

Numerical Analysis of Thermal Environments Achieved by Different Indoor-Unit Types of Decentralized Air-Conditioner in South Korean Residential Buildings

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ABSTRACT: This research was conducted as a fundamental study in presenting efficient installation standards for decentralized air-conditioning systems in residential buildings. Ergo, the study observed the current status and issues of residential air-conditioning in South Korea and selected the most commonly used indoor package air-conditioning system types. Then CFD numerical analysis was performed to compare and analyze the indoor thermal environment achieved by each type of package air-conditioning system.

Keywords: thermal environment, indoor air-conditioning unit, residential building

1. INTRODUCTION

Active discussions and debates across the globe on the subject of sustainable developments have led to global and multifaceted efforts aimed at energy-savings. South Korean researchers and scientists have also responded to this international trend and embarked on seeking out new energy solutions. One of the major energy-related issues in South Korea today is the elevating living standards and the consequent increase in the level of heating and cooling energy consumption by residential buildings.

Owing to the country's relatively short summer season and the distinct lifestyle of its citizens, designing and building residential buildings in South Korea have historically focused solely on heating systems and with very little regard for air-

conditioning systems. This means that South Korea has no energy consumption standards or design guidelines whatsoever when it comes to residential air-conditioning systems and that residents in the country still rely on purchasing and installing decentralized air-conditioning units for their homes as their individual needs and means allow.

Specifically, increasing air-conditioning loads brought on by the taller and increasingly hermetic designs of modern residential structures and greater demand for residential comfort in respect to indoor thermal environment transformed the air-conditioning system into a must-have feature in residential buildings.

This development led to an increase in the number of unregulated package air-conditioning system installation cases, which in turn gave rise to various problems

for the nation and individual users during cooling seasons.

Accordingly, this paper serves as a fundamental study presenting standards for installation of residential energy-efficient package air-conditioning systems and compares indoor thermal environment achieved by different types of indoor air-conditioning systems. The paper describes the current status and issues of residential air-conditioning in South Korea and identifies the most common indoor package air-conditioning system in use. Lastly, the paper summarises CFD numerical analysis results gained from comparing the temperature conditions achieved by the different types of package air-conditioning systems.

2. ISSUES WITH DECENTRALIZED PACKAGE AIR-CONDITIONING

2.1 On the National Level

Korea Power Exchange (2006) reported that the penetration rate of air-conditioners in 1985 was 0.02 per house, and that it increased year on year until it reached 0.48 per house in 2006, a steep 14.29% increase from 0.42 in 2004.

Package air-conditioners use electricity to power their compressors. Therefore, the penetration increase of a highly electric, energy-dependent air-conditioner will lead to an increase in the electricity consumption. It will also lead to an increase in the maximum power demand and to a decrease in the power reserve rate in summer, which is expected to stir the public. Moreover, it will cause a considerable increase in the power demand in summer, which will in turn induce an increase in the investment expense for the expansion of the power generation plant and to a decrease in the usage rate of power supply facilities, which will decrease the effectiveness of the national power supply system. The increase in power demand and the decrease in the effectiveness of the power supply system

will result in an increase in the CO₂ emission due to the increase in the primary energy needed to produce electrical energy.

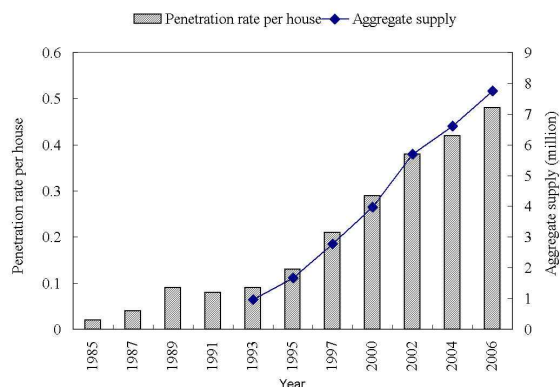


Figure 1: Changes in residential air-conditioning system ownership and supply by year

2.2 On the Personal Level

Progressive taxation applies to residential electric charges in South Korea, based on the amount of electrical power used by the household. Therefore, when a household operates a package air-conditioner in summer, it should pay the weighted charge, the additional electric charge for the package air-conditioner. For example, if a household consumes 300KW electricity per a month on average, the corresponding electric charge is 39,960 won (about 42 USD), calculated using the usual method as of May 2008. If the household, however, uses a package air-conditioner that consumes 2KWh electricity for 8 hour per a day, for 30 days per a month, in summer, the total amount of electricity consumed in a month will be 780 KWh, and the household should pay 326,600 won (about 344 USD), 286,640 won (about 302 USD) more than what it paid in those months that it did not use a package air-conditioner. Consequently, the electric charge will be 8.2 times more despite the fact that the weighted charge covers only 2.6 times the actual amount of electricity consumed. Such energy expense burden serves to discourage people from using air-conditioners even when they need it.

The phenomenon caused by the air-conditioning energy expense burden also influenced the installation locations and operation times of air-conditioners in Korea. In Korea, air-conditioners are most often installed in the living room, where all the family members usually gather. As for the operation time, the ratio of the households that restrictively operate air-conditioners between 7 p.m. and 9 p.m., when all the family members gather together, is very high.

Another problem that is caused by the energy expense burden is the indoor air quality. Users tend not to ventilate while the air-conditioner is in operation, to prevent the indoor temperature from rising due to the entry of the warmer air from outside. This operation pattern causes many problems, such as the contamination of the indoor air and of the air-conditioning system as there is no ventilation when the air-conditioner is being operated.

2.3 Evolution of Indoor Air-Conditioning Unit Type

The mass production of air-conditioners began in the late 1960s. Since then, the air-conditioning system has developed in a variety of ways, according to the consumers' need for greater cooling capacity and for premium and multifunction products. Indoor air-conditioning systems are classified into the first-generation window type, the second-generation wall mounted type, the third-generation floor standing type, and the fourth-generation ceiling cassette type. Since recently, most houses have been using package air-conditioners, particularly the wall mounted, floor standing, and ceiling cassette types.

3. OVERVIEW OF CFD ANALYSIS

3.1 Target Space

The most common-sized and common-shaped Korean house was selected as the target space for the CFD numerical analysis

that was conducted in this study, as shown in Fig. 2. The target space was also limited to the living room area, considering the fact that the most common installation place of air-conditioners in Korea is the living room. In addition, since the living room area is generally connected to the kitchen and other adjacent rooms by a spacious aisle, the adjacent open area was also included in the target space so that the interaction effect of the adjacent open area with the living room could be examined. The dimensions of the target space were 7.1m (W) × 8.1m (D) × 2.3m (H), and it had a floor area of 36.6 m².

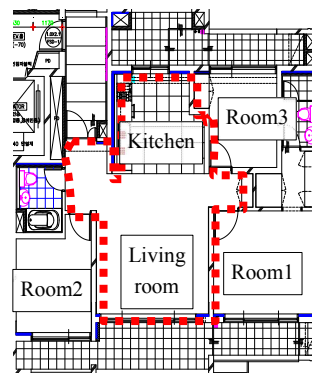


Figure 2: CFD analysis space floor plan

3.2 Analysis Case

For the analysis, figural copies of the wall mounted, floor standing, and ceiling cassette types that had been installed in the target space were made. An individual package air-conditioner consists of an indoor unit and an outdoor unit. As regards the arrangement of the indoor and outdoor units, the outdoor unit is generally installed at the terrace, and the indoor unit in the living room, near the terrace, to increase the effectiveness of the installation and the efficiency of the air-conditioning by shortening the length of the refrigerants' pipe. The installation place for the indoor unit in each case is as shown in Fig. 3.

3.3 Mesh for CFD Analysis

Tetrahedral mesh was used for the space division for CFD analysis. Although slightly different for each analysis case, the volume

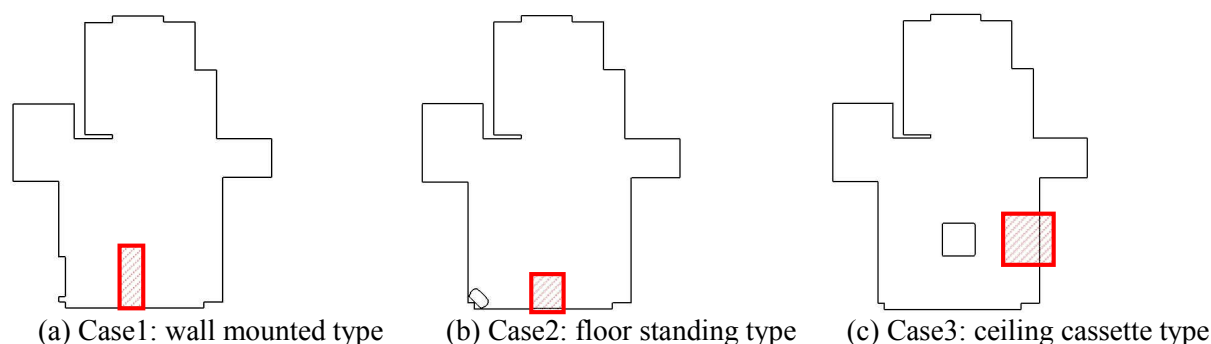
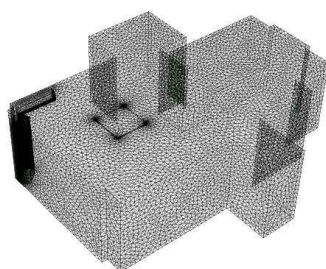
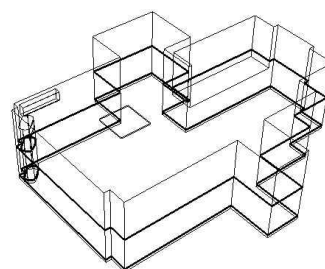


Figure 3: CFD analysis case



(a) Mesh for CFD analysis



(b) Analysis section

Figure 4: CFD analysis mesh and result sections

was divided into 150,000 volume meshes and the surface into 300,000 surface meshes. Analytic findings of this paper express the results from sections on Figure 4 (b) cross section diagram.

3.4 CFD Analysis Model and Boundary Conditions

CFD analysis utilized the standard $k-\epsilon$ turbulence model of STAR-CD, a commercially available CFD code, to derive steady and unsteady state analysis. Boundary conditions are listed in Table 1.

The indoor thermal environment in all the cases, according to the indoor unit type, was examined at equivalent supply air temperature and volume condition by fixing the volume and the temperature at equivalent level. Assuming that the target space was located at the middle of the floor and that the adjacent rooms were also air-conditioned, with temperatures equivalent to that of the target space, the walls were set as adiabatic. The windows of the living room and of the kitchen were the areas that came in contact with the outside air, whose

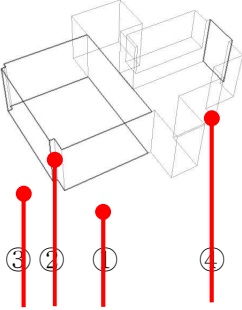
temperature was set at 309.3K. The heat transfer coefficient was $3\text{W/m}^2\text{K}$. The heat transfer from the human body was set based on 70W (sensible heat) for 1.1 met for an adult man, amounting to a total of 234.5W for a family of four (one male adult, one female adult, and two children). In addition, assuming that the heating rate from the basic electric home appliances was 100W, a total of 334.5W of heating was evenly distributed to the about 15.7m^2 living room floor on the plane figure. The heat from the lights was set at 15W/m^2 from the ceiling.

Radiation calculation was performed for all cases to factor in the effects of radiation. Unsteady state analysis's runtime was set to 0.1 second intervals from 0 for 410 seconds.

3.5 Indoor Thermal Environment Analysis Method

To analyze the indoor thermal environment conditions achieved by the different types of indoor air-conditioning units, unsteady state analysis was conducted on volume averaged temperature decline patterns 1.5m and below the occupied zone

Table 1: Boundary conditions for CFD analysis

Wall				Body and equipments load (①)	• Body convective heat transfer: 234.5W 1) Male: 70.0W (100%) 2) Female: 59.5W (85%) 3) Childs: 52.5W (75%)×2(person) • Equipments: 100W
				Lighting load (②)	• 15W/m²
				Convection (③, ④)	• Outdoor temperature: 309.3K • Heat transfer coefficient: 3W/m²K
				Radiation	• Emissivity: 0.9 • Reflectivity: 0.1
Air-conditioning	Supply air	Case1	Case2	Case3	
		• Volume: 0.2m³/s • Temperature: 291K • Velocity: 2.4m/s • Size: 0.98m×0.085m • Direction: Downward 15° • Turbulence intensity: 10%	• Volume: 0.2m³/s • Temperature: 291K • Velocity: 1.9m/s • Size: 0.44m×0.24m • Direction: Upward 30° • Turbulence intensity: 10%	• Volume: 0.2m³/s • Temperature: 291K • Velocity: 1.7m/s • Size: 0.42m×0.07m×4 • Direction: Downward 30° • Turbulence intensity: 10%	
	Return air	• Size: 1.09m×0.11m	• Size: 0.07m×0.86m×2	• Size: 0.46m×0.46m	

for all the cases, under identical cooling wind velocity and temperature. Furthermore, steady state analysis was performed to compare the air current field, temperature distribution, wind velocity distribution, and other indoor temperature conditions achieved under the different cases. The range of evaluation was limited to the living room in consideration of the lifestyle of the South Korean people.

4. CFD ANALYSIS RESULTS

4.1 Air Current Field

In Case1 (wall mounted type), the air current exiting from the unit's vent immediately followed along the ceiling until met with a wall in the direction of the current and then suddenly drops down and spreads out wide, moving toward the kitchen, an adjacent open area. The air current from Case1 circulated the entire living room and the kitchen.

In Case2 (floor standing type), the air current moved a relatively long distance along the ceiling until it met the wall structure of a corridor that leads into an adjacent room. At this point, the air current simply dispersed. In addition, the succeed-

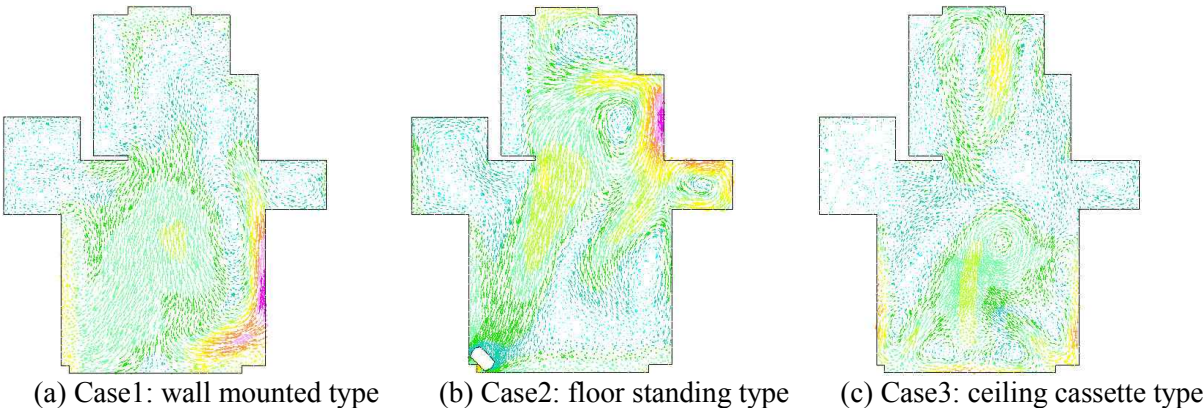
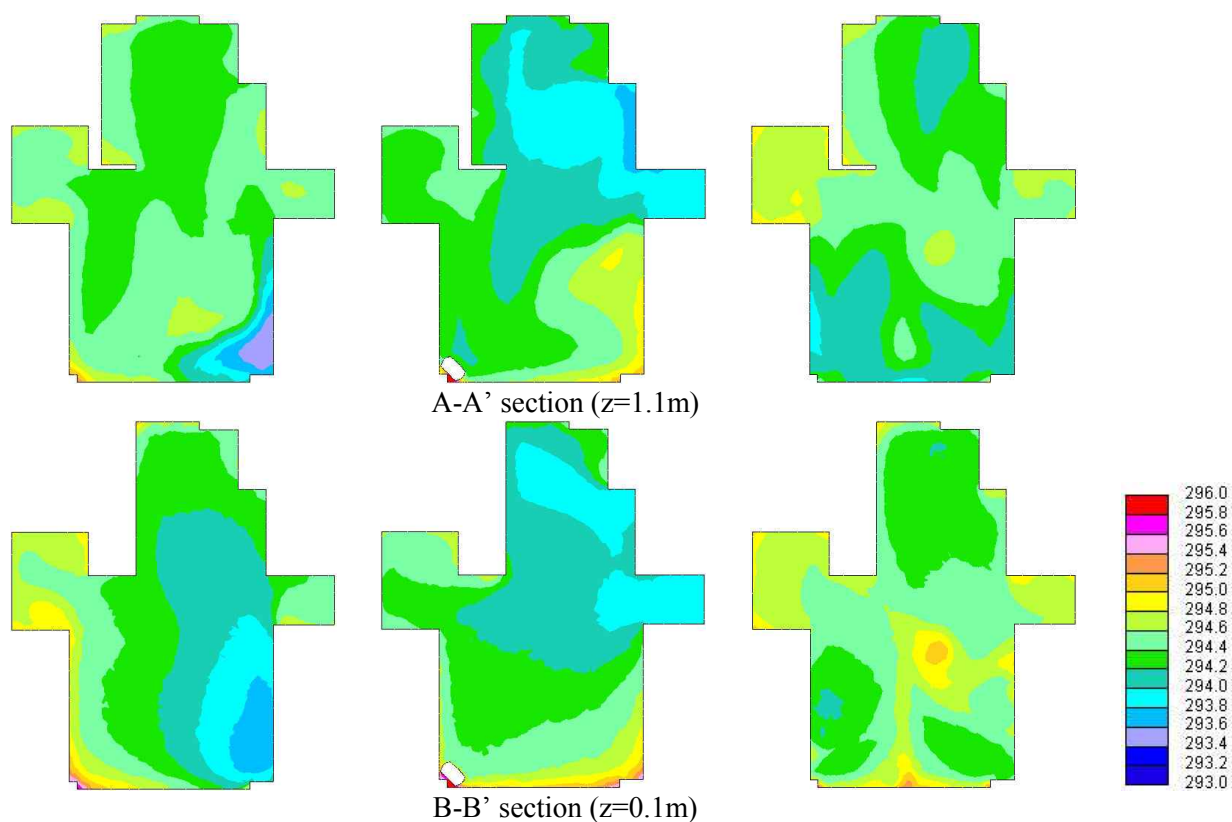


Figure 5: A-A' (z=1.1m) cross section air current field by case



(a) Case1: wall mounted type (b) Case2: floor standing type (c) Case3: ceiling cassette type

Figure 6: A-A'(z=1.1m), B-B'(z=0.1m) cross section temperature distribution by case

ing air current met with the original current to divide the current stream in two parts along their original path inside the target space.

In Case3 (ceiling cassette type), the air current exited in four directions. The cold air travelled along the ceiling until it met a wall structure in the direction of its travel and then quickly dropped down to the floor. Compared to other cases, air current in Case3 travels inside the space at a relatively low velocity albeit in multiple directions and thus forms limited and yet even air current fields inside the living room, where the unit is installed, and the kitchen, an adjacent area.

4.2 Temperature Distribution

In Case1 (wall mounted type), the air current that exits the unit toward the opposite wall and circulate through the kitchen and the living room lowered the temperature below the ambient level. In addition, temperature near the floor was low.

In Case2 (floor standing type), the air current's flow split into two parts in the direction of its travel, lowering the temperature in parts of the kitchen area, which is on the left of the direction of travel. The air current created a dead zone at the lower right corner of the living room (on the right of the direction of travel), and the air current was unable to directly reach the dead zone. Therefore, the temperature in this zone was approximately 1K higher than the surrounding air.

In Case3 (ceiling cassette type), temperature in the living room and the kitchen (an adjacent room) was lower than other areas. This is attributed to the fact that cold air travels in four directions and travels through the living room and the kitchen in a shorter duration of time. Furthermore, the air-conditioning unit in Case3 has more vents than units from Case1 and Case2. The vents themselves are smaller, cold air exits at a relatively lower velocity, and the vents

are located on the ceiling (farthest away from the floor) in Case3. Ergo, chilled air exiting the unit mixes with the surrounding air before reaching the lower section of the rooms, resulting in not as effective delivery of cold air to these sections. This also means that temperature at the higher section is lower than in the lower section.

All cases exhibited slight differences in terms of temperature distribution. However, analyzing the volume averaged temperature at 1.5m and below levels in the living room produced figures of 294.30K for Case1, 294.39K for Case2, and 294.34K for Case3. In short, the average indoor temperature achieved by the indoor air-conditioning units is similar, irrespective of their type.

4.3 Time to Reach Set-Point

Indoor air-conditioning units from all the cases were started from an initial indoor temperature of 302.8K and then unsteady state analysis was performed to measure the time it took for each of the types to achieve 299K of volume averaged temperature at 1.5m and below levels in the occupied zone. Results of the analysis are described in Fig. 7.

Time to reach set-point 299K was 142.0 seconds in Case1 (wall mounted type), 144.0 seconds in Case2 (floor standing type), and 123.2 seconds in Case3 (ceiling cassette type). In addition, indoor temperature drops after reaching the set-point were realized in virtually identical sequence and intervals.

Case3's ceiling cassette type spread stable and fast supply of cold air toward living room enclosures, realizing the shortest configured temperature reaching time.

As for Case1 (wall mounted type), the initial temperature drop was quick due to the fast delivery of cold air, but the subsequent diffusion of the cold air into the kitchen and other adjacent open rooms was slowest in all the cases.

The large electricity consumption of package air-conditioning units is caused by the compressor. Turning off the compressor

unless necessary can therefore, reduce the air-conditioning unit's electricity consumption. Realizing this requires a high indoor temperature setting and effective distribution of cold air throughout the rooms. From this perspective, ceiling cassette types are more effective in terms of cold air distribution than stand or wall mounted type and thus uses the compressor less, suggesting at the lowest level of power consumption.

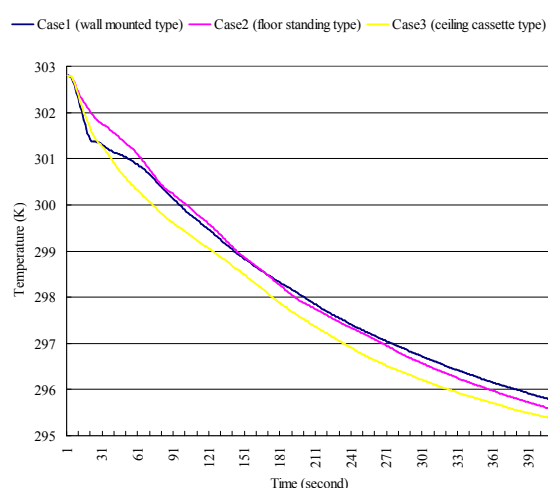


Figure 7: Living Room Temperature Changes following Commencement of Cooling

4.4 Wind Velocity Distribution

Volume average wind velocity at the 1.5m and below levels was 0.21m/s for Case1 (wall mounted type), 0.14m/s for Case2 (floor standing type), and 0.15m/s for Case3 (ceiling cassette type).

Fig. 8 depicts areas at 1.5m and below levels where the wind velocity exceeded 0.25m/s. Volume of areas where the wind velocity was exceeded than 0.25m/s was 6.0m³ for Case1, 1.2m³ for Case2, and 1.2m³ for Case3. Long-term exposure to such areas has a high probability of localization discomfort, due to the destruction of heat rising layer near the skin and draft. Case1's wall mounted type produces 0.25m/s or higher wind velocity at approximately 25% of the 23.5m³ of the indoor space and carries a high risk of draft-induced discomfort.

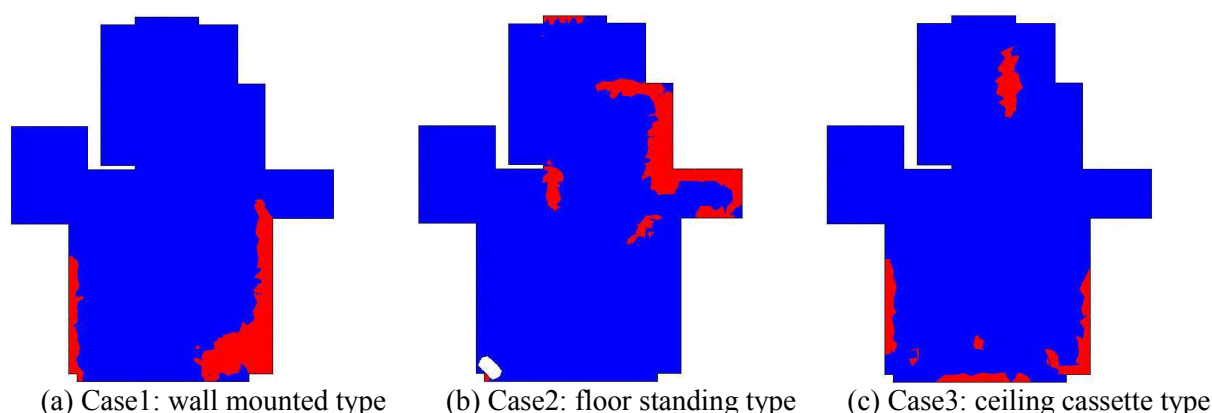


Figure 8: 0.25m/s or higher wind velocity zones in the living room (A-A'(z=1.1m))

5. CONCLUSION

As a fundamental study offering standards for energy-efficient installation of decentralized air-conditioning systems in residential buildings, this research compared different types of indoor air-conditioning units using CFD numerical analysis.

Assessment of volume averaged temperature formed at 1.5m and below levels all the cases achieved the identical average temperature. However, analysis of the duration it took for the air-conditioning unit to reach 299K from a preconfigured indoor temperature of 302.8K identified Case3 as the fastest, achieving the target temperature in 123.2 seconds. Therefore, ceiling cassette type achieved the temperature quicker than the other cases fixing volume and temperature. This means shorter running time for the decentralized air-conditioning system's compressor and that the ceiling cassette type is the most energy-efficient.

Assessing the volume of living room areas where the wind velocity exceeded 0.25m/s found that the wall mounted type carried the biggest risk of draft-induced discomfort.

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