24.4 °C in the main area. This change was made to be consistent with the ASHRAE 55 standard of ideal indoor design temperature of 24.4 °C [6]. This change helped display the appropriate thermal comfort parameter values, specifically the PMV.

Table 7. The included SimScale heating simulations with the various scenario descriptions.

Heating Simulations			
Simulation Length	**Temperature Difference**	**Room Inlet**	**Main Inlets**
100 seconds	N/A	Cycled off after 25 seconds	Cycled off after 25 seconds
100 seconds	N/A	Cycled on	Cycled off after 25 seconds
100 seconds	N/A	Cycled off after 25 seconds	Cycled on
150 seconds	N/A	Cycled off	Cycled off
150 seconds	2 °C	Cycled off	Cycled off
150 seconds	5.5 °C	Cycled off	Cycled off
250 seconds	N/A	Cycled off after 25 seconds	Cycled off after 25 seconds
250 seconds	4 °C	Cycled off	Cycled off
360 seconds	N/A	Cycled off	Cycled off
360 seconds	2 °C	Cycled off	Cycled off
360 seconds	5.5 °C	Cycled off	Cycled off
400 seconds	N/A	Cycled off	Cycled off
600 seconds	N/A	Cycled off	Cycled off
600 seconds	2 °C	Cycled off	Cycled off
600 seconds	5.5 °C	Cycled off	Cycled off

Table 8. The included SimScale cooling simulations with the various scenario descriptions.

Cooling Simulations			
Simulation Length	**Temperature Difference**	**Room Inlet**	**Main Inlets**
100 seconds	N/A	Cycled off after 25 seconds	Cycled off after 25 seconds
100 seconds	N/A	Cycled on	Cycled off after 25 seconds
100 seconds	N/A	Cycled off after 25 seconds	Cycled on
150 seconds	N/A	Cycled off	Cycled off
150 seconds	2 °C	Cycled off	Cycled off
150 seconds	5.5 °C	Cycled off	Cycled off
250 seconds	N/A	Cycled off after 25 seconds	Cycled off after 25 seconds
250 seconds	4 °C	Cycled Off	Cycled Off
360 seconds	N/A	Cycled off	Cycled off
360 seconds	2 °C	Cycled off	Cycled off
360 seconds	5.5 °C	Cycled off	Cycled off
400 seconds	N/A	Cycled off	Cycled off
600 seconds	N/A	Cycled off	Cycled off
600 seconds	2 °C	Cycled off	Cycled off
600 seconds	5.5 °C	Cycled off	Cycled off

4. RESULTS AND DISCUSSION

4.1 Air Movement in Cooling Scenarios

As a part of the analysis of the completed simulations, the air movement in the cooling scenarios was tracked to understand the cause of the disruption in thermal comfort. In the below section, the air movement in each cooling scenario is described along with the driving forces, and causes, of the air movement.

4.1.1 Inlets Cycled Off

The first cooling scenario analyzed was the situation when all inlets cycled off with the entire flow region at the same temperature. Again, in a cooling scenario simulation, the entire flow region (inside of the building) begins at 24.4 °C. The outside temperature is set to 37.8 °C, with the heat flux coming into the building. The inlets are shut off, as they would be when the building reaches the set-point temperature. The heat begins to enter the building through the main walls, ceiling, and two of the room walls. As the heat enters the building, the air near a wall absorbs the energy and heats up. When the air rises in temperature, the density of the air decreases and is lower than the density of the surrounding air. As a result, the air begins to rise near the walls towards the ceiling. Since the air is close to the walls, the air continues to absorb energy, which allows the air to maintain the lower density and continue to rise. Because the building can't have any spaces void of air, the air towards the middle-upper portion of the flow region falls towards the floor to replace the air rising towards the ceiling. In addition, when the air rising towards the ceiling begins to cool, because of less heat flux occurring at the ceiling due to the lower U-value, the decrease in density allows the rising air near the walls to force the cooler air away from the ceiling. This allows circulation to begin, buoyancy-driven flow, due to the density differences in the air and the dispersion of the air filling void areas in the flow region.

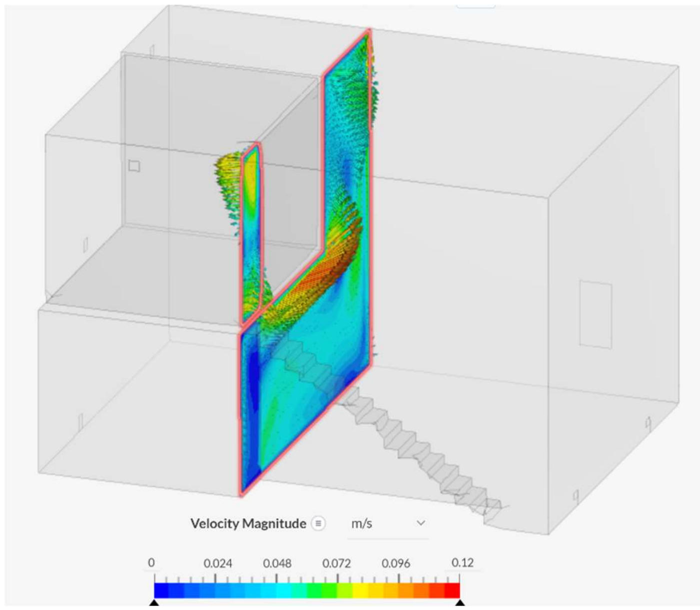

Figure 4. The air exchange through the doorway at 150 seconds is shown.

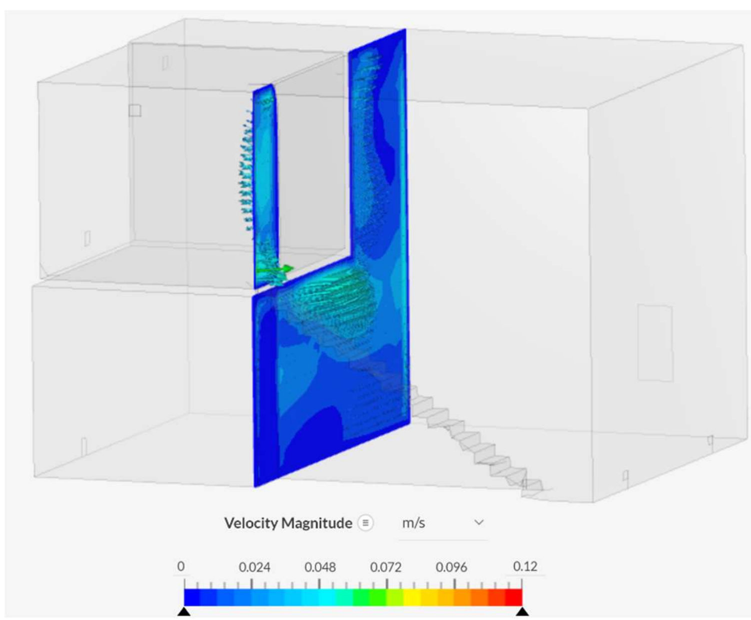

Figure 5. The air exchange through the doorway at 600 seconds is shown.

The rising air near the room opening, that does not recirculate down towards the floor, will flow over the ceiling and into the room since the room is near the top of the building. Air flows into the room through the upper opening of the doorway. Since the upper room has a larger portion of its total area to allow a heat-flux to occur, along with warm air entering through the doorway, the air in the room will be at a higher temperature than air at the main level. Similar to the natural circulation occurring near the walls in the main area, the room will have rising and falling air within the space. The air near the exterior walls, within the room, will absorb energy, producing a decrease in density, causing the air to flow upwards the ceiling. The highest velocities of the rising air occur in the corners of the building due to a relative increase in available area to transfer heat.

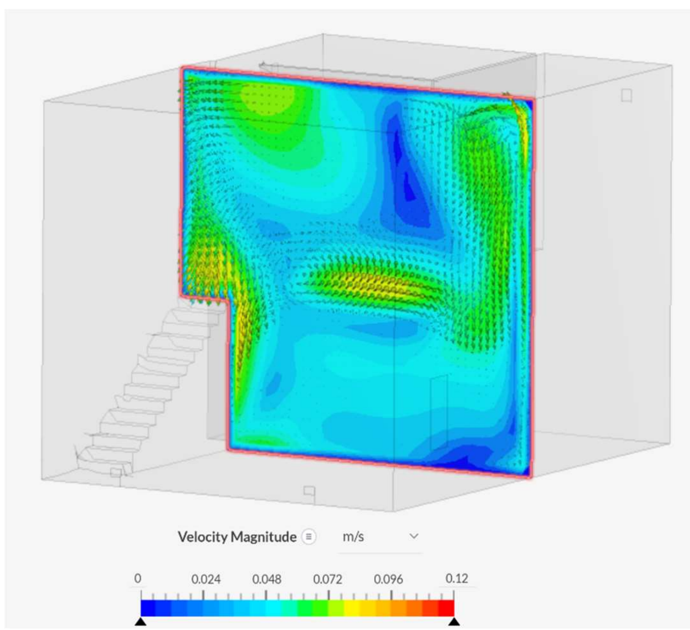

Figure 6. The airflow down and over the stairs is shown at 150-seconds.

To prevent a higher pressure localized in the room, cooler air must leave through the bottom of the doorway, as shown in Figures 4 and 5. The air near the middle of the room will be forced out of the space by the incoming warm air. Noticing the same scale of values for the flow velocity in Figures 4 and 5, the longer simulation has lower flow velocity. This was a trend noticed through the increased simulation lengths. As the air leaves the room, the air falls down the stairway towards the main area. Displayed in Figures 6 and 7, a portion of the falling air dumps over the side of the staircase as the air continues to flow. The dumped air causes the area near the staircase to have a small current of air and a slightly different temperature than the middle of the main area. As noticed in the figure below, the rate of air flow over the stairs slows as the simulations length increases, which was noticed through the increased simulation lengths.

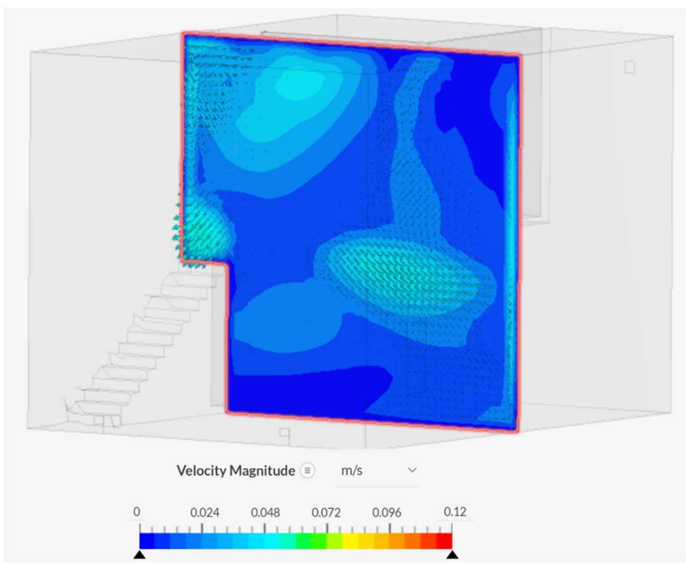

Figure 7. The airflow down and over the stairs is shown at 600 seconds.

4.1.2 Inlets Cycled Off with Warmer Upper Room

In this scenario, all the inlets in the building are cycled off, with the upper room either 2 or 5.5 °C warmer than the main area. This is to simulate either the upper room having a higher set-point temperature or the upper room having the cooling shut off completely. These situations may arise with an upper room that is used infrequently, so there is no need to keep it at a low and comfortable temperature. In all three scenarios, the main area has a temperature of 24.4 °C. The upper room has temperatures of 26.1 and 30 °C. The temperature difference can occur when the upper room is completely shut off from the other areas of the house and left alone to gather heat through the walls. The simulation looks at the case when the door separating the upper room and staircase is suddenly opened after these temperature variations take place.

The only source of additional heat added to the system is through the walls of the building. Therefore, the room has additional heat coming in due to the outdoor temperature of 37.8 °C. The main area has additional heat coming from both the upper room and through the walls. Many of the mechanisms discussed in previous scenarios still take place. The movement of warm air rising near the walls, with cooler air falling to fill the voids, still takes place everywhere in the building. The warm air from the room leaves through the upper region of the doorway, with the cooler air from the main area entering the room.

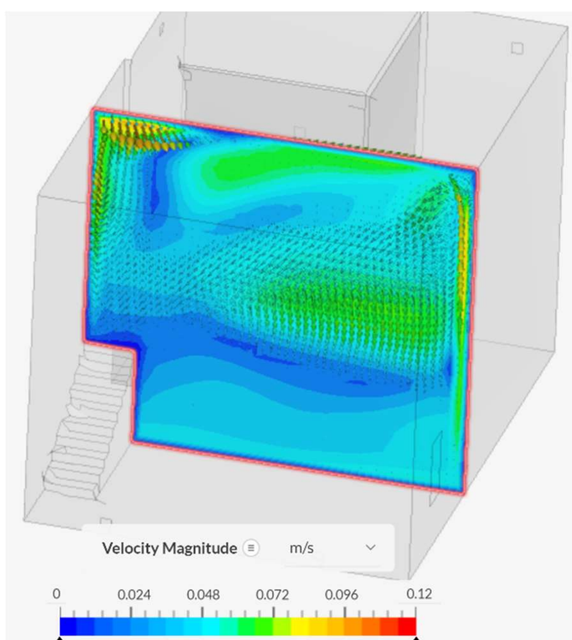

Figure 8. Warm air leaves the upper room and spreading across the ceiling at 150 seconds with the upper room starting at 2 °C warmer.

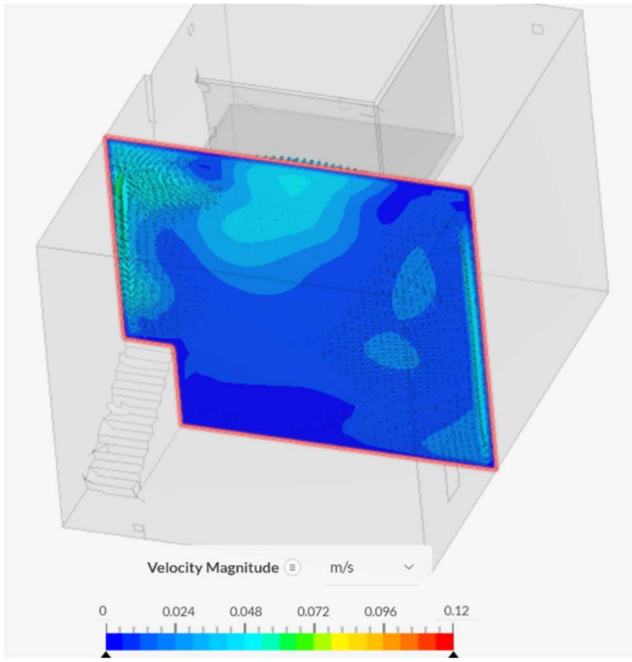

Figure 9. Warm air leaves the upper room and spreading across the ceiling at 600 seconds with the upper room starting at 2 °C warmer.

The highest air speed occurs through the door, with both the air coming into the room and leaving. The warm air leaving the upper room stays near the ceiling while flowing out away from the doorway and towards the opposite wall, as shown in Figures 8 and 9. Then, the air begins to spread and cover the ceiling while moving towards the opposite corner of the building. The air coming into the room originates from the upper-middle region of the main area near the outer wall of the room. The fluid flows over the wall and turns the corner to go inside of the room. Since the air is entering a smaller region, the fluid picks up speed while entering the room. As shown in Figures 10 and 11, the air entering the room fills more area in the doorway than the air leaving the room; therefore, the air entering the room flows at a slightly lower speed.

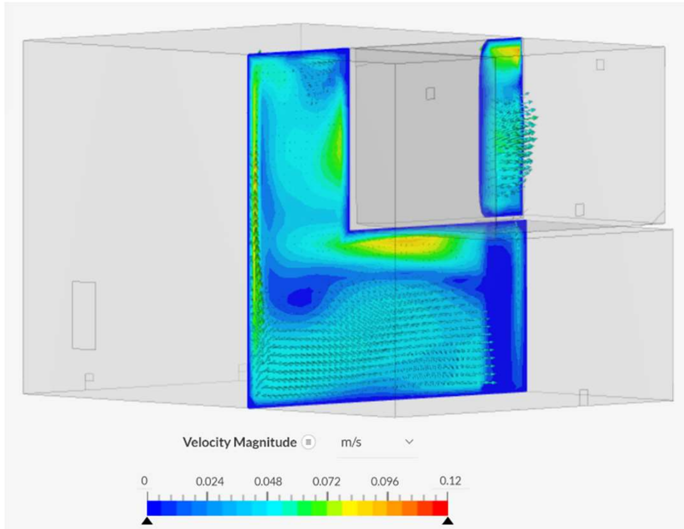

Figure 10. The air exchange through the doorway, from a rear view, is shown at 150 seconds with the upper room 2 °C warmer.

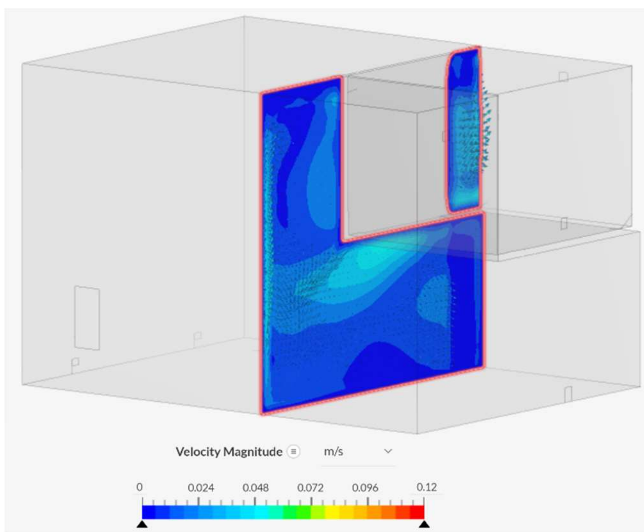

Figure 11. The air exchange through the doorway, from a rear view, is shown at 600 seconds with the upper room 2 °C warmer.

Since the air leaving the room is less dense than the air in the main area, the warm air leaving the room displaces the denser fluid down and away from the ceiling, along with mixing with cooler air. In addition, due to the air leaving the room forcing itself towards the diagonally opposite corner of the building, the fluid that filled the opposite corner makes its way towards the back wall of the building. As a result, most of the horizontal air flow takes place in the upper region of the building, specifically around the upper two meters of the building. The denser fluid moving away from the ceiling has a domino effect and pushes air down to the floor. This effect causes warmer air to flow into the occupied space of the main area, which causes the entire living space to become warmer. However, the space near the stairs becomes warmer than the rest of the main area. This is due to the warm air leaving the upper room flowing into air rising near the walls. Since the air rising near the walls is relatively cool compared to the air leaving the room, the air mixes to become denser than the warm air from the room flowing behind it. This forces the relatively cool air, yet warmer than the air in the occupied area, to flow down towards the stairs. Anyone near the staircase will experience warm air flowing around them due to the mixing of fluid from the upper room with fluid in the upper region of the main area.

As the temperature difference increases from 2 °C to 5.5 °C, there are a couple of differences shown in the simulations. A very noticeable difference is the speed at which air leaves and enters the room. This difference is seen when comparing Figures 10 and 11 to Figures 12 and 13. As the temperature difference increases, the air exchange through the doorway increases, and the speed at which the exchange takes place increases. This causes a quicker exchange of fluid in the upper portion of the main area where the fluid flow near the ceiling moves at a higher speed. The increase in speed of the fluid moving along the ceiling also affects the speed at which the fluid moves towards the floor. Specifically, the mixing of air near the doorway opening over the stairs happens at a quicker speed and this, in turn, increases the flow of air near the stairs. However, as the simulation length increases, the rate of exchange through the doorway lessens due to the building moving toward a steady-state situation.

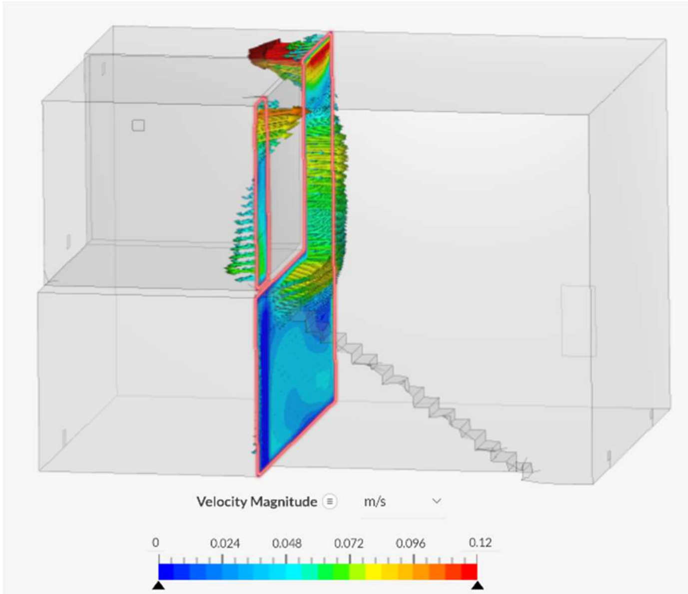

Figure 12. The air exchange through the doorway is shown at 150 seconds with the upper room 5.5 °C warmer.

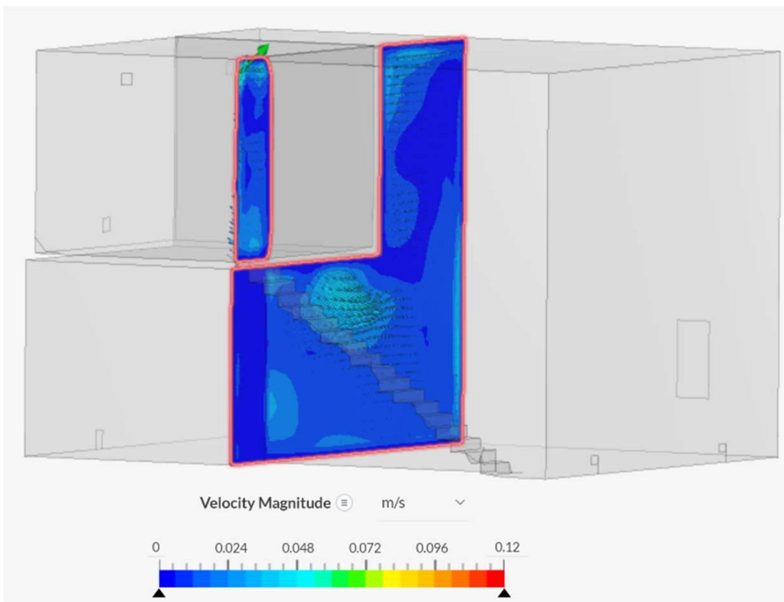

Figure 13. The air exchange through the doorway is shown at 600 seconds with the upper room 5.5 °C warmer.

The other noticeable difference is the temperature of the occupied zone in the main area. More “hot spots” appear when the temperature difference increases, specifically near the stairs. Although the temperature difference is small, there is a noticeable difference in only 150 seconds, as shown in Figures 14 and 15.

So, if the upper-room door were left open, and the AC system was turned off, the main area would get warmer due to the air exchange happening in the upper region of the building. This would force the main area to rise above the set-point temperature and cause the AC to cycle on. The increase in temperature in the main area is shown in Figures 14 to 17. The air-conditioning would then have to compensate for both the heat coming in through the walls and the heat coming from the upper room. Since the inlet flows are sized for the expected heat gain in an area, the upper room could provide an unforeseen source of heat that the AC would have to counteract. This additional heat could make the AC cycle on for longer periods with shorter cycles off, which would increase the energy usage.

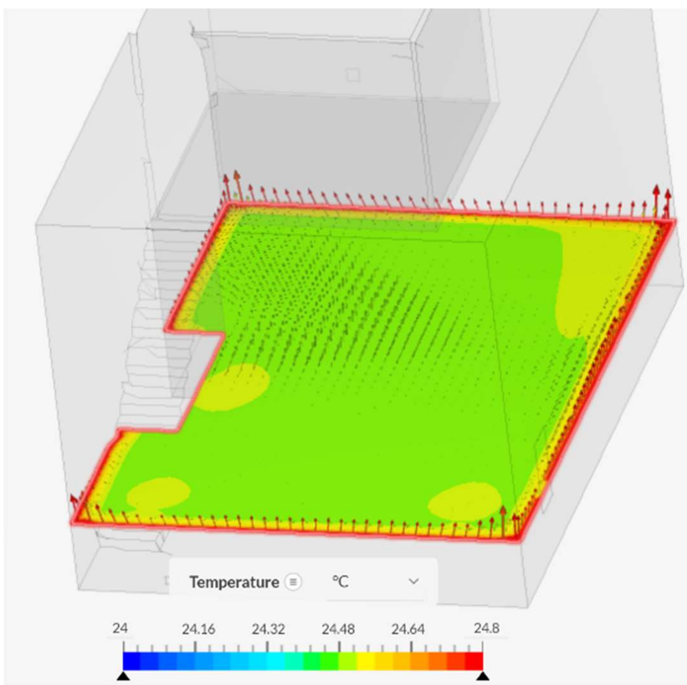

Figure 14. Air temperature 1.1 meters above the ground, at 150 seconds, with a temperature difference of 2 °C.

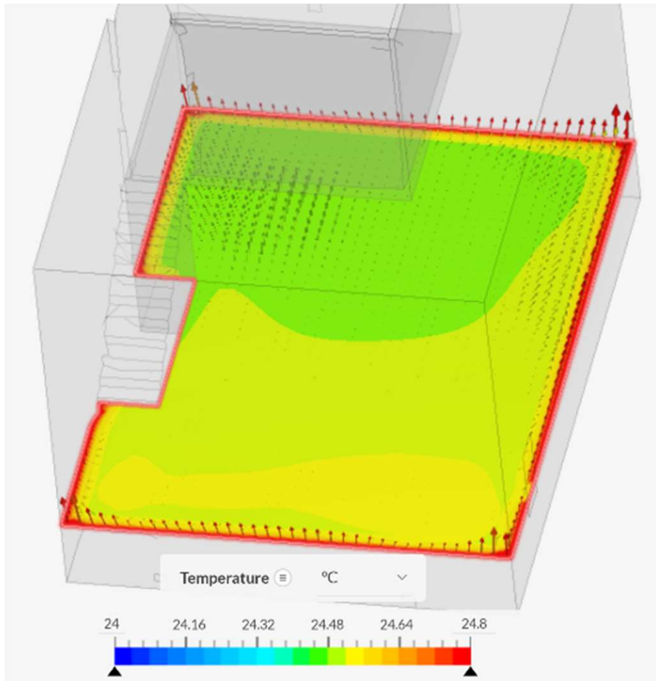

Figure 15. Air temperature 1.1 meters above the ground, at 150 seconds, with a temperature difference of 5.5 °C.

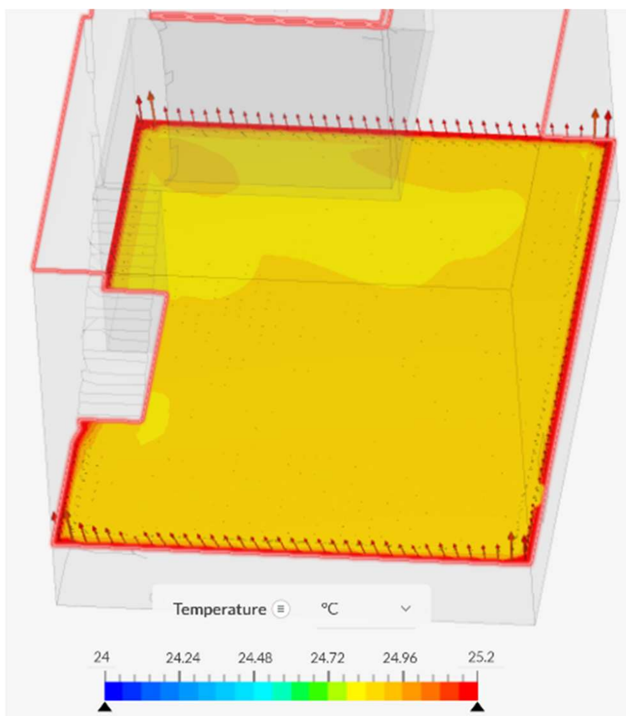

Figure 16. Air temperature 1.1 meters above the ground, at 600 seconds, with a temperature difference of 2 °C.

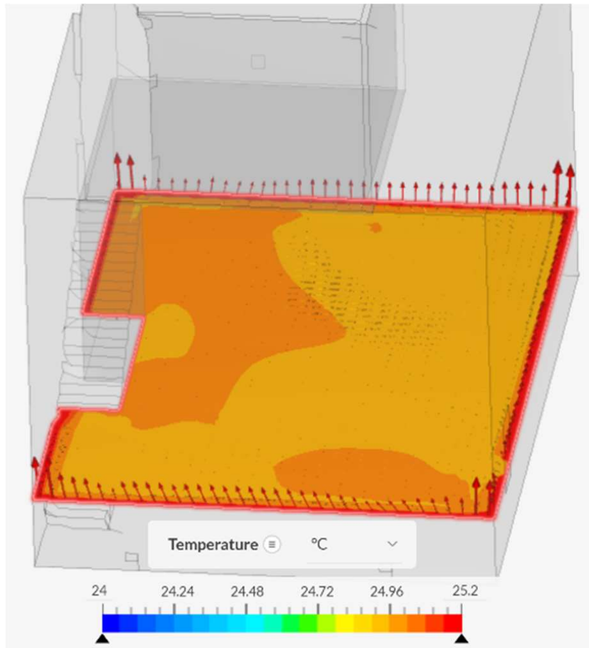

Figure 17. Air temperature 1.1 meters above the ground, at 600 seconds, with a temperature difference of 5.5 °C.

4.1.3 Main Inlets Cycled On

In this scenario, the main area has both inlets cycled on, while the upper room has the inlet cycled off. This is to simulate the upper room reaching the set-point temperature before the main area. The simulation has the upper room inlet shut off after 25 seconds, with the total simulation being 100 seconds. The initial temperature of the entire flow region was set to 24.4 °C. In the main area, the two inlets have cool air coming into the building with a rather aggressive drop. The inlet near the floor, and stairs, stays near the floor and flows over to the right side of the building. The main inlet near the ceiling, on the back wall, moves towards the left and drops towards the floor. As shown in Figure 18 below, once the inlet air reaches the floor it separates and spreads towards the walls. Since all the inlet air is cooler than the existing air in the building, the cool inlet air drops and stays in the main area. As a result, the main area can maintain a temperature of around 24.4 °C through the entirety of the simulation. In addition, the

PMV stays around zero from the start to the end of the simulation. As the air near the walls rises to the ceiling, the air flows over the ceiling and towards the center. Once the air reaches the outer room next to the stairs, the air splits and flows in two opposite directions. Part of the air flows towards the doorway entry to the upper room.

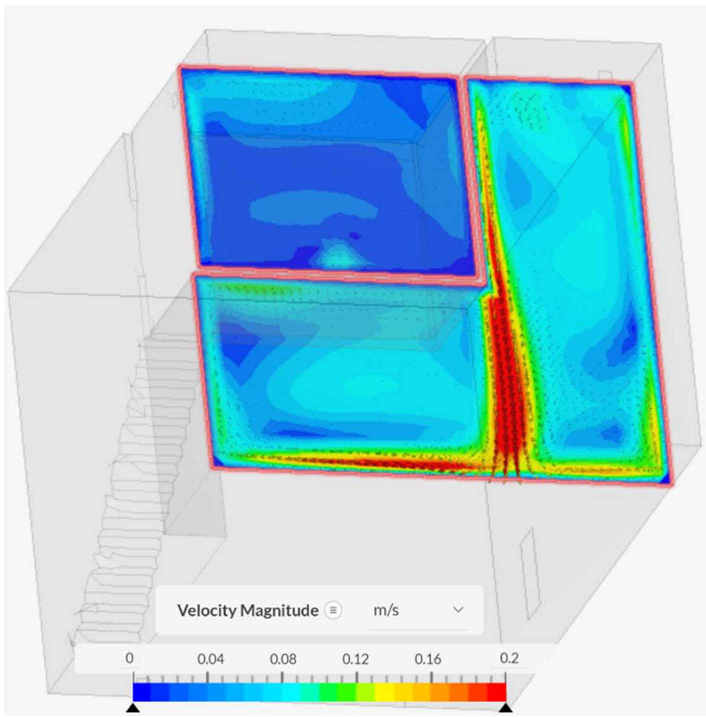

Figure 18. The air from the main inlet on the back wall comes into the building and crashes down into the main area at the 100 second mark.

As the air flows towards the doorway over the outer-room wall, it rounds the edge of the doorway to enter the upper room. The air flowing into the room is slightly warmer than the current air, as it has a temperature of around 25 °C. Once in the room, the air flows towards the ceiling and spreads to the other walls. As the warm air enters, it displaces cooler air and forces air to leave through the bottom of the doorway. The two exterior room walls cool the air in the room and create a flow down towards the floor and to the opposite walls in the room. The cool air flows around the floor of the room and leaves out the bottom of the doorway. As the cooler air is leaving, it flows down the stairs to the main area. The air leaving the room is around 24.2 °C, which is only slightly cooler than the average temperature of the main area. Figure 19 below shows the temperature in the main area 1.7 meters above the floor. The vectors show the cooler zones at that elevation are from the inlet air, judging from the flow directions. This displays that the cool air coming down from the upper room has little to no impact on the temperature of the main area in this 100-second simulation. However, the average temperature of the upper room increased by almost 0.4 °C from start to finish in the simulation. This result shows that the upper room will slowly increase in temperature from the warmer air entering through the doorway and the heat flux into the room. As a result, one could infer that the cooler air leaving the room will slowly increase in temperature with time. The air coming down the stairs will most likely be at a higher temperature than the existing air in the main area. This will cause the average temperature of the main area to slowly increase with time or at least counteract the cool inlet air, causing the inlets to be cycled on longer.

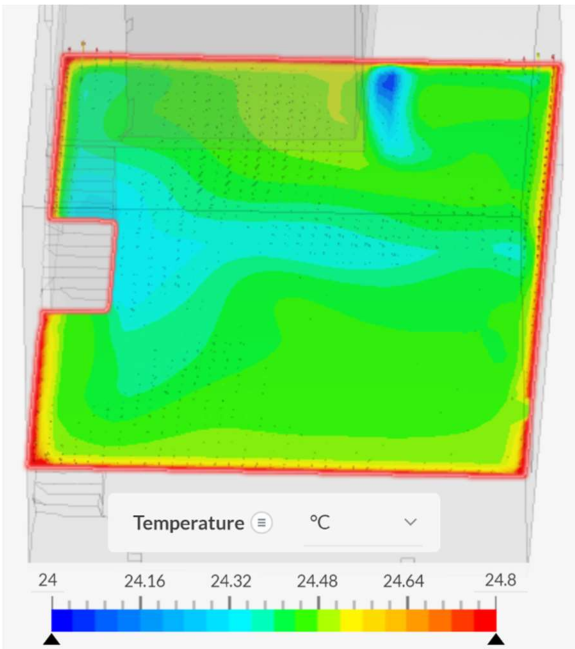

Figure 19. In the figure above, the temperature 1.7 meters above the floor at 100 seconds is shown.

4.1.4 Room Inlet Cycled On

In this scenario, the only inlet cycled on is the inlet in the upper room. This simulation is to simulate the situation when the main area has reached the target temperature, but the upper room has not. In the simulation, the main inlets shut off after 25 seconds, with the total simulation being 100 seconds. The main cooling source for the building is now just the upper-room inlet until the main area's temperature becomes lower than the set-point range. The influx of energy into the building continues to cause the air near the main walls to increase in temperature and decrease in density. The air continues to rise near the walls and the cooler air, near the rising warm air, fills the void space. As a result, the main area still has circulation from the buoyant-driven flow.

Within the upper room, the inlet air comes into the space with around a three-meter throw and drops to the floor. Next, the air spreads out towards the side walls of the room. The air moving towards the wall opposite of the staircase circles around the walls and back toward the center of the room. Consequently, the air continues to circle the bottom of the room until it leaves through the outlet. The air moving towards the wall next to the doorway circles around toward the stairs and flows down the staircase into the main area. The rising air near the walls no longer is the driving force of air movement within the area, due to the significantly cooler air from the inlet absorbing the energy. As the air moves down the staircase, the rising warm air, due to the heat flux from the walls, near the doorway moves into the room to fill the void area, as shown in Figure 20 below. The amount of air movement moving down towards the main area, either by the inlet air moving down the stairs or the air within the natural circulation, is much higher than the air moving up towards the upper portion of the building. The air moving towards the main area is cooler, specifically around the staircase. The open doorway allowing the cool inlet air to escape the upper room and roam down the staircase promotes the influx of cool air into the main area. The air flowing over the staircase has portions of the flow spill over the side of the stairs before reaching the bottom, displayed in Figure 21 below.

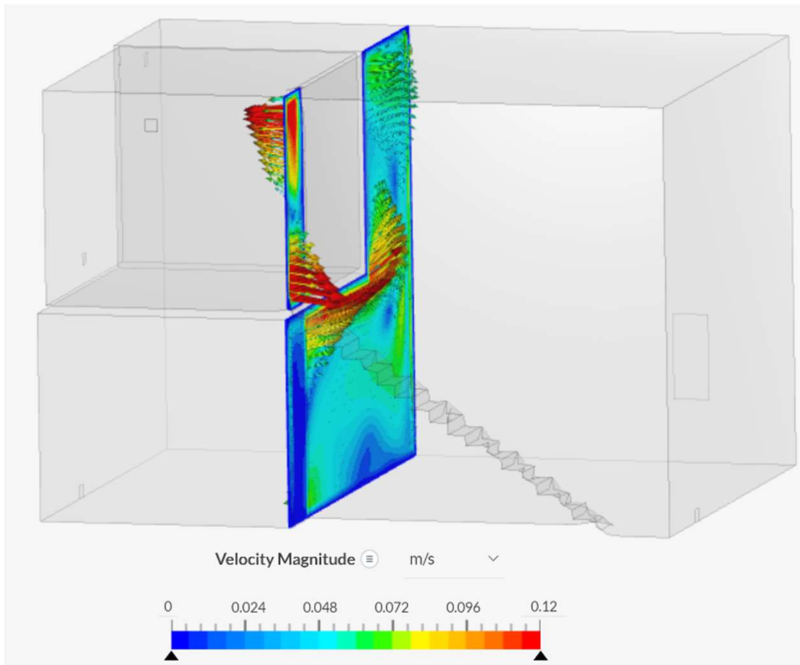

Figure 20. The air exchange through the doorway is shown at a time of 100 seconds.

Therefore, most of the flow near the staircase is directed down towards the floor, with the aid of the warmer air near the walls rising towards the ceiling. The difference in density between the cooler and warmer air allows for the cooler air to stay near the occupancy zone in the main area. Even though the cool air flowing down the stairs is near the same temperature as the air currently occupying the main area, with a difference of around 0.3 °C, the influx of cool air down the stairs aids in keeping the main area at a cooler temperature.

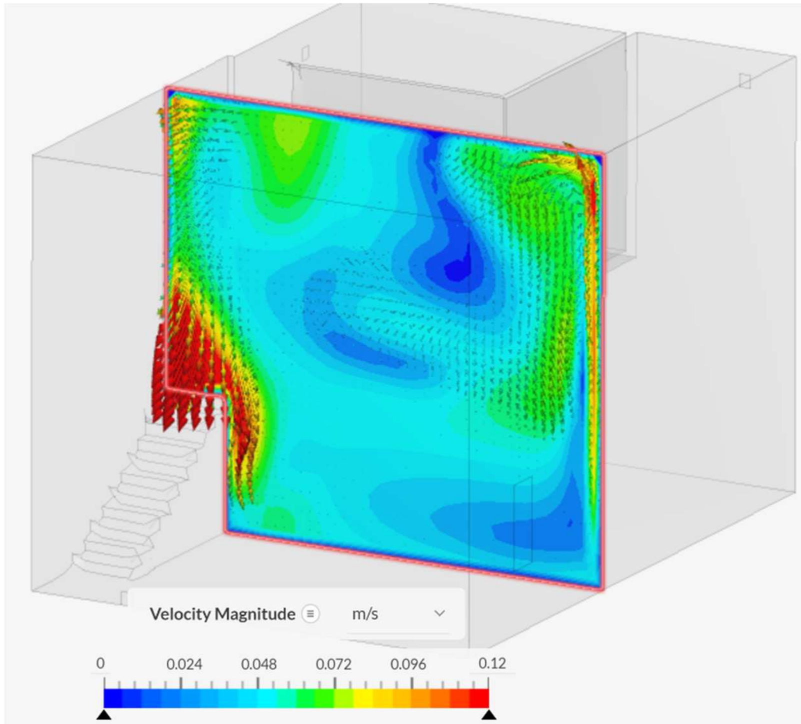

Figure 21. In the figure above, the air is shown to move down the stair and partly spill over the side into the main area at 100 seconds.

4.2 Air Movement in Heating Scenarios

As a part of the analysis of the completed simulations, the air movement in the heating scenarios was tracked to understand the cause of the disruption in thermal comfort. In the below section, similar to the above section, the air movement in each heating scenario is described along with the driving forces, and causes, of the air movement.

4.2.1 Inlets Cycled Off.

In a heating scenario simulation, the entire flow region begins at 24.4 °C. The outside temperature is set to 4.44 °C, with the heat flux leaving the building. The inlets cycle off after a few seconds, as they would be when the building just reaches the set-point temperature. The scenario was simulated for both for multiple time steps, as shown in Table 7 above. The heat begins to leave the building through the main walls, ceiling, and two-room walls. As the heat leaves the building, the air near the walls loses energy and cools down. When the air lowers in temperature, the density of the air increases and is denser than the surrounding air. As a result, the air begins to fall near the walls towards the floor, displayed in Figures 22 and 23. Since the air is close to the walls, the air continues to lose energy, which allows the air to maintain a higher density as it falls. Once the air reaches the floor, the fluid continues to flow over the floor of the main area towards the center of the room, as shown in Figures 24 and 25. Because this occurs at each wall in the building, there is a large flux of air moving towards the center of the main area. The cool air flowing over the floor of the main area moves towards the staircase and separates to flow in opposite directions upon contact. To fill the void space near the ceiling, the warmer and less dense air flows up. This constant cooling of air near the wall, with warmer air taking its place, creates a natural buoyancy-driven circulation loop near all the walls.

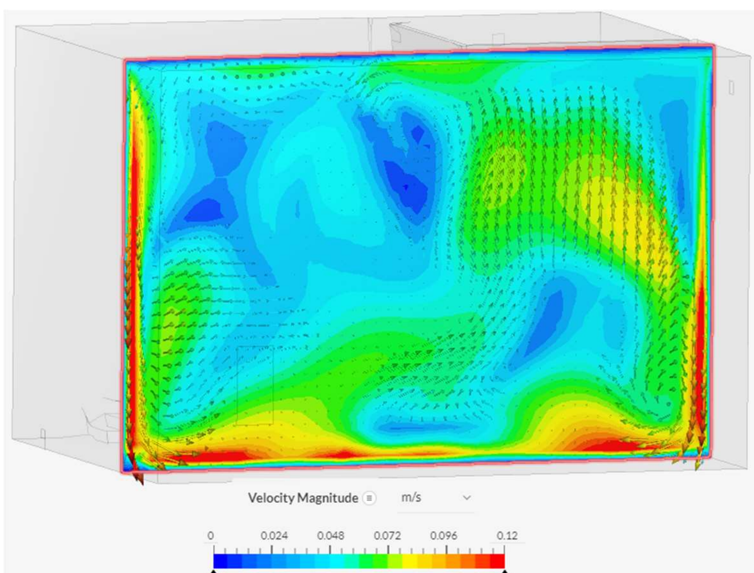

Figure 22. The natural circulation of air near the walls is shown at 150 seconds.

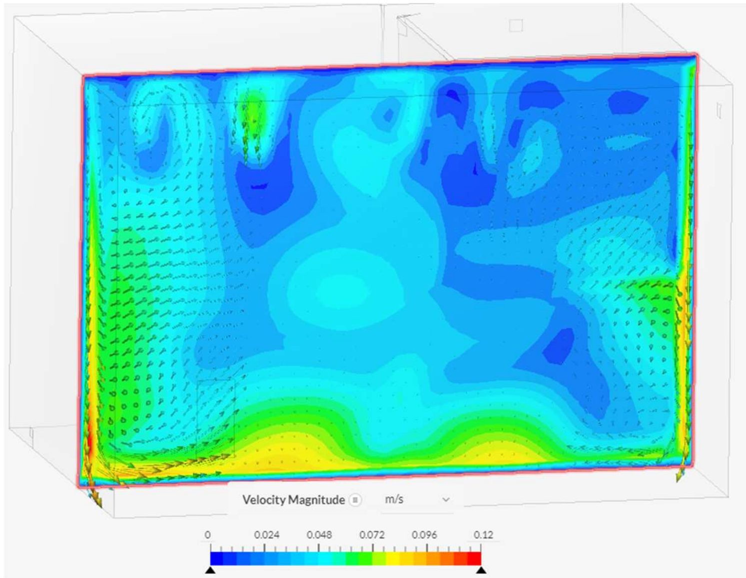

Figure 23. The natural circulation of air near the walls is shown at 600 seconds.

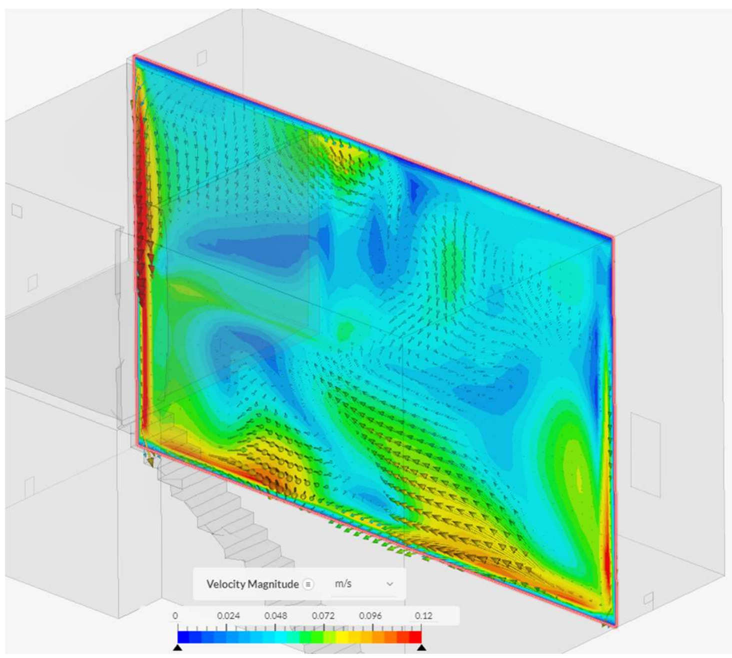

Figure 24. The air flows towards the staircase across the floor at 150 seconds.

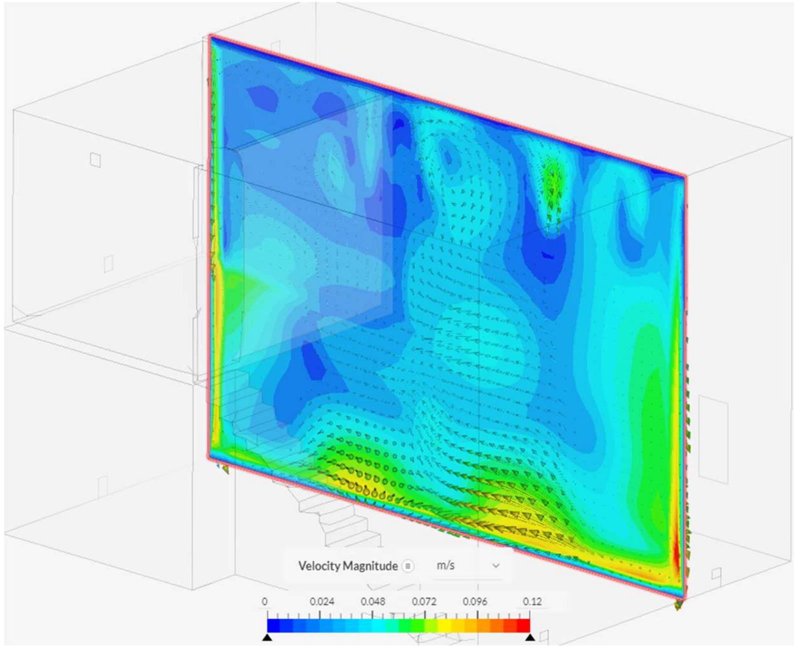

Figure 25. The air flows towards the staircase across the floor at 600 seconds.

Within the upper room, the same flow mechanics take place as in the main area, except on a smaller scale. The buoyancy-driven flow occurs near the two exterior walls, but not the other two walls. The other two, as discussed above, do not have a heat flux through them since they were treated as a zero-flux wall in the simulation. The cool air flowing down the two exterior walls dominates the air currents near the bottom of the room. Due to the layout of the room, the current of air makes its way towards the doorway and down the stairs. The air moving down the stairs is cool air that picks up speed as it flows out of the doorway, as shown in Figures 26 and 27.

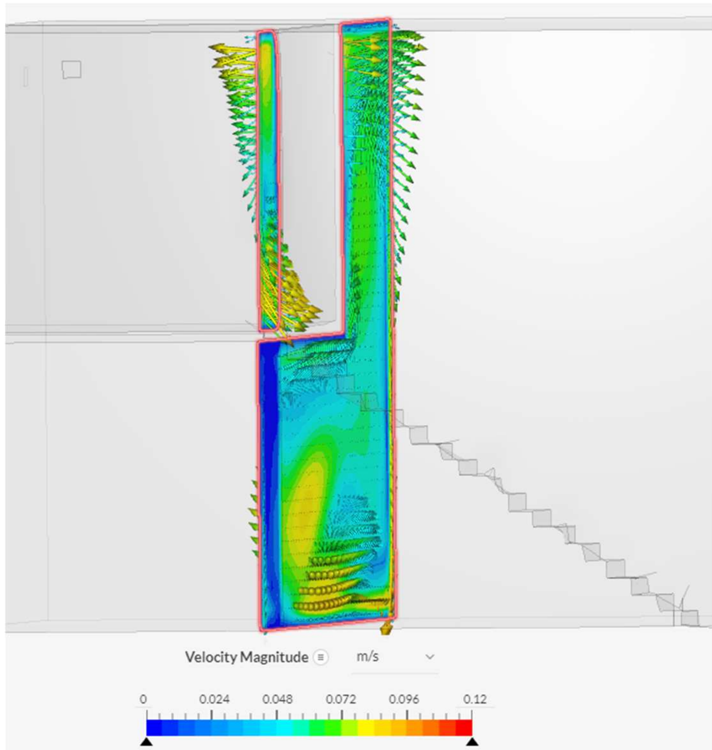

Figure 26. The air exchange through the doorway is shown at 150 seconds.

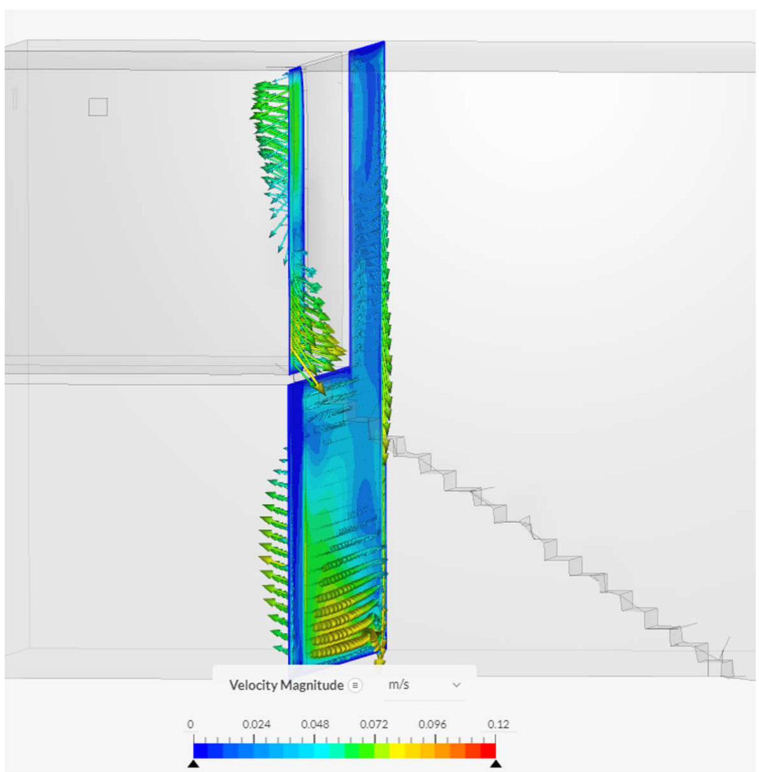

Figure 27. The air exchange through the doorway is shown at 600 seconds.

Air flowing down the stairs eventually mixes with the air that separated at the staircase base, along with some of the air spilling over the edge. The mix creates a large flux of cool air that circles in the corner of the building and flows back towards the center of the room, as presented in Figures 28 and 29. A noticeable difference between Figures 28 and 29 is how developed the circulation is at the bottom of the stairs. At the 600 second mark, the circulation is well-developed. This constant circulation aids in creating a cooler environment within the main area of the building. Only 150 seconds into the simulation, the main area had an average temperature of 0.8 °C lower than the starting temperature. In the 600 second simulation, the average temperature was 2 lower than the starting temperature.

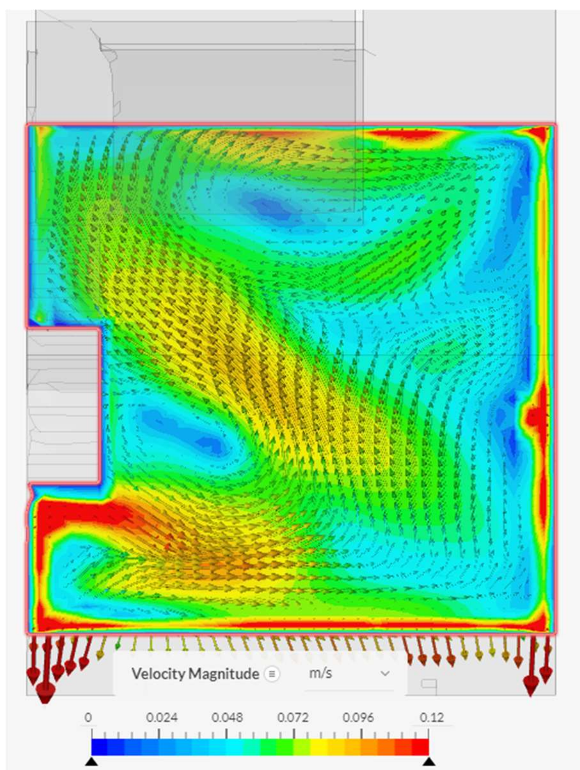

Figure 28. The circulation of cool air 1.1 meters above the floor at 150 seconds is shown.

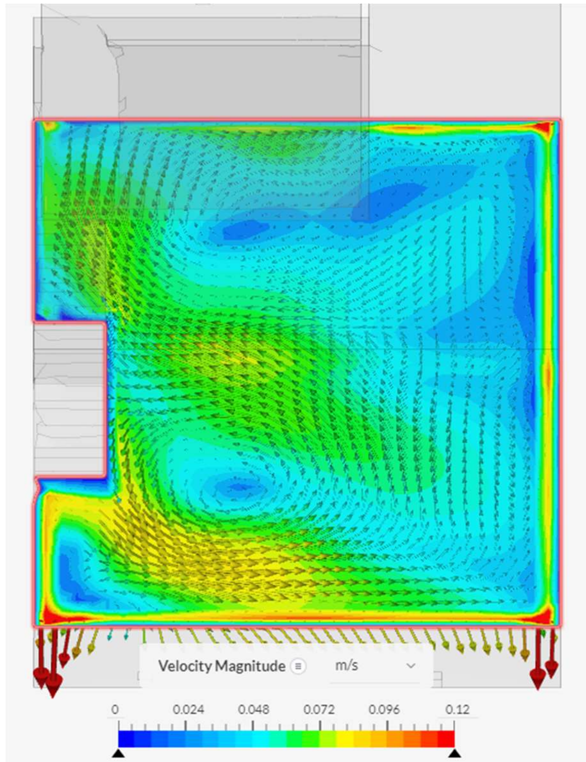

Figure 29. The circulation of cool air 1.1 meters above the floor at 600 seconds is shown.

To fill the void area within the room, from the air flowing down the stairs, air near the ceiling around the doorway flows through the upper portion of the door, presented in Figures 26 and 27 above. Air entering the room is the warmer air in the building since it is less dense. The warm air is around 0.5 °C warmer than the air leaving the room. As time passes, the air within the building becomes cooler. This means the air coming into the room is warmer at the beginning of the simulation and cooler towards the end. Even though the upper room is receiving the warmer air in the building, the room temperature will eventually fall along with the main area. However, the main area will always have a lower temperature than the upper room due to the flow mechanics of the staircase, even if the temperature difference is minimal.

4.2.2 Inlets Cycled Off with Cooler Upper Room.

In this scenario, the upper room has either a lower set-point temperature or has the heating turned off. The upper room would then be at a lower temperature than the main area of the building. If the upper room and main area were allowed to exchange air, such as a door being left open, the below scenario would take place. The initial simulation was 150 seconds long, with both inlets cycled off. As shown in Table 6 above, additional simulations were conducted, up to the simulation length of 600 seconds. The upper room was set to a temperature of 22.8 °C and 18.9 °C in the simulations, while the lower area was set to a temperature of 24.4 °C. Between the air near the walls falling towards the floor and the air leaving the room, cool air made its way into the main area.

Within the room, the air near the two exterior walls falls towards the floor as the density increases. However, this buoyant-driven flow is disrupted by the incoming air to the room. Once the air reaches the opposite wall from the doorway, the air loses energy. A portion of the air falls towards the ground, while the other portion circles around to the right. It appears that all the air that reaches the opposite wall begins to circulate clockwise within the room, making its way back towards the doorway. The portion near the bottom of the doorway leaves the room, while the portion near the ceiling gets pushed back into the room by the incoming air. This is due to the warm air in the main area rising towards the ceiling and replacing the air leaving the room. As a result, the upper room will steadily get warmer, as it is exchanging the warm air from the main area with its cooler air.

As the temperature difference increased to 5.5 °C, the velocity of air exchange increases through the doorway. For the 150-second and 600-second simulations, the temperature difference caused an increase in flow velocity both through the doorway and around the staircase. The flow mechanics and flow patterns remained similar through the simulations, but the flow velocity was the main difference, as shown in Figures 30 to 35 below.

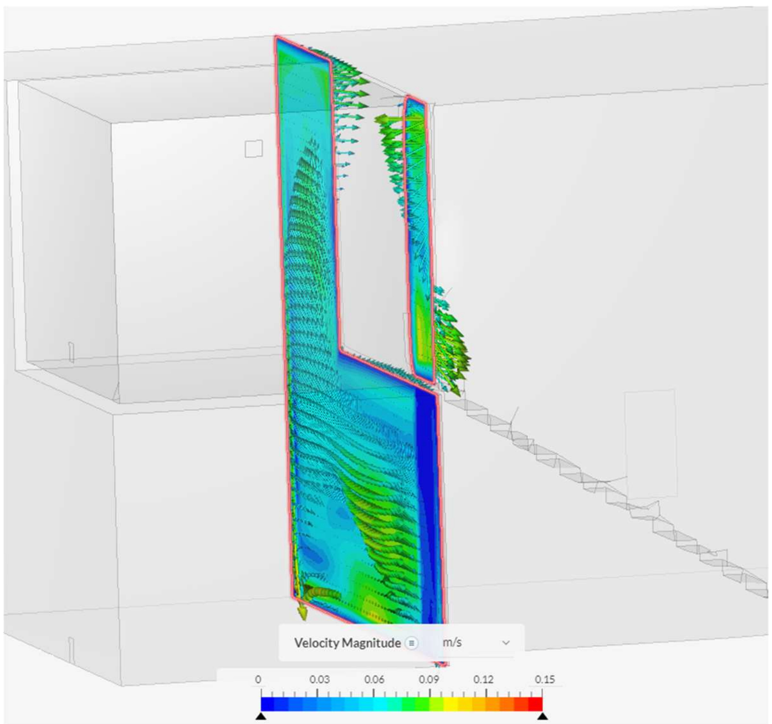

Figure 30. The air exchange through the doorway at 150 seconds is shown for no initial temperature difference.

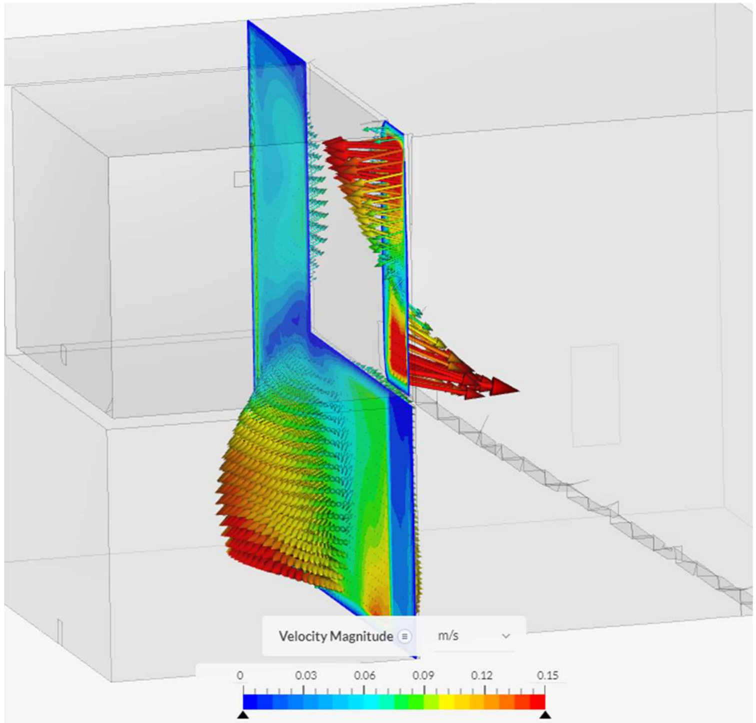

Figure 31. The air exchange through the doorway at 150 seconds is shown for a 2 °C initial temperature difference.

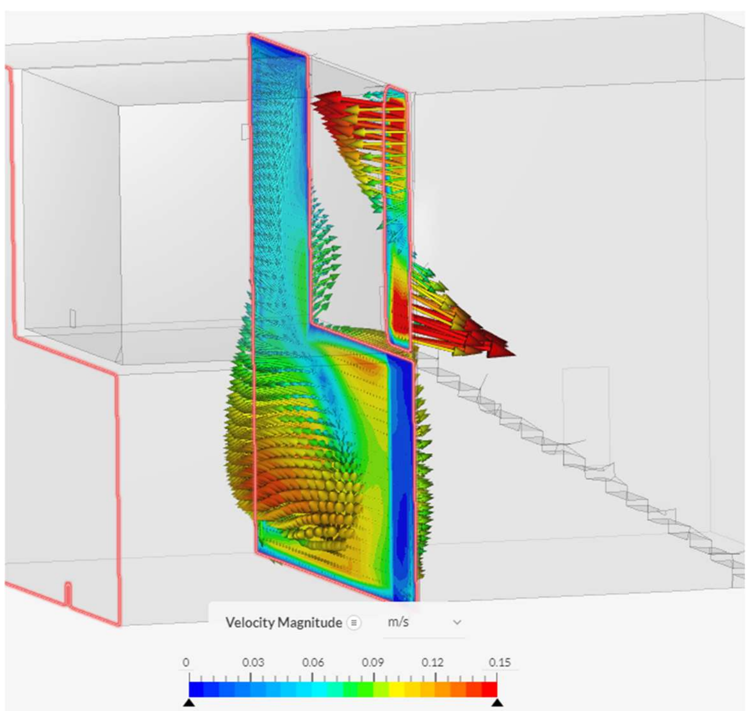

Figure 32. The air exchange through the doorway at 150 seconds is shown for a 5.5 °C initial temperature difference

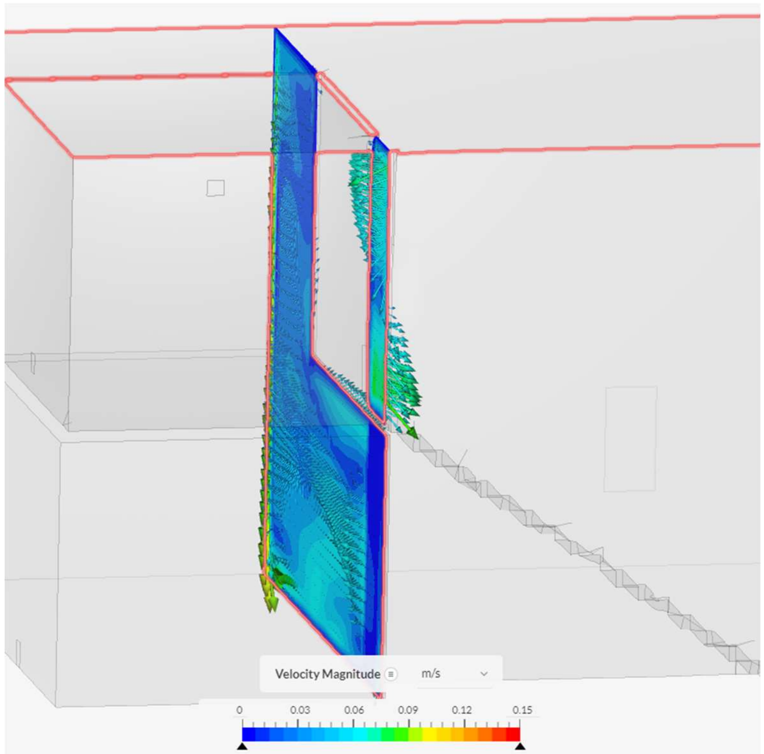

Figure 33. The air exchange through the doorway at 600 seconds is shown for a no initial temperature difference.

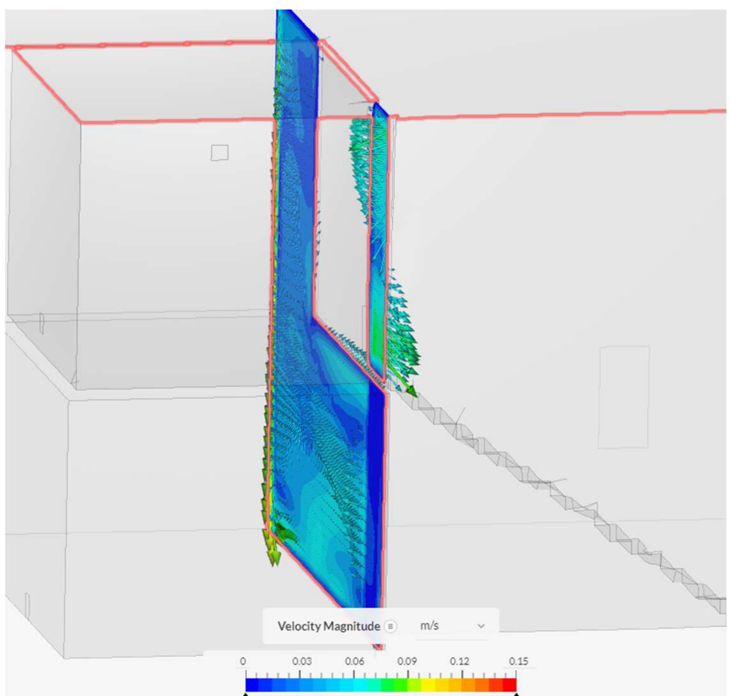

Figure 34. The air exchange through the doorway at 600 seconds is shown for a 2 °C initial temperature difference.

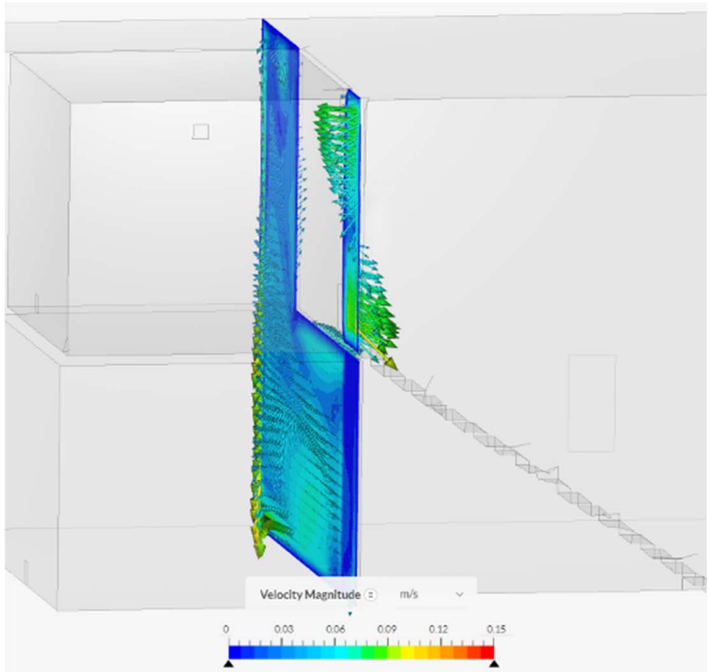

Figure 35. The air exchange through the doorway at 600 seconds is shown for a 5.5 °C initial temperature difference.

As the air moves down the stairs, most of the air spills over the edge and falls into the main area. This combination of air speed and cooler temperature makes a cooler environment around the staircase, which is undesirable. As the air reaches a few steps up from the bottom of the stairs, it circles counterclockwise into the main area. Figures 36 to 41 below show the temperature change in the main area and the air direction 1.1 meters above the floor. The figures display the cooler zones in the main area due to the air from the upper room and demonstrate the change in temperature in the main area due to the cooler air from the upper room.

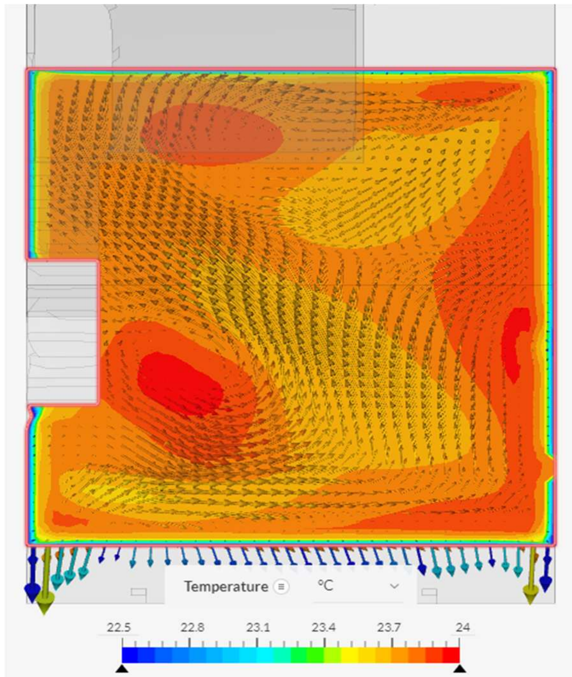

Figure 36. Air temperature 1.1 meters above the ground at 150 seconds with no initial temperature difference.

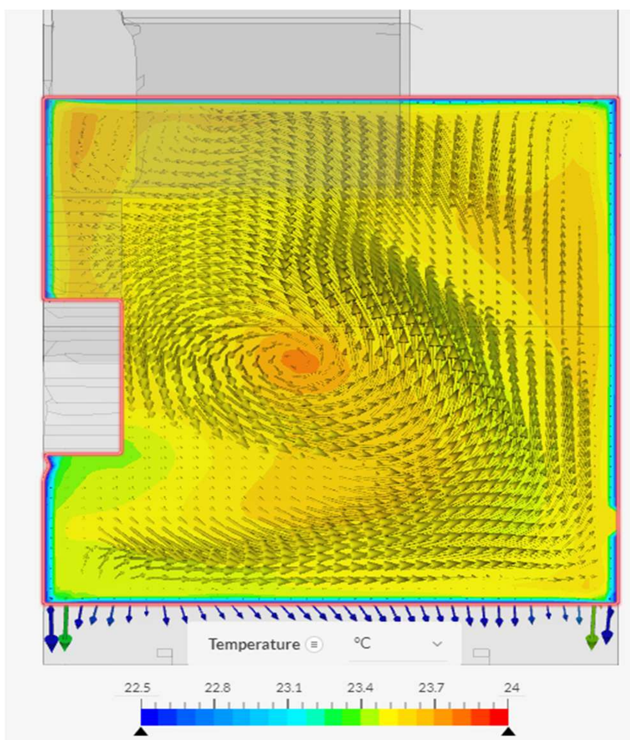

Figure 37. Air temperature 1.1 meters above the ground at 150 seconds with a 2 °C initial temperature difference.

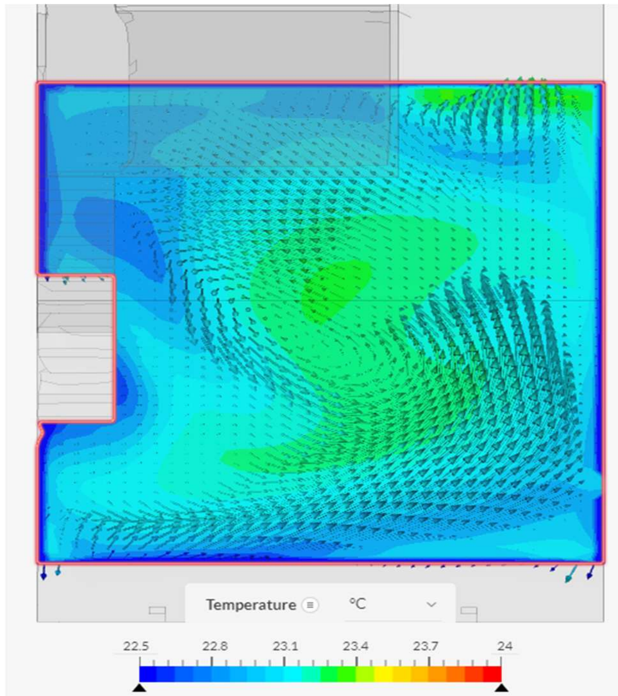

Figure 38. Air temperature 1.1 meters above the ground at 150 seconds with a 5.5 °C initial temperature difference.

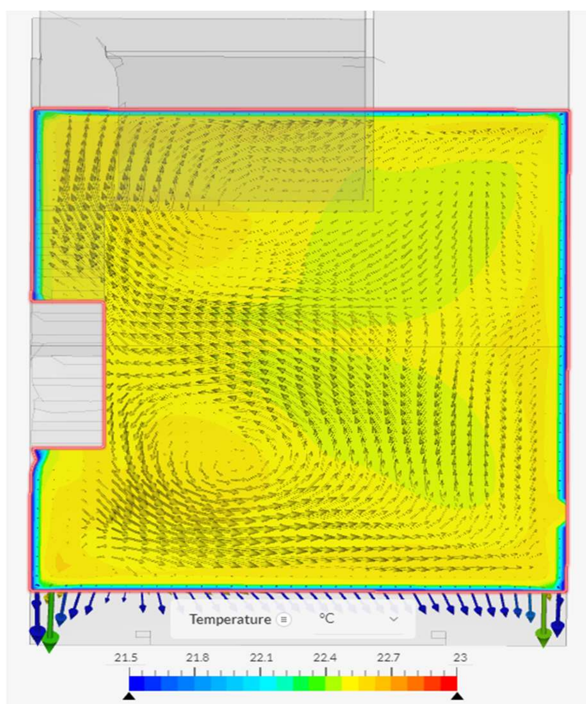

Figure 39. Air temperature 1.1 meters above the ground at 600 seconds with no initial temperature difference.

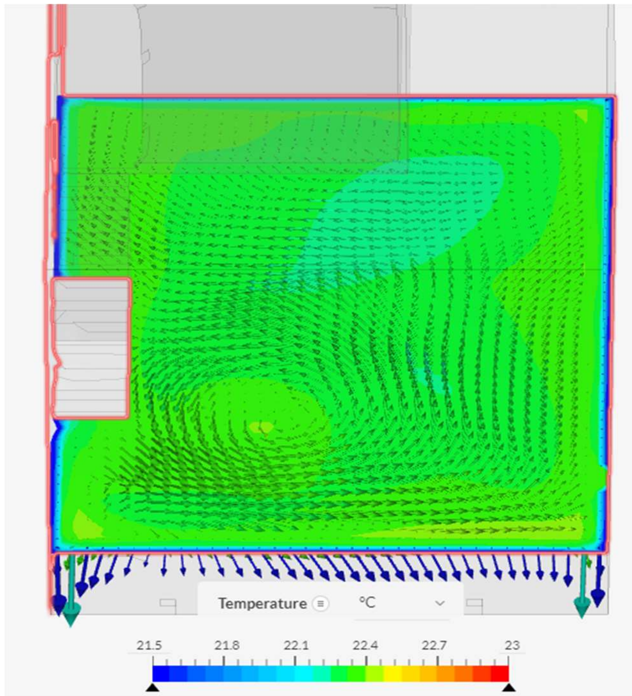

Figure 40. Air temperature 1.1 meters above the ground at 600 seconds with a 2 °C initial temperature difference.

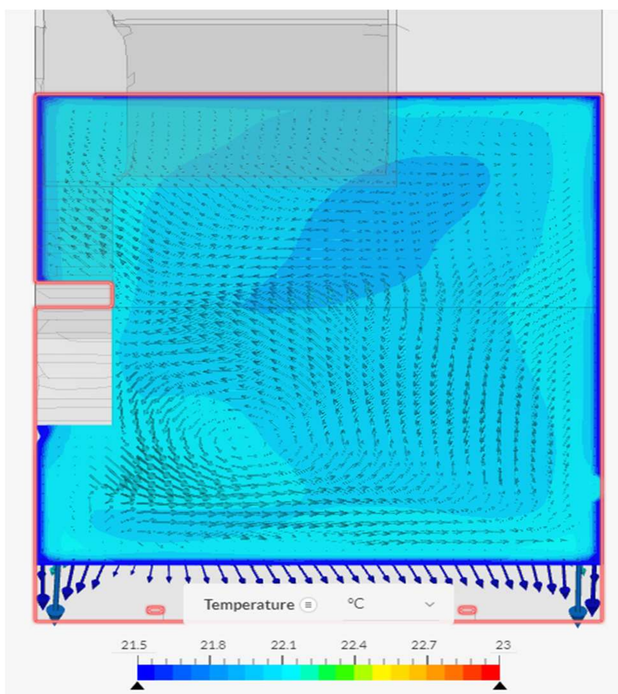

Figure 41. Air temperature 1.1 meters above the ground at 600 seconds with a 5.5 °C initial temperature difference.

4.2.3 Main Inlets Cycled On.

In this scenario, the upper room has the inlets cycle off after 25 seconds into the simulation. The main area has the inlets cycled on for the entirety of the simulation, which is 100 seconds. The entire flow region had an initial temperature of 20 °C. The purpose of this simulation is to see how much effect the main area inlets have on the upper room.

The air coming from the main area inlet near the floor flows towards the right-side of the main area and begins to flow upward. The inlet air makes its way along the right wall of the building and steadily flows upward to meet with the air coming from the other inlet near the ceiling. The other inlet air immediately flows up and towards the left side of the building, as shown in Figure 42. The upper-inlet air parts ways when it reaches the outer wall of the room. Part of the air moves down along the wall, and the other portion moves around the wall towards the doorway, as shown in Figure 43 below. Once the air reaches the wall above the stairs, it splits again with a portion going into the room and the majority moving down towards the stairs. However, the portion of air moving down towards the stairs mixes with the cooler air coming down the wall.

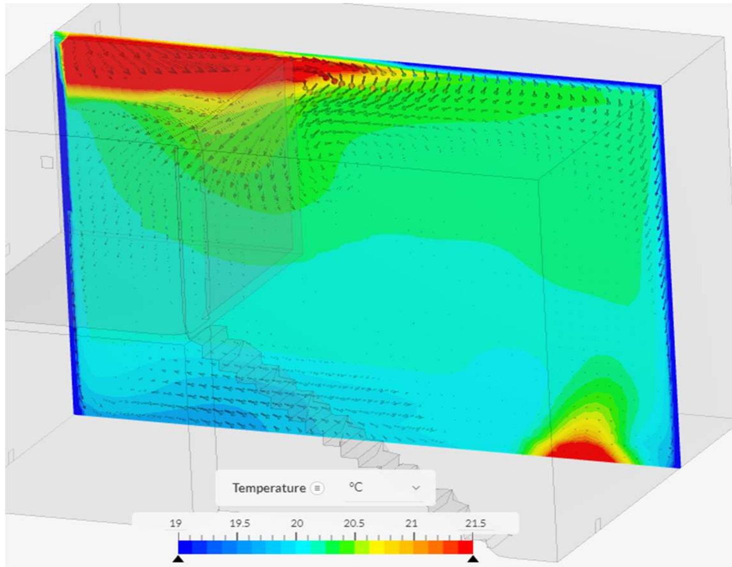

Figure 42. In this view from the left side of the building at 100 seconds, the inlet air is seen moving towards the left wall and wrapping around the outside of the room wall.

The portion of the inlet air that flows into the room has lost most of its heat by this point. The average temperature moving through the top of the doorway is 20 °C, with a maximum temperature of 20.1 °C. The average temperature within the room sits around 19.72 °C, which is slightly lower than the 19.77 °C temperature of the occupied zone in the main area. The air coming out of the room is the same temperature as the average room temperature. The air coming down the stairs and spilling over into the main area has a temperature of around 19.72 °C. The air spilling over may be the cause of the inlet air near the stairs moving towards the right wall. With just a 100 second simulation, the room temperature can keep a similar temperature as the main area. This may be due to the short simulation not being able to consider the heat flux into the walls. However, the upper room does appear to have a portion of the inlet air come into the room. The temperature difference of the air coming into and leaving the room is around 0.3 °C, so the impact of an open doorway seems to be insignificant within the first 75 seconds of the room inlet cycling off.

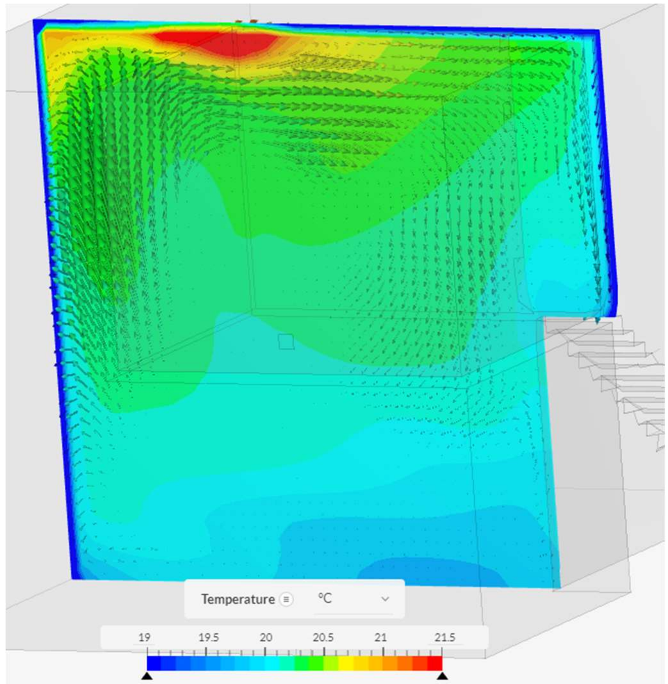

Figure 43. From the rear view of the building at 100 seconds, the air from the upper portion of the main area wraps around the doorway and enters the room.

4.2.4 Room Inlet Cycled On

Similarly, to the cooling simulation, the only inlet cycled on is the upper room inlet. This simulation is to simulate the situation when the main area has reached the target temperature, but the upper room has not. The simulation has the main inlets shut off after 25 seconds, with the total simulation being 100 seconds. The main heating source for the building is now just the upper-room inlet until the main area's temperature becomes higher than the set-point range. The heat flux through the main walls, ceiling, and room still occurs. This outflux of energy from the building continues to cause the air near the main walls to decrease in temperature and increase in density. The air continues to fall near the walls and the warmer air fills the void space. As a result, the main area still has circulation from the buoyant-driven flow.

Within the room, the inlet air comes in at a much higher temperature than the existing air. As a result, the air flows up towards the ceiling and spreads out as it flows towards the opposite wall. The warm air stays near the ceiling, which does not effectively circulate throughout the room. Therefore, most of the inlet air stays within the upper room. The inlet air forces itself to the opposite side of the room while pushing the existing air down and towards the wall with the inlet. Part of the air that circulates back towards the inlet moves across the ceiling and out the doorway. The forced flow out of the doorway causes a slight drop in pressure in that area. This causes the air on the main area side of the room wall to have a slight lift. However, since the uplifted air is cooler than the air near the ceiling it is forced back down. The mixture of pressure difference and buoyant forces creates a circulation of air near the top of the stairs, as displayed in Figure 44.

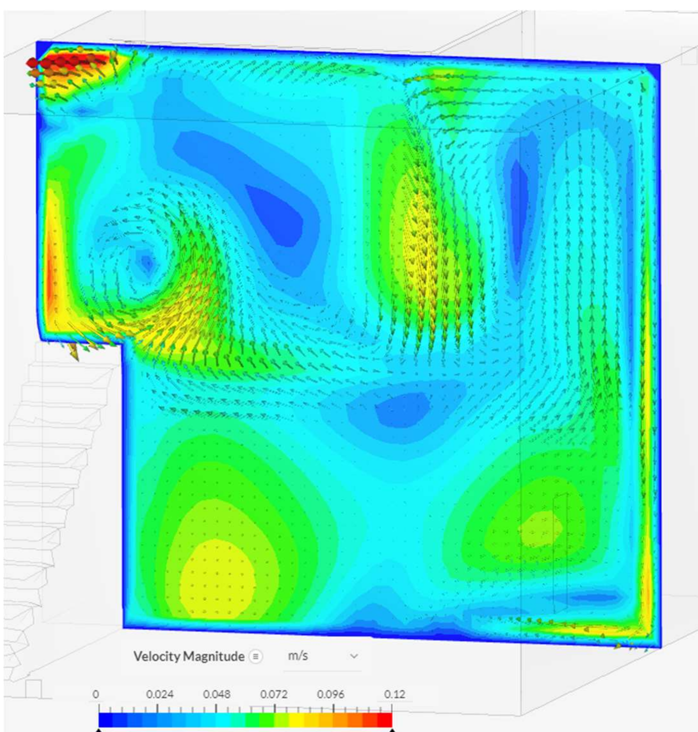

Figure 44. The circulation of air outside of the doorway is shown at 100 seconds the top of the stairs.

There is a combination of air falling down the wall over the stairs with the cooler air falling down the stairs. This causes the air in the mid-area of the room, around a meter above the ground, to flow towards the stairs and combine flows. However, the impact of the flow down the stairs in this scenario seems to be small. The image below shows the temperature distribution 1.58 meters above the ground. There is only a 0.5 °C difference between the warmest area and the coolest. Around the stairs, the cooler air seems to have a slight uplift that allows the air to split ways at the stairs. The uplift may be caused by the air going down the stairs and walls forcing the existing air up, due to density differences.

4.3 Energy Impact

Within the various scenarios, the air movement between the two floors in the building has an impact on the energy consumption of the building. Since the air carries a lower or higher temperature, depending on if the simulation is a heating or cooling scenario, the air carries either higher or lower energy than the air in the main area. Once the air flows out of the upper room, the main area is affected by the mixing of air, which causes the HVAC system to eventually cycle on to bring the main area back into the target temperature.

To estimate the total energy impact, the change in energy in Watts was calculated using equation three below. The volumetric flow rate was estimated by measuring the average velocity of the air leaving the upper room through the doorway and conservatively estimating the area of the doorway the leaving air occupies. The enthalpies were determined by measuring the average temperature of the air leaving the upper room and the average temperature of the main area 1.1 meters above the floor. Then, using the relative humidity of 60% set in the simulation, the enthalpies were taken from the ASHRAE psychrometric chart.

$$q_{total} = 1.204 * \dot{V} * \Delta h \qquad \text{(Eq. 3)}$$

where

$\dot{V}$ = volumetric flowrate in liters per second

Δh = change in enthalpy in kilojoules per kilogram

The worst-case scenario for both heating and cooling was selected to be the simulations analyzed to determine if the highest energy impact situation was significant. For both the heating and cooling scenarios, the most aggressive and highest flow situation was the 150-second simulation with a 5.5 °C initial temperature difference. In the cooling setup, the average temperature of the main area was 24.66 °C, and the air leaving the room had an average temperature of 27 °C. Using the psychrometric chart, the enthalpies were conservatively estimated to be 55 kJ/kg and 61.5 kJ/kg. The average velocity of the air leaving the upper room through the doorway was 0.09 m/s, which occupied 33% of the doorway area. Using a total doorway area of 2.53 m^2, the volumetric flow rate was 75.9 L/s. Using equation three above, the total energy change in the main area due to the air from the upper room was 595 Watts cooling load.

To calculate the power input to counteract this energy change, a few assumptions were made. Assuming a ten-minute cycle time of the building HVAC system, which conservatively over-estimates the cycle-on time of the system, the value of 360 hours cycled on per month was used. In addition, the system was assumed to have a coefficient of performance (COP) value of three. Using a value of $0.124/kWh, which is the U.S. West South Central average residential cost of electricity, in conjunction with the above assumptions, the total cost of cooling for six months was determined to be $52.93 extra due to the influence of the air leaving the upper room [21].

In the heating setup, the average temperature of the main area was 22.76 °C, and the average temperature of the air leaving the upper room was 22 °C. Using the psychrometric chart, the enthalpies were estimated to be 49.8 kJ/kg and 47.9 kJ/kg. The average velocity of the air leaving the upper room through the doorway was 0.22 m/s, which occupied 40% of the doorway area. Using a doorway area of 2.53 m^2, the volumetric flow rate was 223 L/s. Using equation three above, the total energy change in the main area due to the air from the upper room was 455.7 Watts heating load.

To calculate the power input, the same assumptions were made as in the cooling calculation. With the ten-minute cycle time, the value of 360 hours per month and COP of three were used. In addition, a system efficiency of 80% was assumed. Using the above assumptions, the input was calculated to be 0.7 MMBtu per month. Using a value of $23.24/MMBtu, the total cost of heating for the sixth month period was calculated to be $94.13 extra due to the influence of the staircase and the air from the upper room [22]. The extra cost of $52.93 and $94.13 over a six-month period is not negligible. However, the actual increase in cost over the six months is expected to be lower than these values due to the assumptions made in the calculations. The extra load will not require a change in the HVAC system, but rather change the cycling time of the system. As a result, the impact of the air movement, from the upper room on and around the stairs, mainly affects the thermal comfort rather than the energy usage.

4.4 Thermal Comfort Impact

Within the various scenarios, the air movement, on and around the stairs, plays a part in the thermal comfort in the building, specifically the lower main area. To display this impact, data points were sampled from the main area. To be more comprehensive for the cooling scenarios, and quantitatively show the air movement, the velocity and temperature stratification graphs are included in this section. The data points were taken vertically to track the temperature stratification and air speed in the building. The data points were taken 1.2 meters from the stairs, towards the center of the room, with the measurement points increasing in height. For the heating scenarios, the data points were taken 1.1 and 1.7 meters above the ground in correspondence to ASHRAE Standard 55, as shown in Figure 45 [6]. The data measurements began at the stairs and ended around 2 meters from the stairs towards the center of the room. The areas selected for measurement were a fair representation of the thermal comfort impact. All the following figures and data points were taken from the main area to show the impact of the air movement described above. In addition, the thermal comfort parameter PMV index is shown in the table below.

Table 9. Predicted Mean Vote (PMV) values and the corresponding sensation by the occupant.

Value	Sensation
-3	Cold
-2	Cool
-1	Slightly Cool
0	Neutral
1	Slightly Warm
2	Warm
3	Hot

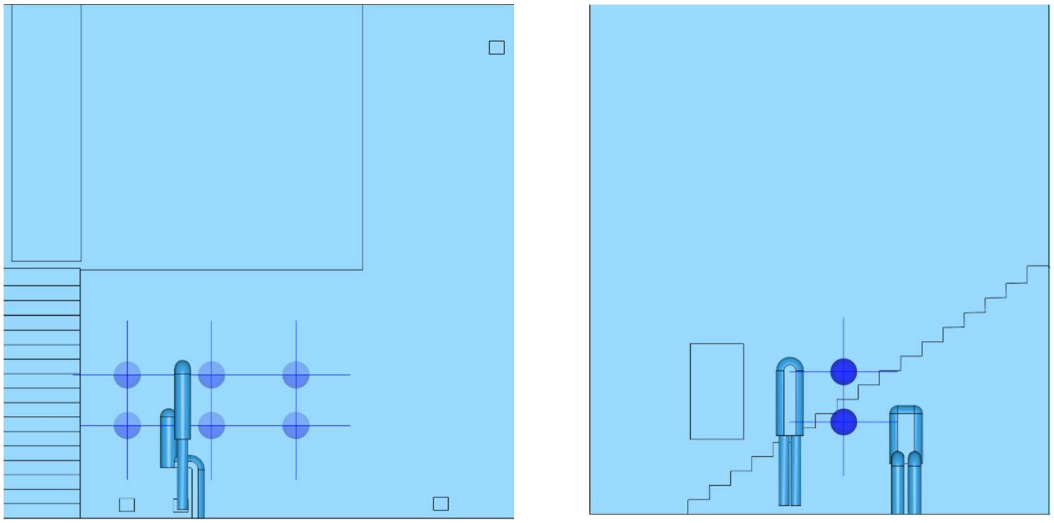

Figure 45. The heights of 1.1 and 1.7 meters above the ground are shown. The occupant to the left is standing, and the occupant to the right is sitting.

4.4.1 Thermal Comfort Impact in Cooling Scenarios.

In the cooling scenarios, the thermal comfort of the main area is impacted by airflow out of the upper room. The temperature increase in the main area happens over time, and at a slightly quicker rate when the upper room is warmer to begin. In the 150 second simulation, the change in the main area's average temperature was insignificant at just 0.2 °C. In the 600 second simulation, the increase in temperature within the main area was 0.5 °C. However, when the upper room is at a higher temperature, the temperature increase in the main area is larger. The most extreme case tested, the 600-second simulation with the upper room 5.5 °C warmer, the temperature increase in the main area was 1 °C. In the 150 second simulation with a 5.5 °C temperature difference, the increase in the main area's temperature was still minimal at less than a fourth of a degree.

As described above, the warm air leaving the upper room, and air rising near the walls, stay close to the ceiling at the top of the building. The temperature increase in the main area occurs when the temperature of the relatively warm air near the top of the building is displaced and mixed with warmer air. This results in a temperature stratification in the building, with higher speeds of air movement occurring near the top of the building, as shown below in Figures 46 and 47. As the time of the simulations increase, the temperature difference from the bottom and top of the building increases, as shown in Figures 48 and 49.

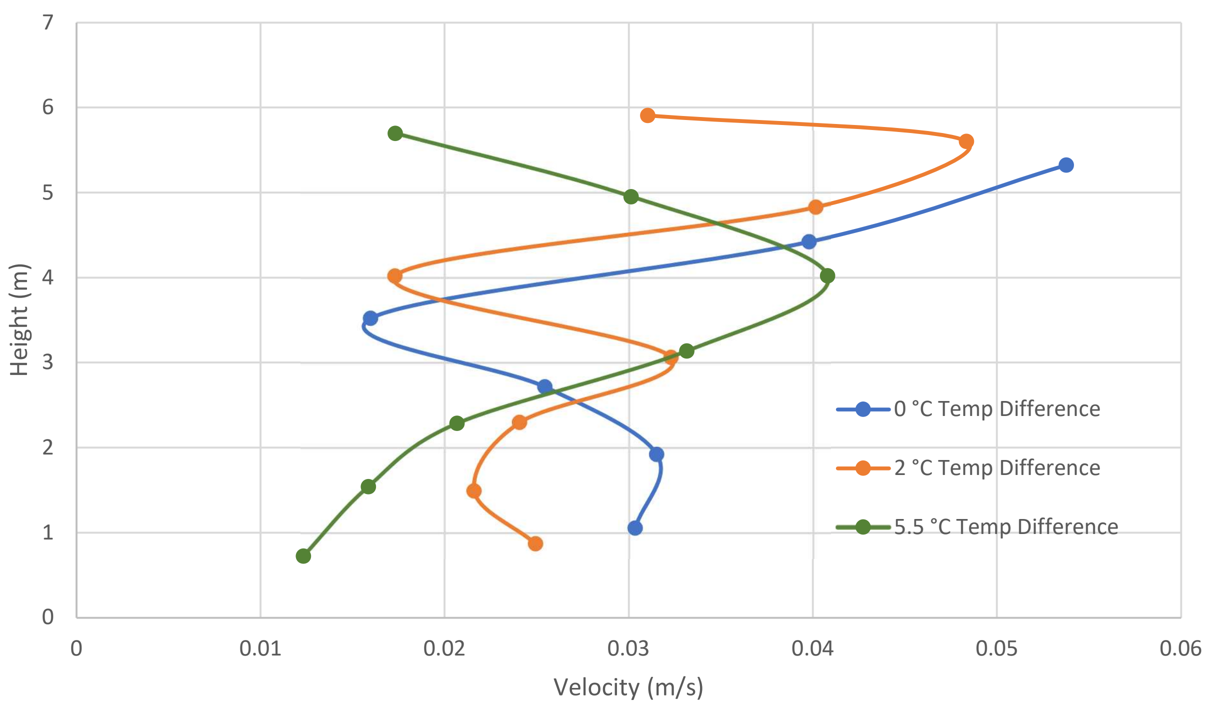

Figure 46. In the figure above, the air velocity, at 150 seconds, at varying heights for the 150-second cooling simulation is shown.

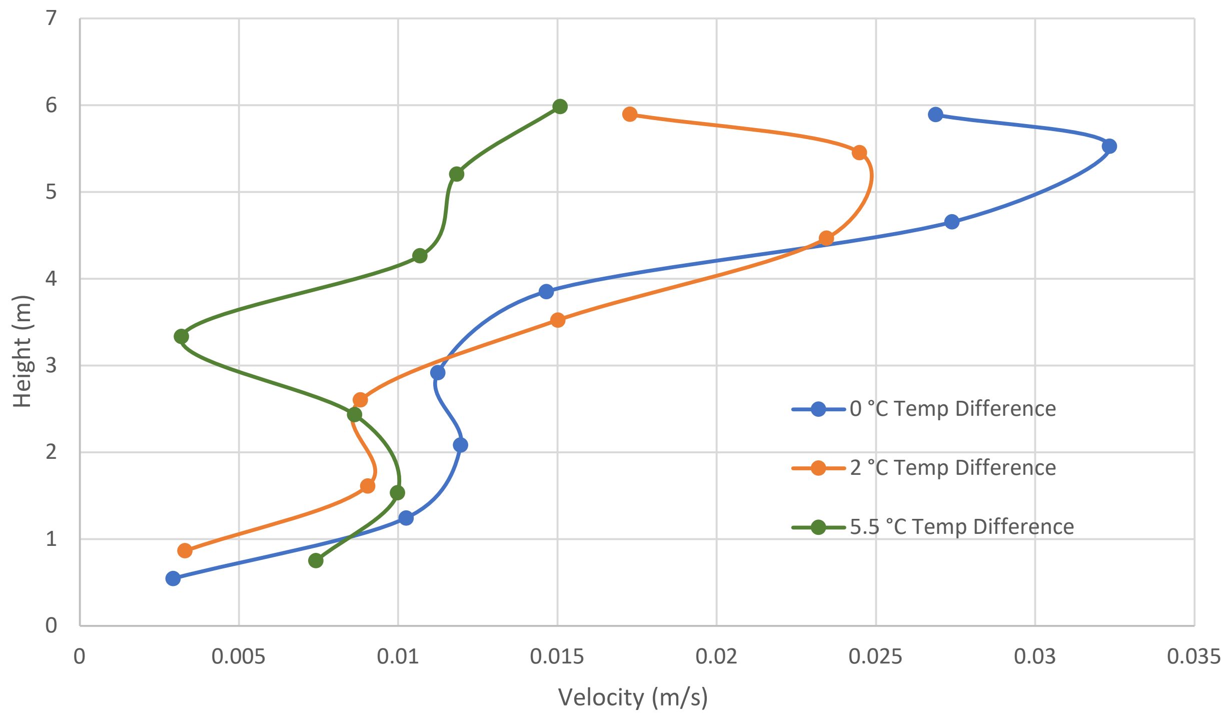

Figure 47. In the figure above, the air velocity, at 600 seconds, at varying heights for the 600-second cooling simulation is shown.

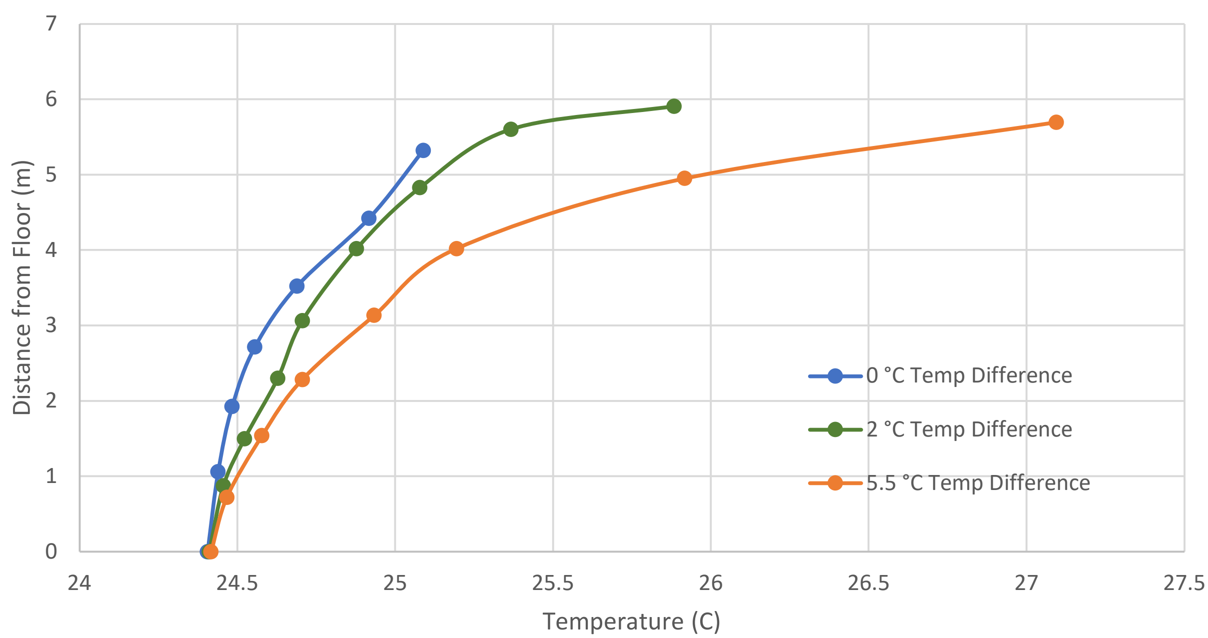

Figure 48. In the figure above, the air temperature, at 150 seconds, at varying heights for the 150-second cooling simulation is shown.

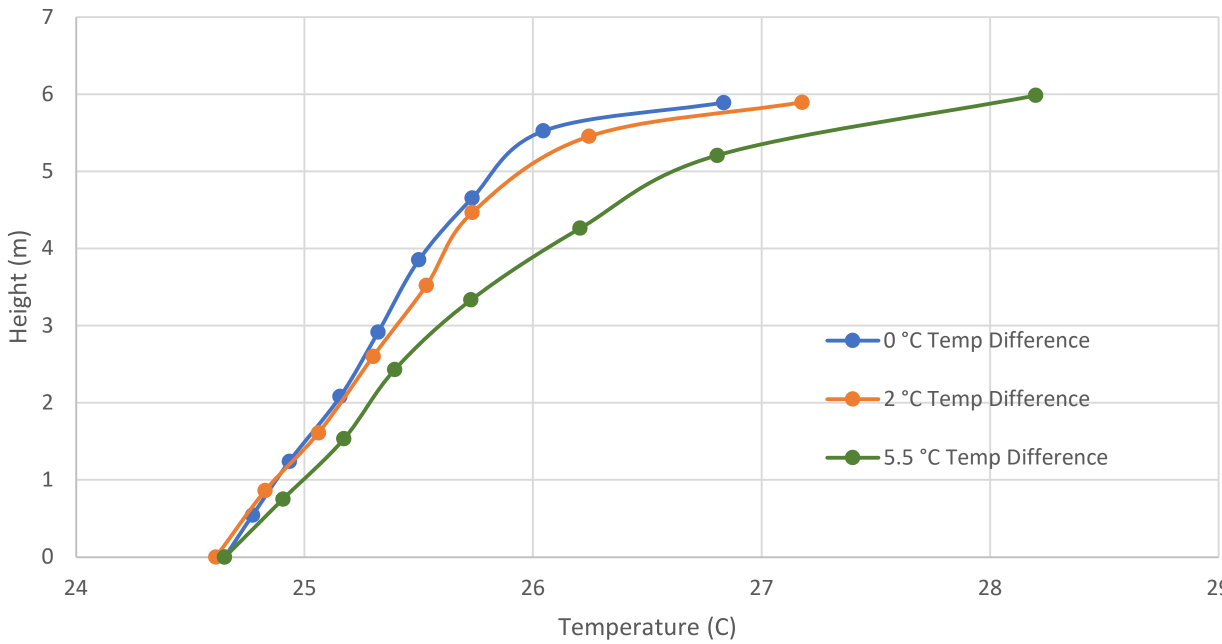

Figure 49. In the figure above, the air temperature, at 600 seconds, at varying heights for the 600-second cooling simulation is shown.

Since the warm air is rising towards the ceiling, the warmest part of the building is near the ceiling. This allows the occupied zone in the main area to remain cooler than the rest of the building just by natural circulation. Even when the upper room is warmer to begin the simulation, the main area was slightly impacted within the cooling scenarios. In the 150 second simulation with no initial temperature difference, the average PMV of the main area was just 0.09. With a 5.5 °C initial temperature difference in the 150-second simulation, the PMV of the main area became 0.2, which is a slight increase. In both scenarios, the PMV is still within the ideal range for thermal comfort. In the 600 second simulation, with no initial temperature difference, the average PMV of the main area was 0.46. When there is a 5.5 °C temperature difference, the average PMV becomes 0.60. The PMV values are slightly outside of the ideal range, but these values are still considered to be comfortable for the occupants. The changes in PMV with increased distance from the stairs is shown below in Figures 50, 51, and 52.

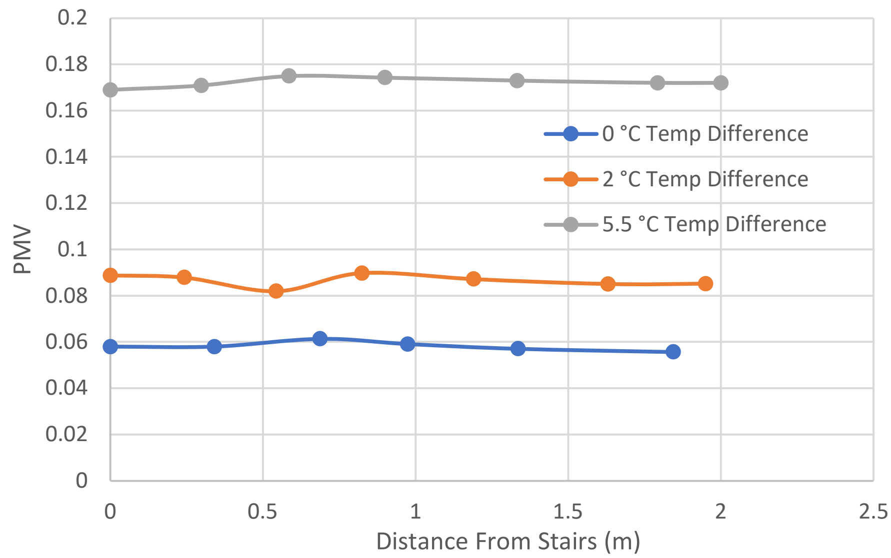

Figure 50. The Predicted Mean Vote in the main area at 150 seconds is shown.

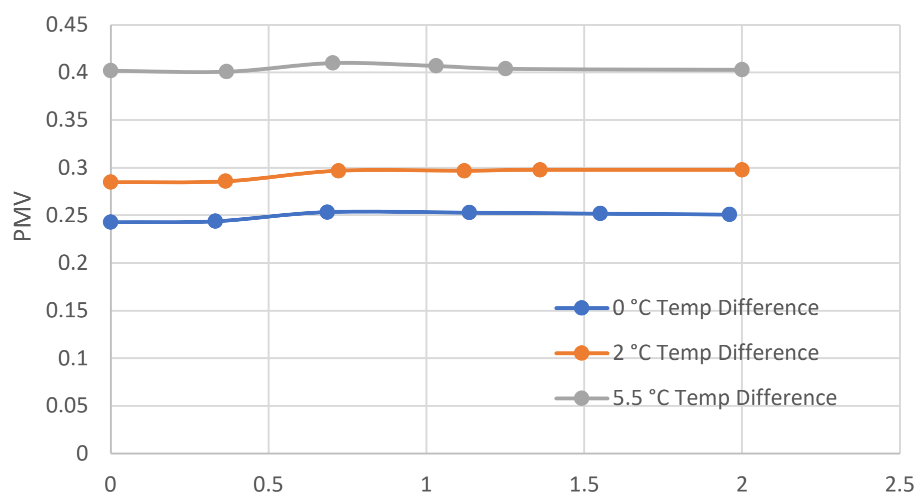

Figure 51. The Predicted Mean Vote in the main area at 360 seconds is shown.

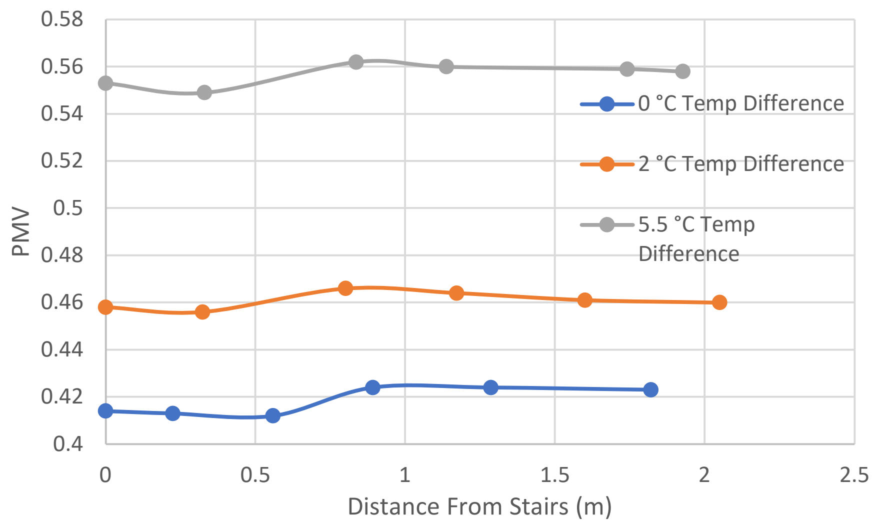

Figure 52. The Predicted Mean Vote in the main area at 600 seconds is shown.

In conclusion, in the 150 second simulation, the temperature increase in the main area, for all scenarios simulated, was between 0.20-0.25 °C. The change in average PMV in the main area, for no temperature difference, was 0.09. With a 5.5 °C temperature difference, the average PMV was 0.20. This shows that the upper room and staircase have a very small impact on the thermal comfort in the main area of the building in just two and a half minutes. In the 600 second simulation the increase in temperature in the main area, for all the scenarios simulated, was between 0.5-1.0 °C. The average PMV for the main area with the normal setup was 0.46. With the initial temperature differential of 5.5 °C, the average PMV became 0.60.

4.4.2 Thermal Comfort Impact in Heating Scenarios.

In the heating scenarios, like the cooling scenarios, the thermal comfort of the main area is impacted by airflow out of the upper room. However, the airflow out of the upper room flows down/over the stairs and dumps into the main area of the building, as described in the above sections. This air movement causes the upper room, and stairs, to have a larger impact on the thermal comfort in the main area of the building. The air temperature and velocity were measured 1.1 and 1.7 meters above the ground at the center of the staircase. This was also near the center line of the room, which was determined to be a good and fair indication of the main area. At 1.1 meters above the ground, the thermal comfort, and relative parameters such as air temperature and velocity, are measured for sitting occupants. At 1.7 meters above the ground, the air temperature and velocity are measured for standing occupants. These heights were chosen to be consistent with ASHRAE Standard 55 [2].

As explained above, the air temperature of the entire main area was set to 24.44 °C at the start of every simulation. With the air coming down the stairs, the air temperature has a drop near the stairs, as shown below in Figures 53, 54, and 55. This is due to the cool air coming down the stairs and dumping into the main area. As the temperature of the upper room has lower air temperatures to begin the simulation, the main area sees a larger drop in air temperature around the staircase and eventually in the entire main area.

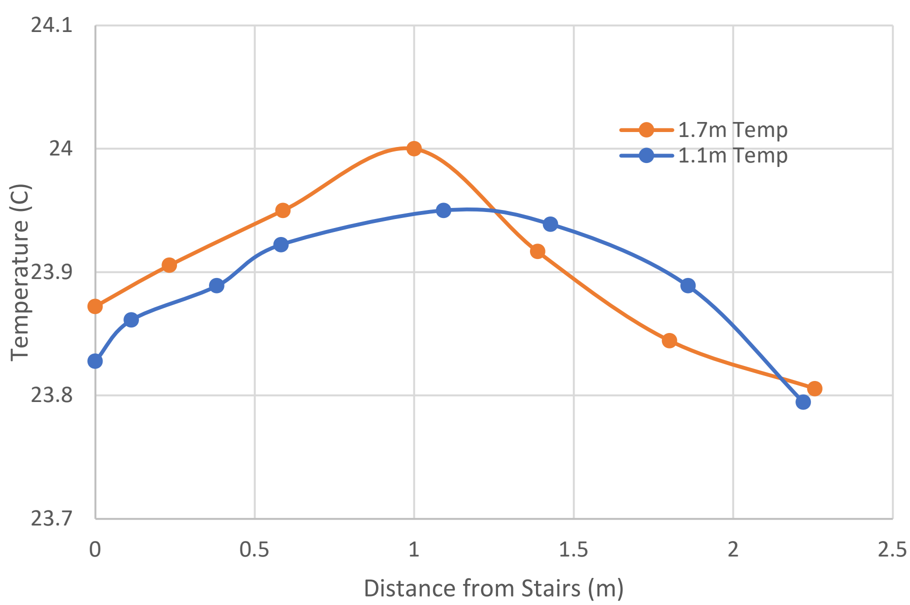

Figure 53. The air temperature, at 150 seconds, at 1.1 and 1.7 meters for the 150-second heating simulation is shown.

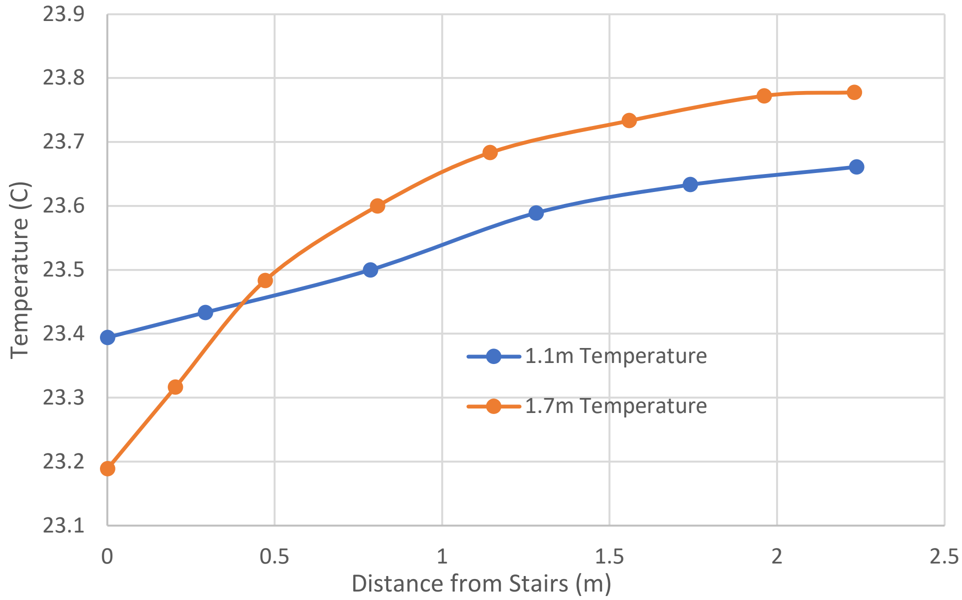

Figure 54. The air temperature at 1.1 and 1.7 meters for the 150-second heating simulation, with a 2 °C temperature difference, is shown.

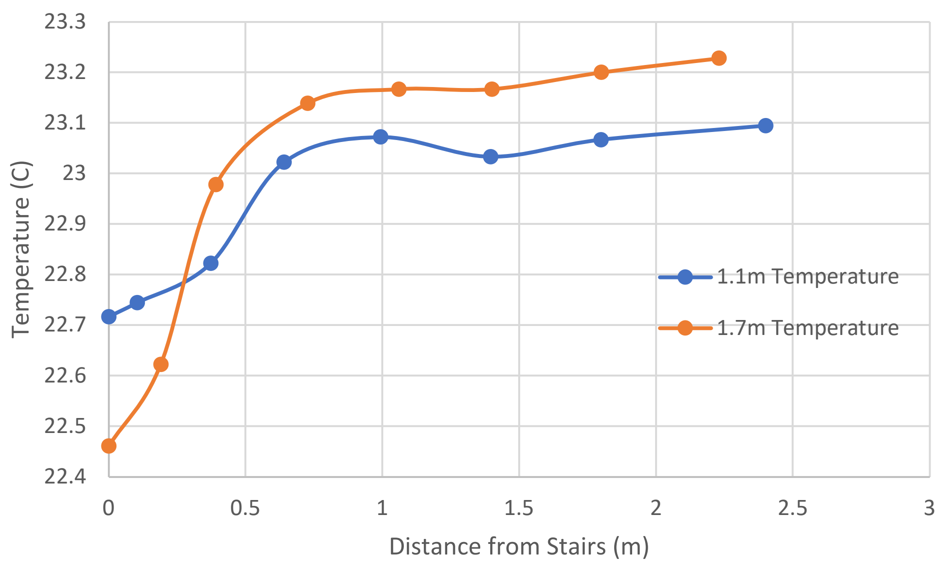

Figure 55. The air temperature at 150 seconds 1.1 and 1.7 meters for the 150-second heating simulation, with a 5.5 °C temperature difference, is shown.

The trend shown above in 150 seconds for air temperature can be seen in the 600-second simulation as well. With the standard setup, with the main area and upper room having the same start temperatures, there is a smaller temperature range in the data. This is due to the relatively cool air leaving the upper room and mixing with air that is of similar temperature in the main area. However, when there is a 2 °C or 5.5 °C temperature difference, the temperature range in the figures is larger than the standard setup of the same simulation length. This directly shows the influence of the air dumping into the main area. In addition, as shown by Figure 55 above, the temperature of the main area sees a significant drop in just two and a half minutes when the temperature difference is 5.5 °C. As shown in Figure 54, the main area has a smaller decrease in temperature when the temperature difference is 2 °C to begin, but the drop in air temperature near the stairs is still noticeable.

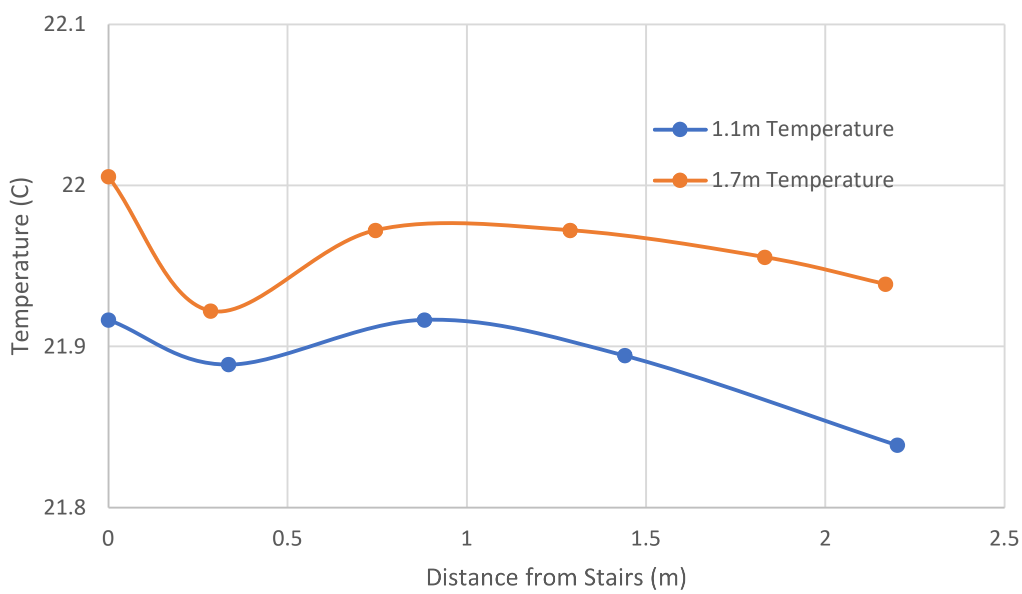

Figure 56. In the figure above, the air temperature, at 600 seconds, at 1.1 and 1.7 meters for the 600-second heating simulation is shown.

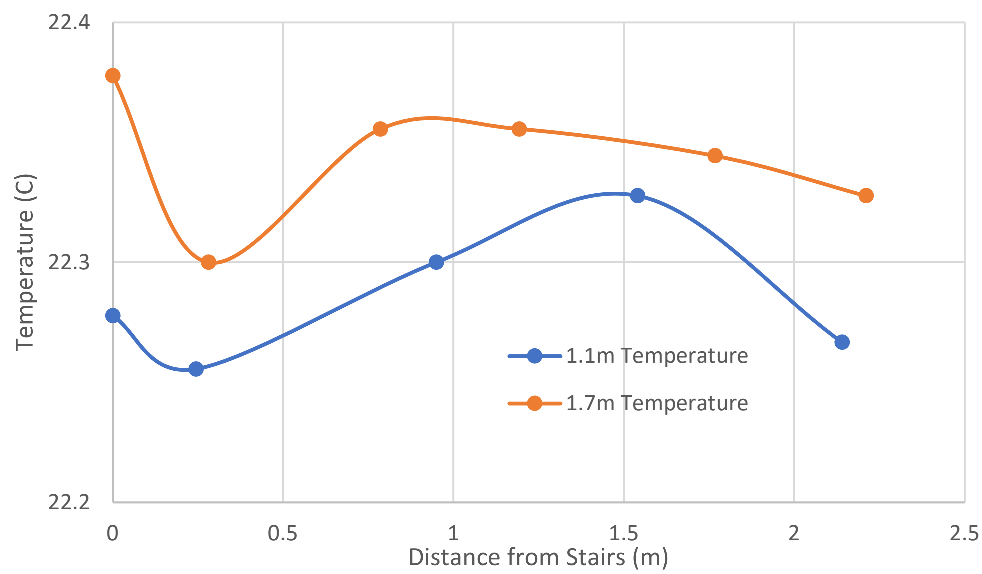

Figure 57. The air temperature at 1.1 and 1.7 meters for the 600-second heating simulation, with a 2 °C temperature difference, is shown.

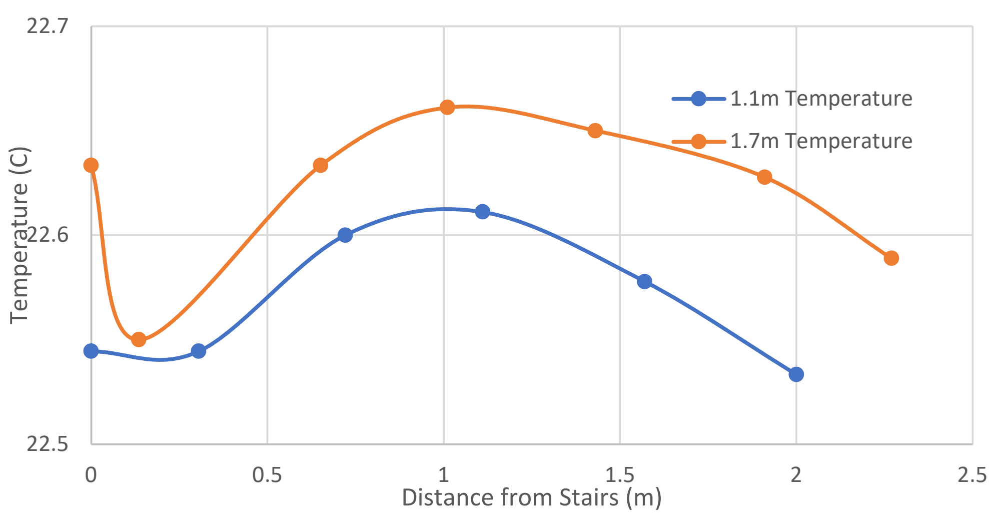

Figure 58. In the figure above, the air temperature, at 600 seconds, at 1.1 and 1.7 meters for the 600-second heating simulation, with a 5.5 °C temperature difference, is shown.

The trend of having a low data point around 0.25 to 0.5 meters from the stairs continued in the 600-second simulation, as shown by Figures 56, 57, and 58. The air temperatures are noticeably lower in the 600-second simulation relative to the 150-second simulation. The air temperature difference between the standard set up in the 150-second simulation and 600-second simulation is over 1 °C difference in the main area. When there is an initial temperature difference of 2 °C and 5.5 °C, the 600-second simulation has data points with a temperature around 1 °C lower than the 150-second simulations, at similar locations, with the same setup.

In 600 seconds, with the standard set up, the main area has a temperature drop of around 1.8 °C from the initial temperature, as shown by Figure 56. In the 600-second simulation with a 2 °C initial temperature difference, the average temperature in the occupied zone of the main area was around 2 °C lower than the initial temperature, displayed in Figure 57. With a temperature difference of 5.5 °C in the 600-second simulation, as shown in Figure 58, the main area has a temperature of almost 2.5 °C lower than the initial temperature. When comparing the figures from the 150-second simulations to the figures from the 600-second simulations, the lowest air temperature in the main area is around the staircase in every scenario. This trend quantitatively shows the impact of the cool air from the upper room flowing down the stairs and dumping into the main area. In addition, the average temperature in the main area is lower in the 600-second simulation than in the 150-second simulation. The average temperature decreases more when there is an initial temperature difference to begin the simulation.

The air velocity was also measured in the same fashion as the air temperature. Data points were taken from each scenario at 1.1 and 1.7 meters from the ground. As shown in Figures 61-66, the air velocity has a maximum value near the stairs. These large values are due to the air coming down the stairs and dumping into the main area. When comparing Figures 59, 60, and 61 below, the air velocity near the stairs increases when there is an initial temperature difference. In addition, when comparing the figures from the 150 simulations to the 600-second simulations, the air velocities for the 600-second simulations are lower. The lower air velocities are due to the air flow calming over time and moving towards a steady state. In the early stages of the simulation, the cool air from the upper room moves down the stairs at higher speeds due to the large difference in buoyant forces.

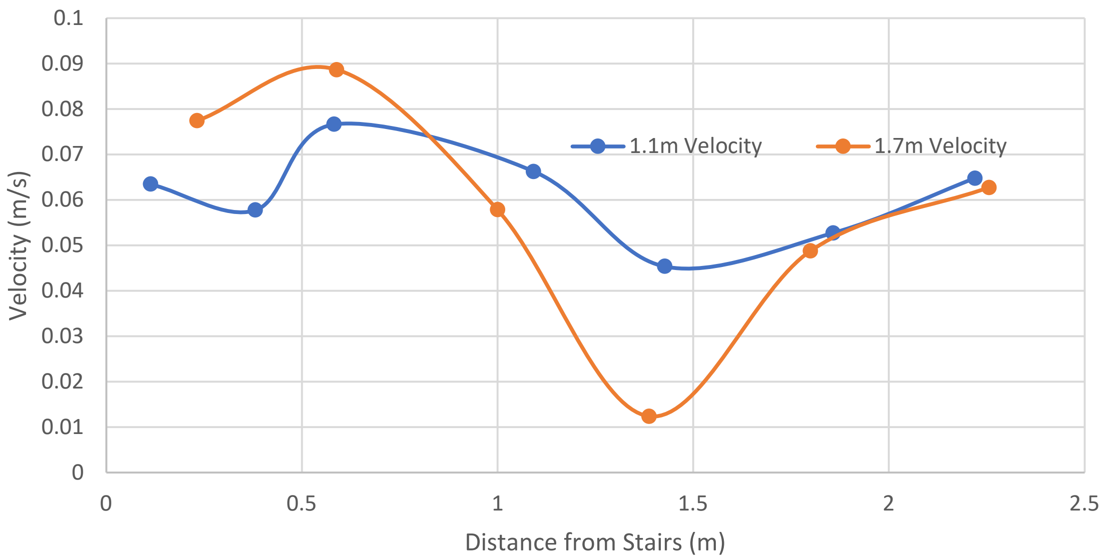

Figure 59. The air velocities at 1.1 and 1.7 meters for the 150-second heating simulation are shown.

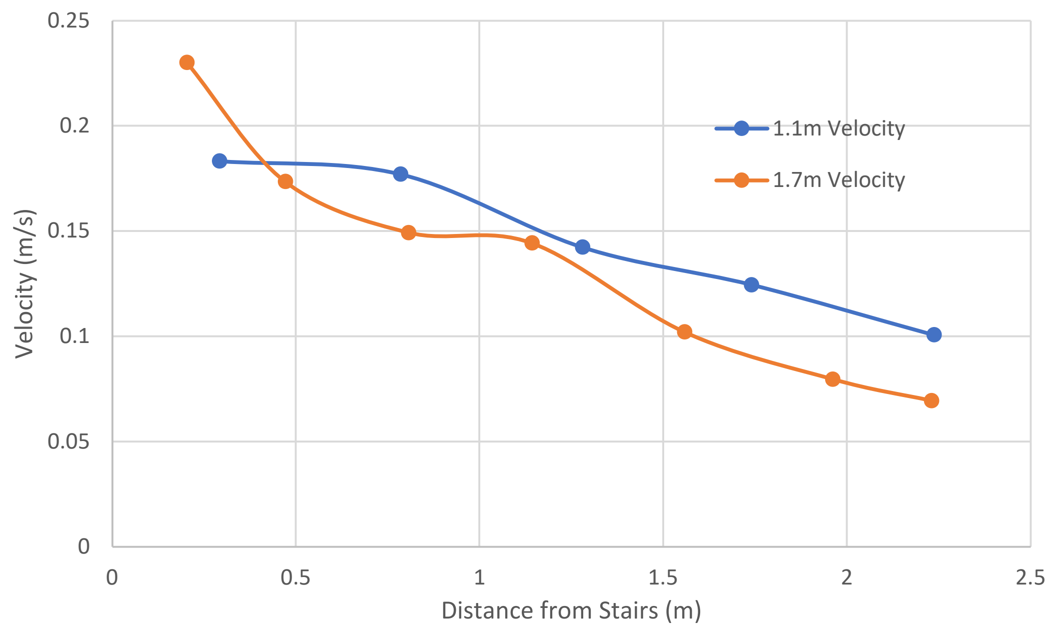

Figure 60. The air velocities at 1.1 and 1.7 meters for the 150-second heating simulation, with a 2 °C temperature difference, are shown.

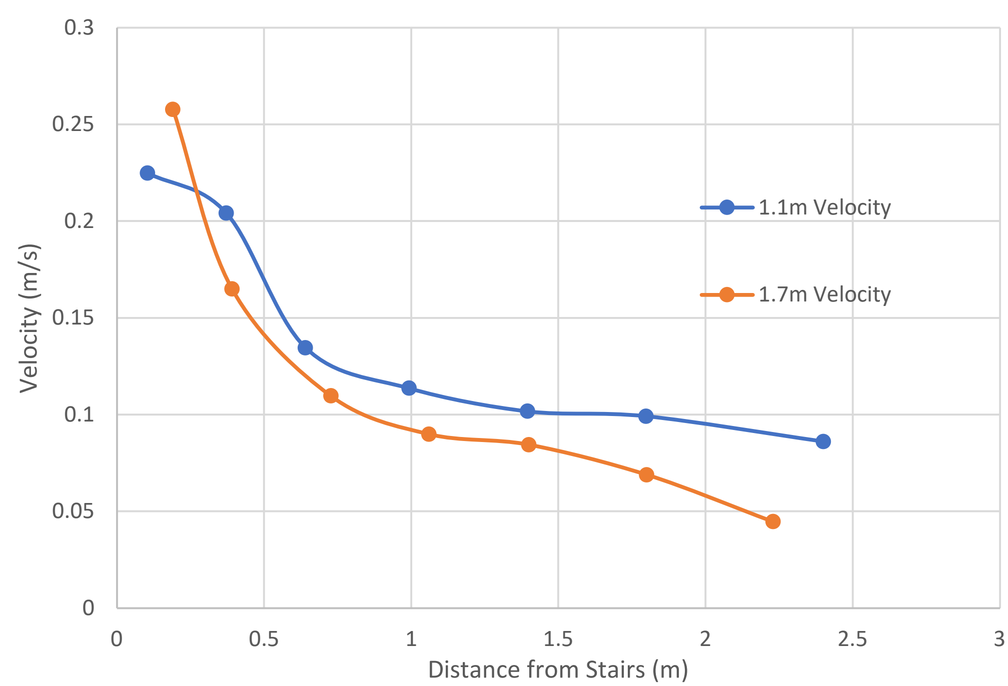

Figure 61. The air velocities at 1.1 and 1.7 meters at 150 seconds in the heating simulation, with a 5.5 °C temperature difference, are shown.

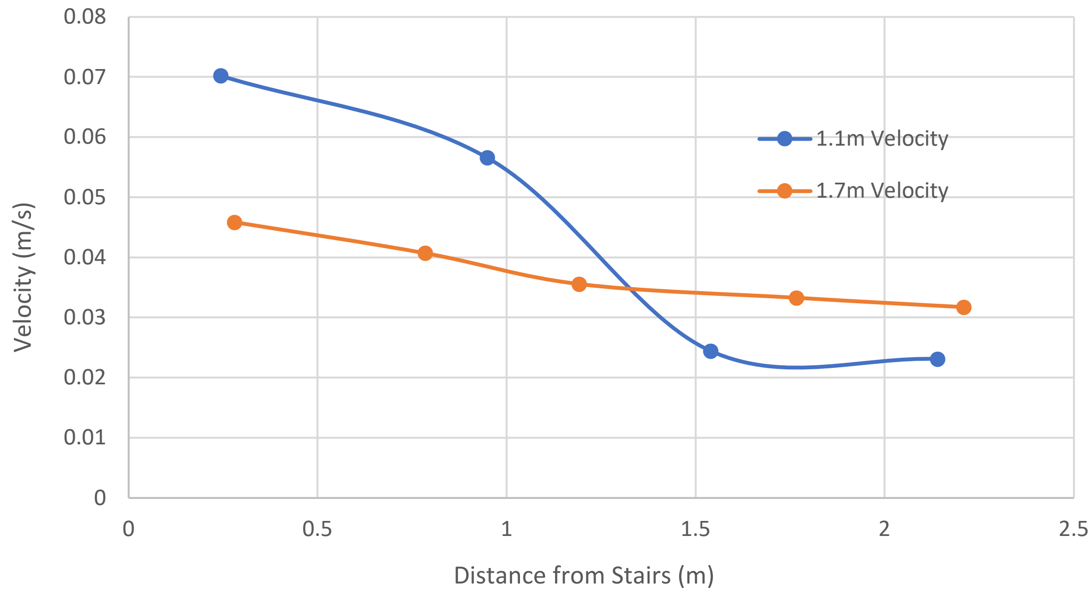

Figure 62. The air velocities at 1.1 and 1.7 meters for the 600-second heating simulation are shown.

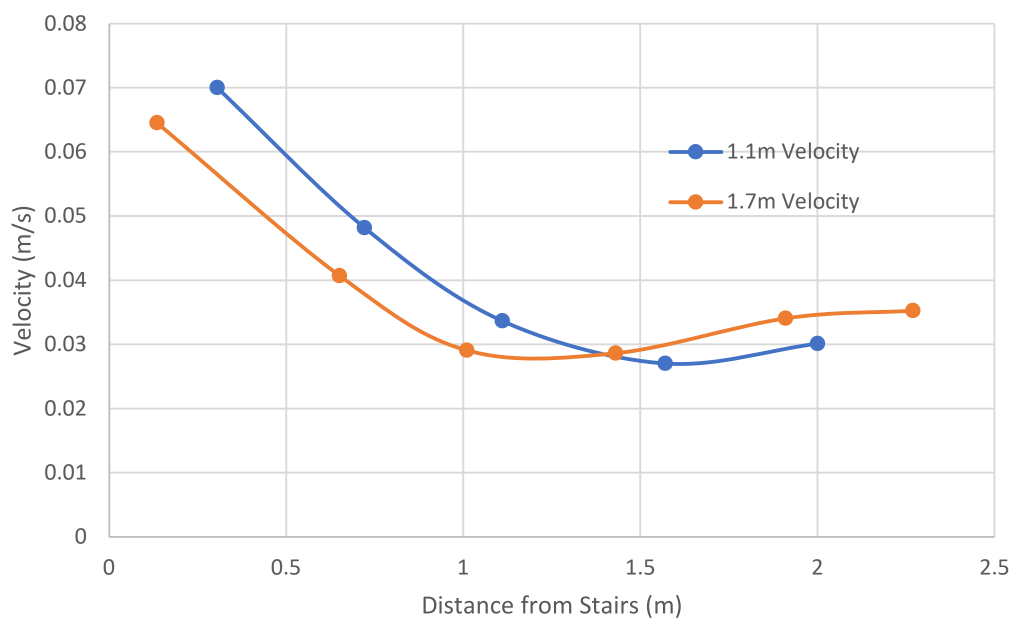

Figure 63. The air velocities at 1.1 and 1.7 meters at 600 seconds in the heating simulation, with a 2 °C temperature difference, are shown.

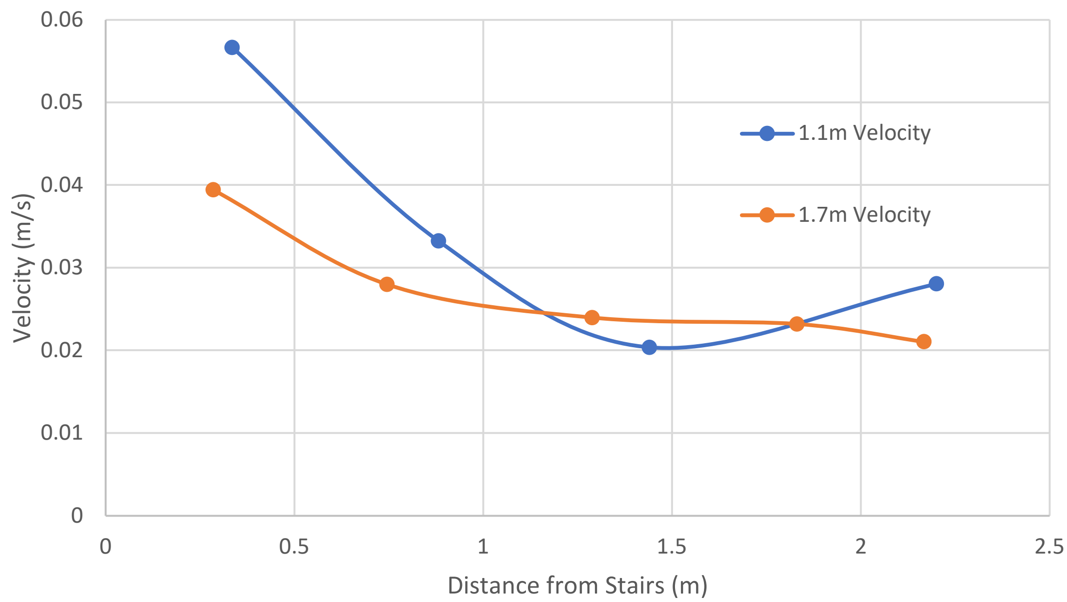

Figure 64. The air velocities at 1.1 and 1.7 meters for the 600-second heating simulation, with a 5.5 °C temperature difference, are shown.

The increase in air speed and lower air temperature around the staircase impacts the thermal comfort on and around the staircase. The Predicted Mean Vote (PMV) is the thermal comfort parameter measured in the simulations, as explained above, and is related to the air speed and temperature. Figures 65, 66, and 67 below display the drop in PMV around the staircase for the various scenarios in the 150, 360, and 600-second simulations. Since the initial temperature of the main area was 24.44 °C, the PMV for the main area was zero at the start of every simulation. The air temperature of 24.44 °C with a very low air speed is considered ideal for thermal comfort according to ASHRAE Standard 55 [6].

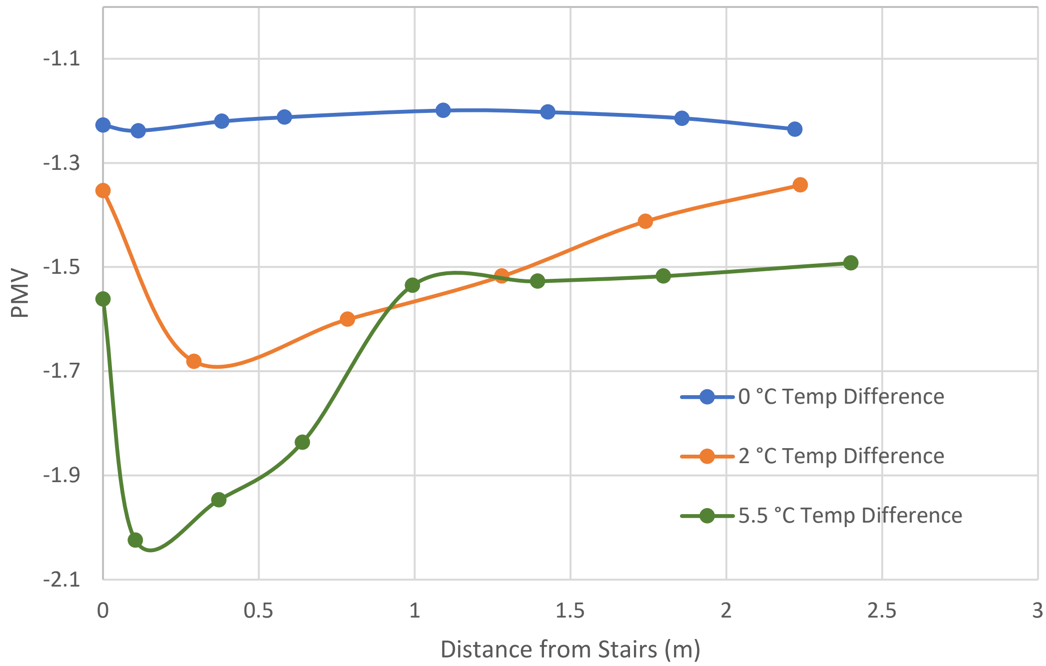

Figure 65. The Predicted Mean Vote in the main area at 150 seconds is shown.

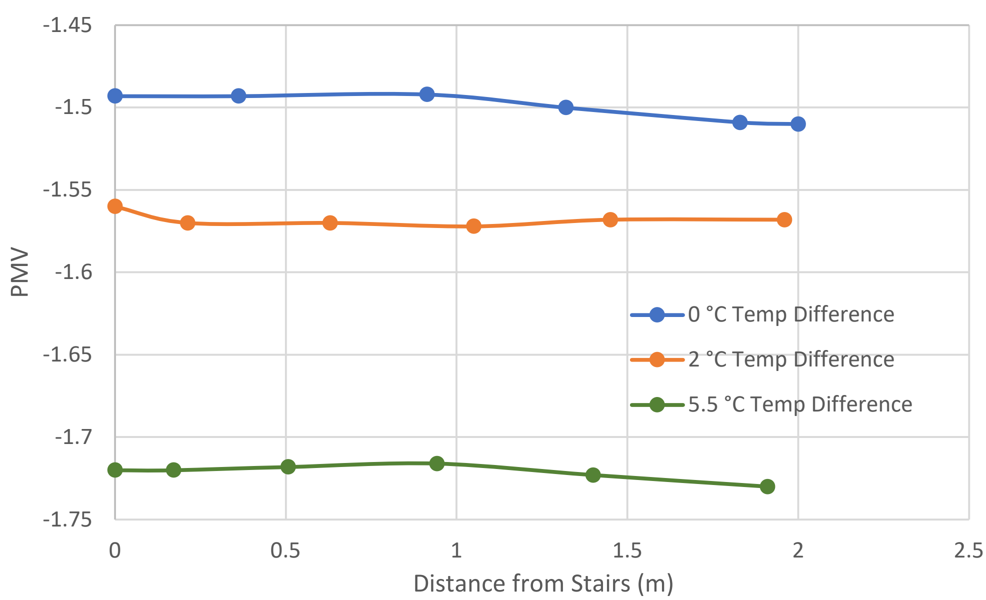

Figure 66. The Predicted Mean Vote in the main area at 360 seconds is shown.

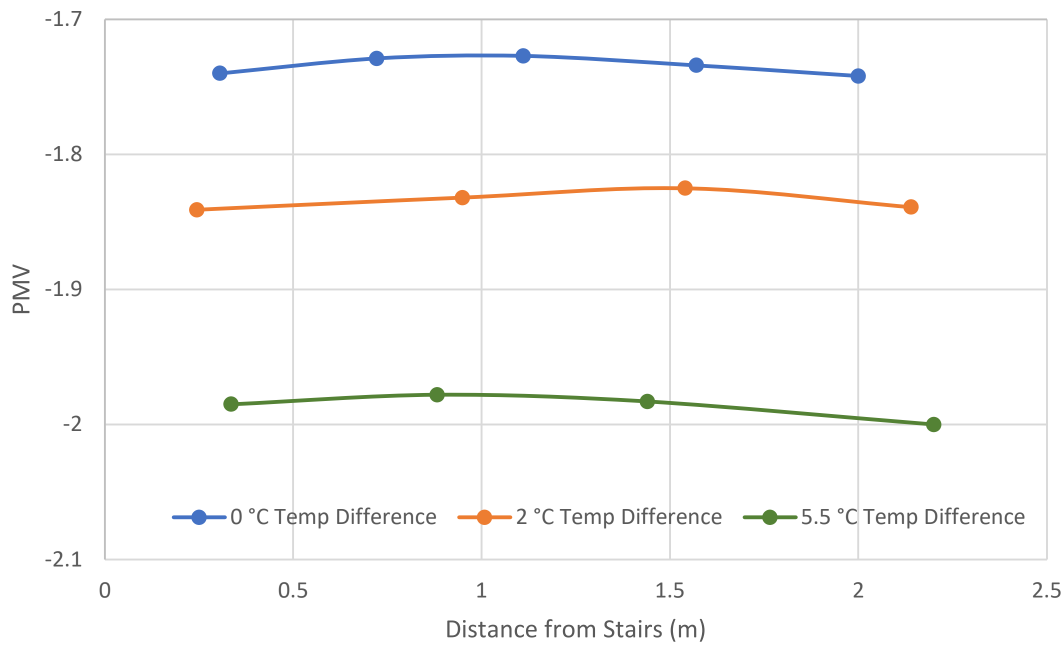

Figure 67. The Predicted Mean Vote in the main area at 600 second is shown.

In Figure 65 above, the PMV dropped below negative one in 150 seconds for each scenario. The negative one on the PMV scale is considered slightly cool and people begin to feel uncomfortable. When looking at less than a meter from the stairs, the PMV drops around negative two for the scenarios with an initial temperature difference. This low PMV measurement is considered cool, and uncomfortable, for the occupants. The average PMV measurements for the entire occupied zone in the main area are below negative one for all three scenarios after 150 seconds. This shows that the cool air, combined with the increased air speed, dumping into the main area negatively affects the thermal comfort.

The same is shown for the ten-minute simulation in Figure 67. The PMV for all three scenarios is well below negative one and nearing negative two. These PMV values indicate that an occupant would feel cool in these areas. When comparing the figures from the two simulation lengths, the drop in PMV near the stairs is not shown in the 600-second simulation as in the 150-

second simulation. This is most likely due to the air flow nearing a steady-state value after ten minutes of circulation, so the low air temperature is the main contributor. The constant values of the PMV indicate that the entire main area is now cool for all the occupants.

The combination of airflow down the stairs and the natural circulation occurring near the walls causes a very large drop in the PMV in the occupied zone of the main area. Since the air leaving the room is flowing down the stairs, the air flowing down the wall directly over the stairs combines with cool air from the room, as described in the above sections. This creates a lower PMV measurement near the staircase that the temperature alone does not account for. The low-temperature air moving down the stairs coupled with the increased airspeed creates a more uncomfortable environment for the occupants in the main area.

In conclusion, for the 150 second simulations, there was a 0.80-1.68 °C decrease in average temperature for the main area. In addition, the airspeed around the stairs ranged from 0.06-0.23 m/s in these simulations. The larger values come from the simulations with the 5.5 °C initial temperature difference. For the 600 second simulations, the decrease in average temperature in the main area ranged from 2.12-2.79 °C. However, since the air had longer to find a steady-state in the 600-second simulations, the average airspeed around the stairs ranged from 0.057-0.07 m/s. The PMV for the 150-second heating simulations has a drop in value around the stairs, specifically within 0.5 meters from the stairs towards the center of the main area due to the increased airspeed. With the initial temperature differential between the upper room and main area, the PMV has a noticeable decrease in all heating simulations. For the 150 second simulations, looking at less than 0.5 meters from the stairs, the PMV has a difference of almost 0.80. When moving farther away to where the values become constant, the difference in PMV is around 0.2. For the 600 second simulations, the values are somewhat constant regardless of distance from the stairs. Again, this is most likely due to the lower airspeed around the stairs since the simulation length allows the air more time to find a steady state. The difference in PMV values in the 600-second simulations is between 0.20-0.25. However, the PMV reached values of -1.73 to -2 for the 600-second simulations, which is an uncomfortable environment for occupants.

5. SUMMARY AND CONCLUSION

The work reviewed the impact of air exchange between floors, connected by stairs, on the thermal comfort in a building using CFD simulations. In both cooling and heating scenarios, the influence of the upper room and staircase harmed both the thermal comfort and energy usage in the building. With the various scenarios simulated, the largest impact from both perspectives was seen when there is an initial temperature difference between the upper room and main area of the building. When the temperature difference increases, the impact on the thermal comfort also increases. Similarly, the larger temperature difference results in a larger system energy usage to counteract the influx of air from the upper room into the main area. When the cycle time increases in duration, the thermal comfort worsens due to the air from the upper room flowing down the staircase.

The cooling scenarios had a slight impact on the energy usage and thermal comfort. The most severe case for the energy impact was the shorter cycle time of 150 seconds with an initial 5.5 °C temperature difference between the upper room and the main area. In the cooling scenarios, the upper room and staircase had only a slight impact on the thermal comfort in the main area. For the shorter cycle times, of two and a half minutes, there were minimal effects on the thermal comfort. For the ten-minute cycle time, the upper room and staircase had a slight impact on the thermal comfort in the main area. This is most likely due to the air leaving through the top of the upper room doorway and not directly flowing down the stairs, which did not result in a noticeable increase in airspeed or immediate drop in temperature around the stairs.

In the heating scenarios, the decrease in temperature in the main area was more rapid and considerable than in the cooling scenarios. Since the cooler air leaving the upper room is flowing directly down the stairs, there is a more noticeable and significant impact on the thermal comfort in the main area. This can be seen in the change in temperature and PMV around the stairs. The impact is clearly seen in the drop in PMV during the ten-minute cycle time, which reached values as low as -2. This shows that in ten minutes of the system being cycled off, the occupants in the main area begin to feel uncomfortable due to the influence of the upper room and stairs.

When an area's HVAC system is turned off, or has a very broad set point range, there is an energy savings associated with reducing operating time. However, as seen in the above research, the lack of environmental control in the above space has a negative impact on the thermal comfort in the below space. Therefore, there is a trade-off concerning the occupant thermal comfort of one area and the energy savings of another.

6. RECOMMENDED FUTURE RESEARCH

Since the above study is the first to identify the influence of an upper room and staircase over a larger main area, other aspects of this subject can be studied and improved.

- Given that only CFD simulations were conducted on this subject, the agreement of the above results with experimental results could be explored.
- The above study only considered the short-term effects of the upper room and staircase using CFD simulations, so the influence over a longer period could be investigated.
- The influence of the size ratio of the upper room to the main area could be examined. A larger upper room would be expected to have a larger influence on the main area since there would be a larger influx of air. In addition, different building configurations should be considered.
- An evaluation of various staircase designs and nearby HVAC supply/return- air grills may be warranted. Of interest are designs that direct or force air exchanging from the upper floor in ways that minimize or eliminate negative comfort impact.
- Because there seems to be a trade-off due to space use and occupant comfort, the design architectural layout of where occupants are in proximity of a staircase should be studied.

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