

# Chapter 13

## Thermal Image Analysis of Singapore's Housing Infrastructure



**Balakrishnan Naveen Mani Kumar, Mothiki Eswara Anirudh, Dhanabalan Jeevakaarthik, Clayton Miller, and Filip Biljecki**

**Abstract** As a developed and densely populated city, Singapore proves to be a vulnerable victim of the effects of climate change. With Singapore heating up twice as fast as the rest of the world, it is highly important that factors contributing to it are identified and analysed to curb this issue and protect the well-being of the population and the environment. Firstly, with the many infrastructures that dot the city, Singapore falls prey to the urban heat island (UHI) effect. Secondly, with the use of air-conditioning accounting for 25% of the residential electrical consumption, cooling is still one of the largest energy demands for households and buildings. Hence, to obtain a better view as to how these factors come into play, thermal analysis of infrastructure was conducted. This was then coupled with simulations and analyses of thermal data of the flow of air around heated air-conditioning compressors. Results of these investigations revealed differences in temperature of the building with changes in altitude and also the pivotal role that the placements of air-conditioning compressors play in the dispersion of heat around compressors that are concurrently in use across multiple floors. This is crucial to investigate as this might affect the electrical consumption and electricity bills of households. This study also holds significance as it gives rise to a phenomenon known as the urban stack effect where temperature increases with increasing altitude due to the formation of a heat vortex. Moreover, with most modern infrastructures having a similar layout to the building studied in this investigation, this also allows for future studies to be conducted on the design of infrastructures that contribute towards the lessening of the UHI effect.

---

B. Naveen Mani Kumar · M. E. Anirudh · D. Jeevakaarthik  
NUS High School of Math and Science, Singapore, Singapore

C. Miller  
Department of the Built Environment, College of Design and Engineering,  
National University of Singapore, Singapore, Singapore

F. Biljecki (✉)  
Department of Architecture, College of Design and Engineering,  
National University of Singapore, Singapore, Singapore  
e-mail: [filip@nus.edu.sg](mailto:filip@nus.edu.sg)

## 13.1 Introduction

According to the Singapore Climate Research Centre, the city-state is heating up at a rate of  $0.25^{\circ}\text{C}$  per decade with an average temperature increase of  $1^{\circ}\text{C}$  since the 1950s [1, 2]. Climate research experts also believe that at the rate at which temperatures are rising, Singapore's daily maximum temperature could also reach up to  $37\text{--}38^{\circ}\text{C}$  [3]. Coupled with the high humidity levels Singapore faces daily, Singaporeans are in danger of a myriad of health risks such as elevated heat stress, dehydration in the near future. This has led to a high level of importance and essentiality being channelled towards investigating ways in which such rises in temperatures can be countered. Hence, research is currently being done to understand the key contributors to such elevated temperatures and high rates of heating experienced in Singapore. Such research reveals one key factor that is bound to be one of the primary reasons for these elevated temperatures in densely populated tropical cities. This factor is the presence of the urban heat island (UHI) effect [4].

The UHI effect can be described as an effect that results in urban areas being significantly warmer than the rural areas. This difference is due to one of the fundamental characteristics that differ between urban and rural areas—contrast in building density. As the population in urban areas is significantly higher than that in rural areas, consequently, the building density in urban regions will be significantly higher as compared to the rural parts. Such infrastructural differences in urban areas as compared to rural areas give rise to the UHI effect. In Singapore, the key defining infrastructure of urban areas is the dense housing infrastructure. Demographic data report the presence of more than 1.37 million households with up to 80% of Singaporeans living in high-rise buildings (HRBs) such as public housing buildings or condominiums [5].

Consequently, a key contributor to the rapid heating of Singapore is the infrastructure of high-rise buildings. With more than 4.5 million inhabitants living in HRBs [6], they are the most common housing infrastructures in Singapore. This makes them a substantial contributor to the perpetuation of the UHI effect in Singapore. Analyses of the infrastructure and thermoregulation of HRBs will provide for effective identification of factors of HRBs that possibly contribute to the heating of the surrounding atmosphere. Hence, our study aims at analysing trends in the thermal signature of HRBs and infrastructural properties that affect heat absorption and temperature of the surface of HRBs. This will then allow us to gain an understanding of the heat flow of a HRB and the role it plays in the current urban warming issue. Such an understanding would further pave the path to finding the most suitable design of a HRB to combat the UHI effect that affects Singapore's weather to date.

This study focuses on one of the most crucial factors affecting the heating up of surroundings: air-conditioning units; more precisely, the compressors found on the exterior of the building. With the usage of air-conditioning units contributing to more than a quarter of the residential electrical consumption in Singapore, studying the changes in temperature of HRBs due to the use of air-conditioning units proves to be an integral part of our overall analysis of the heat flow of the building. In

particular, our study aims to focus on the prevalence of the stack effect primarily due to the vertically stacked air-conditioning units. This stack effect refers to the effect a compressor has on the region above it in terms of temperature. The stack effect occurs due to the primary nature of hot air rising, which in this scenario is due to the hot air blown out of a compressor, as well as the surrounding air that gains heat from a compressor and rises. The significance of such a study is that firstly, analysing thermal images of the building would allow for detailed studies to be conducted regarding the design of buildings and the thermal flow within the building. Moreover, given that buildings are key contributors to the high rate of urban warming of Singapore, such a study also provides insight into infrastructural designs that can reduce the urban heat island effect. Finally, by understanding how heat flows within a building also opens up possibilities towards obtaining crucial information regarding possible economic disadvantages residents may face. Our study hypothesises that as a consequence of the stack effect, the rise of air heated by the compressors will result in the surrounding atmosphere of the air-conditioning compressors being progressively hotter with rising altitude. Such phenomena might also have an impact on varying indoor thermal comfort of apartments in a building.

## 13.2 Methodology

### 13.2.1 Case Study Object: A Condominium in Clementi

The measurements were conducted aiming at a condominium in Singapore, a high-rise development that was completed in 2019. The analysed buildings are 40-storey twin towers, each with 6–7 housing units per floor, with a total height of 129.5 m. The air-conditioning compressors of the corner units are found at the tails of the H-shaped towers. Meanwhile, the air-conditioning compressors of the centre units are found flush, in between the balconies.

### 13.2.2 Recreation of the Building in Simulation

Numerous studies involving the thermal analysis of infrastructures have made use of simulations to vividly identify and analyse the thermal flow of the building on a more descriptive and dynamic scale [7]. Hence, this investigation also adopts such a technique. Using real dimensions of the air-conditioning ledge and air-conditioning compressors, we modelled the air-conditioning ledge in a computational fluid dynamics (CFD) simulation using COMSOL Multiphysics. Such a simulation allowed for effective viewing of the air and thermal flow of the environment surrounding the

air-conditioning ledge. Hence, this model was then used to simulate and investigate various scenarios of heat convection of running air-conditioning compressors to observe the thermal flow of the surrounding environment in such scenarios.

### 13.2.3 FLIR Camera Deployment and Measurement Setup

Analysis of thermoregulation of high-rise buildings can be effectively carried out through thermal imaging. To do so, this study made use of a forward-looking infrared (FLIR) camera. The FLIR camera can effectively and accurately capture temperature data of structures more than a kilometre away. In our case, the FLIR camera was set up on a high-rise building situated 400 m away. Infrared radiation that is captured through the camera is then digitalised and collated to form a thermal image of the object that is being captured, and in this scenario, the condominium building. For our study, the FLIR camera was placed for a few hours at a location that captures a major part of the building that is studied. This setup allows the thermal imaging of the façade of the building.

The thermal images captured were then analysed using a custom developed Python program that can display the temperature distribution in the exterior of the building as a colour map, thus allowing for a preliminary visual distinction of hotter and cooler regions of the building as seen in Fig. 13.1. The functionality of a FLIR camera is that every image captured by this device has a thermal signature on each of its pixels. This program can then extract temperature data stored in each pixel of the thermal image captured, which allows for extensive study of the overall heat flow of the infrastructure.

The measurements were largely taken during clear weather. The measurements were carried out for a total duration of 7 h from 5 in the evening till midnight over a span of a few days.



**Fig. 13.1** Image on the left is captured by a thermal camera and the image on the right is captured by a conventional camera

### 13.2.4 Privacy Protections

Given the nature of our observational and measurement platform, it is of highest importance to ensure appropriate privacy protections for inhabitants of the HRB. The images that were taken for the subsequent analyses of thermal data were strictly limited in pixel resolution so that building interiors cannot be seen, thus abiding by the respective privacy restrictions. Moreover, no personally identifiable information was collected in the process [8].

### 13.2.5 Flow Diagram of Code Used for Data Analysis

As depicted in the flow diagram in Fig. 13.2, thermal images captured by the FLIR camera were the source of thermal data used for analysis. After running it through a series of programs written using the Python programming language, we obtain the thermal signature and profile of the image captured. The robust design of the program allows for modifications to be readily made to the code to achieve a myriad of functions, such as extraction and comparison of thermal signature [9] of various points, visual discernments of thermal flow of the infrastructure [10], and many more functionalities, which allows us to engage in a holistic analysis of the thermal data at hand.

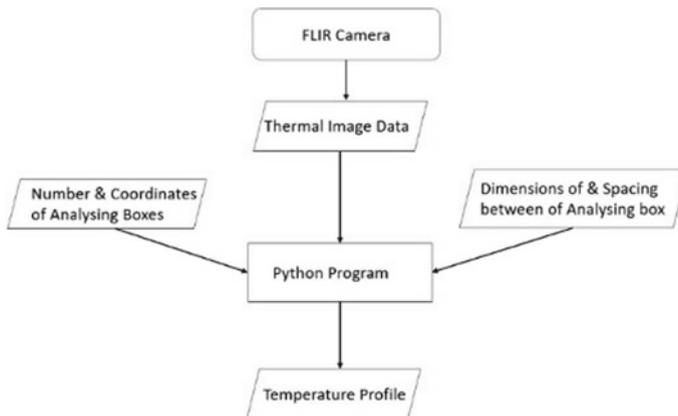


Fig. 13.2 Flow diagram of our python code

### 13.3 Simulations and Thermal Analysis of the Stack Effect

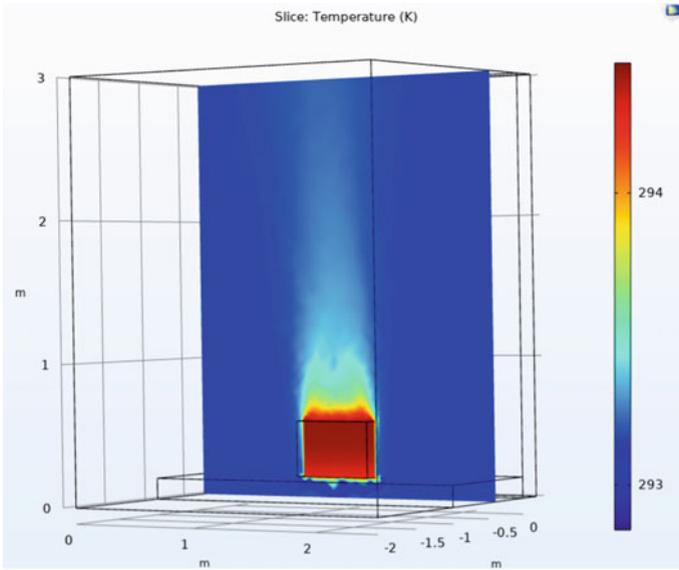
Our study investigates the concept of stack effect present in air-conditioning unit compressors. The stack effect [11] is a phenomenon that occurs primarily due to the nature of hot air rising because of its lower density. When an air-conditioning unit is in use, hot air, that gets heated due to the heat absorbed by the refrigerant, is blown out of a compressor. Air surrounding the compressor also gains this heat, and hence, resulting in an upward-rising mass of air. When this hot air rises and dissipates, it forms a vertical buoyancy-driven airflow [12]. This hot air might then get sucked into another compressor on a higher floor, causing a more shallow thermal conduction gradient between the compressor and the air which would result in even hotter air surrounding the compressor, longer cooling downtime, and higher electricity bill. With a higher number of floors [13] and extended utilisation of air-conditioning as a result of working from home during the recent period, the stack effect becomes increasingly significant. The cumulative effect of all the hot air that rises after gaining heat from the compressors leads to an increase in the temperature of the surrounding air with an increase in altitude. The significance of such an analysis was made possible through the insight obtained on the thermal flow of HRBs and the overall impact HRBs may have on the climate. This is because with the usage of air-conditioning units being significantly high among the Singapore resident population, possible accumulation and release of heat through the stack effect eventually could have drastic impacts on the global warming situation in and thermal signature of Singapore. Our investigation of stack effect comprises of two main aspects—conducting CFD simulations and analysing real-world data collected.

#### 13.3.1 Simulations

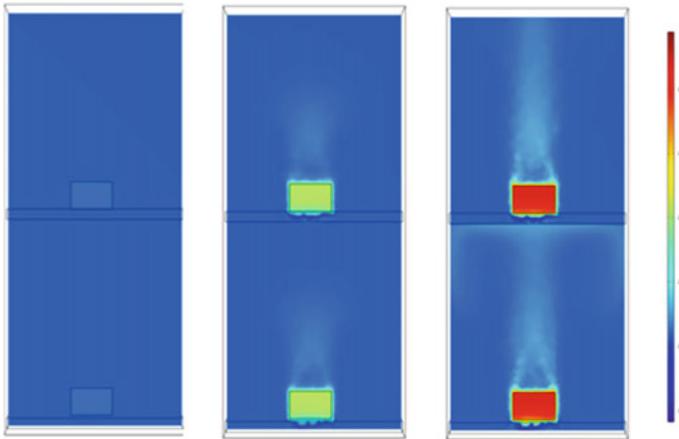
The first study employs the use of computational fluid dynamics (CFD) simulations of the air-conditioning unit compressor stack located on the exterior of the condominium building.

Using a realistic model of the air-conditioning ledge, we simulated the heat flow from the compressor to the surrounding air as seen in Fig. 13.3. The red part indicates the heated compressor with a column of warm air above it. The result from the simulation establishes a firm physics grounding for our theory of vertical buoyancy-driven flow of hot air. Thus, we proceeded ahead to model a stack of such air-conditioning ledge similar to the ones found in the condominium building and ran simulations to find out the temperature and velocity of the surrounding air.

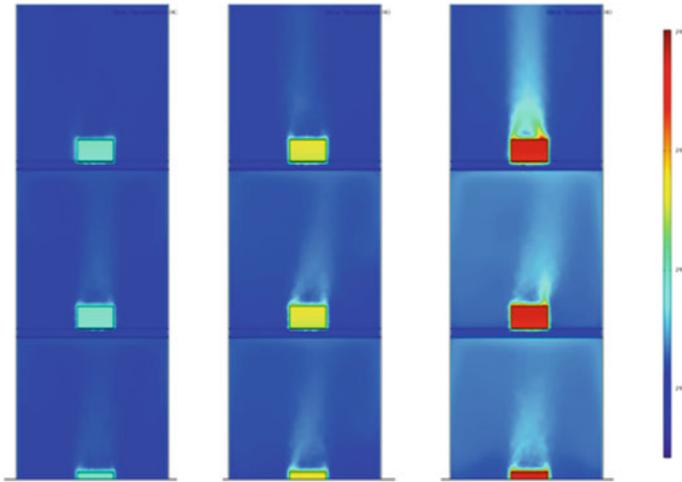
Through simulations of temperature and velocity distributions in Figs. 13.4, 13.5, 13.6 and 13.7, we note that there is significant air and heat flow in the upwards direction from the air-conditioning compressors. As explained by the stack effect, hot air that was surrounding the hotspot, which is the air-conditioning compressor, rises. Moreover, it is worth noting that the velocity of the air rising from the air-



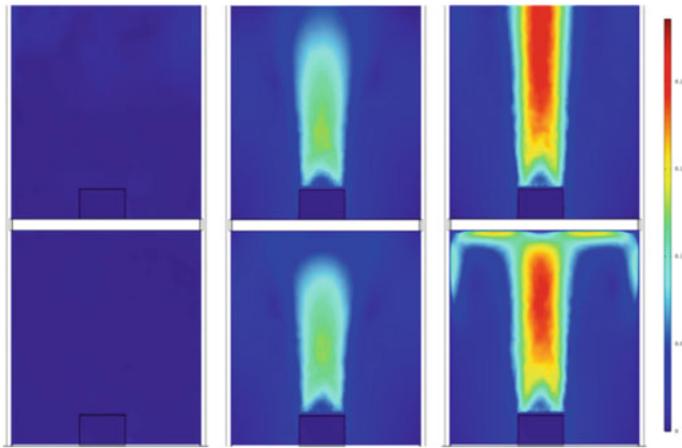
**Fig. 13.3** Replication of the air-conditioning ledge of the condominium building in the simulation



**Fig. 13.4** Snapshots of the simulated temperature (in K) of the air surrounding the air-conditioning compressors across 2 floors

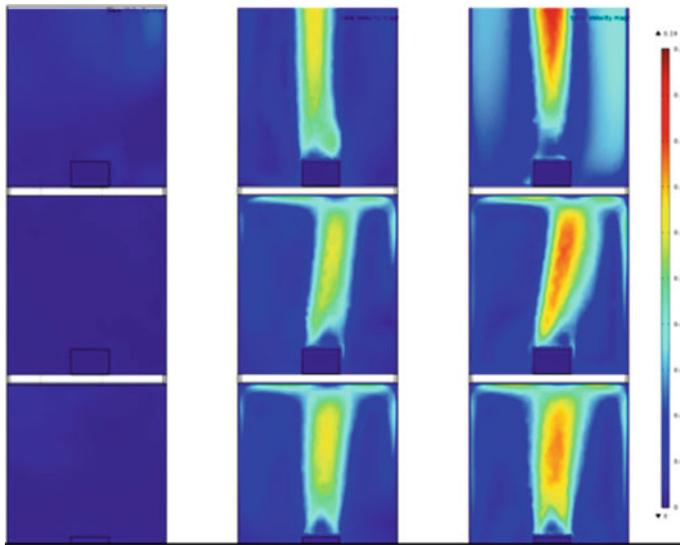


**Fig. 13.5** Snapshots of the simulated temperature (in K) of the air surrounding the air-conditioning compressors across 3 floors



**Fig. 13.6** Snapshots of the simulated velocity (in m/s) of the air surrounding the air-conditioning compressors across 2 floors

conditioning compressor on the higher levels is significantly higher than that of the level below it. As the hot air rises, it gains heat from the compressors above causing it to heat up further, resulting in a vortex of air which gains velocity coupled with heat as it rises, thus proving the existence of the stack effect.



**Fig. 13.7** Snapshots of the simulated velocity (in m/s) of the air surrounding the air-conditioning compressors across 3 floors

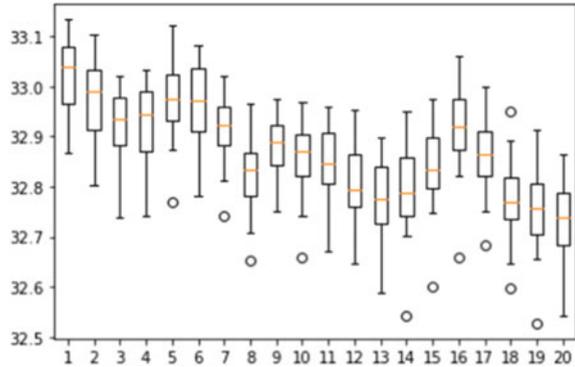
### 13.3.2 Analysis of Real-World Thermal Data

The second study analyses the temperature data of air-conditioning unit compressors found on the exterior of the condominium building. Using the Python program we designed, we analysed the thermal images to calculate the average temperature [15] of each of the air-conditioning compressors in the buildings. We then generated boxplots of the temperatures obtained for each level and matched these boxplots with their respective levels to display any trend in the temperature of compressors with increasing altitude, if any. A significant increase in the temperature of compressors with increasing altitude would indicate the prevalence of the stack effect.

In contrast to the expected results of a rising trend in the temperature as the altitude rises, Fig. 13.8 shows a decreasing trend in the recorded temperature with an increase in altitude, highlighting a possible absence or insignificant level of stack effect being present in this building.

Despite this overall observational absence of stack effect, after zooming in on each of the thermal images obtained, it was observed that on many occasions, there is indeed a stack effect being present, but only on the micro-scale. As seen in Fig. 13.9, there are two regions of the hotspot which show a running air-conditioning compressor and the temperature of the air above the air-conditioning compressor on the higher level is warmer than that of the lower year, thus indicating the presence of this effect in the micro-scale. CFD simulations of a functioning air-conditioning compressors substantiate this presence of stack effect on a micro-scale and the absence of it on a macro-scale.

**Fig. 13.8** Graph of temperature against compressors at the respective levels



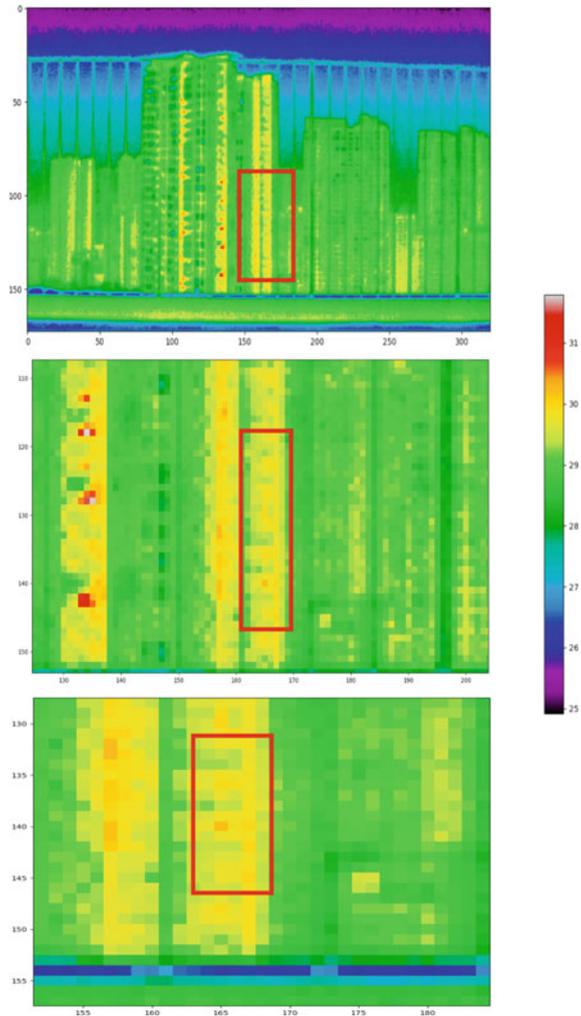
As seen in Figs. 13.9 and 13.10 and the images of the building, each air-conditioning compressor is placed on a ledge. This ledge, which is made of concrete and has a thickness of about 15 cm, proves to be a crucial factor contributing to the absence of the stack effect. This behaviour is because, as seen in the simulations, the hot air from the exhaust of the air-conditioning compressor rises and encounters the ledge above. Once the hot air encounters the ledge, the air's velocity decreases, as the ledge serves as an obstruction of the vertical buoyancy-driven airflow.

Moreover, wind speed and direction due to the location's proximity to the coast and unpredictable weather patterns could have accelerated the rate of heat loss and dispersion of the hot air. Thus, contrary to the theory, such accumulation of heat through the rise of hot air and the stack effect is less significant. Additionally, the results obtained show the success of the strategic positioning of the air-conditioning unit compressors at the ends of the many HRBs constructed in Singapore allow for larger channels for heated air to escape through as well as higher exposure to wind, thus curbing the stack and consequently the UHI effect.

### 13.4 Conclusion

From the results obtained, it can be determined that in HRBs that follow the design of the studied condominium building, the stack effect is less prevalent with the results obtained, highlighting the converse of the hypothesised consequences had there been a prevalent stacking effect, in the building under study. Through extensive modelling of the air-conditioning units in the CFD simulations and analysing real-world thermal data of the building, it was concluded that the ledge present beneath each air-conditioning compressor obstructs the vertical buoyancy-driven airflow, hence preventing the primary contributor to the macro-scale stack effect phenomena, while also providing a significant level of insulation. As a result, the hot air cannot rise in purely vertical manner and is instead dispersed in other directions. This dispersion of the hot air released from every air-conditioning unit allows for it the inflow of

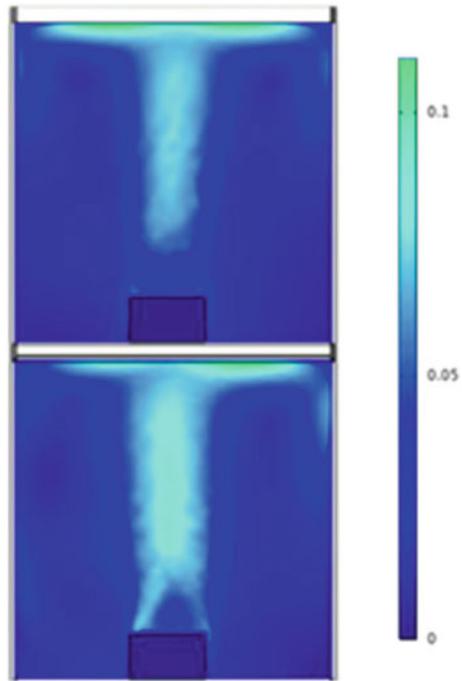
**Fig. 13.9** A progressive zoom in of the snapshot of the colour-mapped thermal image



cooler air into the air-conditioning compressors located above. This, coupled with the phenomenon of temperature decreasing with increasing altitude due to several weather-based factors that accelerate the heat loss by allowing dispersion of hot air, caused a decreasing trend in the temperature of compressors.

Such an analysis reveals that one of the key infrastructural designs and properties that contribute towards the drastic reduction of the stack effect is the presence of various forms of insulation such as the ledges present beneath the air-conditioning compressors located on the exterior of the building. Hence, this investigation shows that placing compressors at an optimal vertical spacing from each other with barriers separating them allows for the reduction of the consequent urban stack effect which

**Fig. 13.10** A snapshot of the simulated velocity that shows micro-scale stack effect



would allow for an even, dispersive thermal flow within the building and the surrounding environment, henceforth mitigating the UHI effect and reducing the overall heating up of the city-state.

### 13.5 Possible Application and Future Work

For a thermal analysis that provides a more complete view, diverse types of infrastructures with varying designs can be examined and analysed to compare the stack effects present in different infrastructural designs. This study currently focuses on only one building due to the COVID-19 pandemic circumstances and restrictions, which during the experiments did not allow a more comprehensive survey. However, in the future, analysing a wider variety of buildings [16], with diverse design aspects that may affect the thermal flow within the building, would allow for a more exhaustive view of the optimal designs that mitigates the UHI effect and the heating of the environment. Analysis can also be done by considering other factors such as the façade colour, material, type, and placement of buildings, which could be also obtained from other sources such as street view imagery [17], and which would account for a greater number of factors that could possibly contribute to the UHI effect. Another plausible factor that could be incorporated into our analysis is elec-

trical consumption data and electricity bills of the buildings under study, as these data would allow for a concrete analysis as to how significant the stack effect and other UHI effects are on the electrical consumption of residents living in such buildings.

The framework used in this study is to investigate the urban stack effect could also prove to be valuable in studies conducted on other environmental effects. For instance, this investigation has analysed the process and functionality of the urban stack effect through vivid and dynamic simulations that can accurately track air and thermal flow. Following this direction, insight was also obtained regarding a possible design—the presence of a ledge—that can be employed to ensure the reduction of this effect. The thermal imaging analysis conducted on the vertical thermal flow along the air-conditioning compressor column of the building also opens up opportunities for in-depth analysis to be done on the placements of air-conditioning compressors as well. This can be done to understand the best possible positioning of compressors to ensure the least effect on the surrounding environment. By obtaining such insight and opportunities for analysis, further research can be done in this area following a similar investigation framework to identify the most optimal infrastructural designs that can reduce the UHI effect that buildings have on the surrounding environment.

**Acknowledgements** We gratefully acknowledge NUS High School of Mathematics and Science for supporting this research project.

## References

1. Ng, M. (2020). Nearly 1000 households in Tengah sign up for centralised cooling system. Retrieved January 20, 2021, from <https://www.straitstimes.com/singapore/housing/nearly-1000-households-in-tengah-have-signed-up-for-centralised-cooling-system>
2. Ng, D. (2020). Why Singapore is heating up twice as fast as the rest of the world. Retrieved January 20, 2021, from <https://www.channelnewsasia.com/news/cnainsider/singapore-hot-weather-urban-heat-effect-temperature-humidity-11115384>
3. Temperatures in Singapore could hit 40 °C as early as 2045: Scientists (n.d.). Retrieved January 20, 2021, from <https://www.todayonline.com/singapore/singapore-could-swelter-through-40degc-days-2045-if-business-usual-emissions>
4. Kardinal Jusuf, S., Wong, N. H., Hagen, E., Anggoro, R., & Hong, Y. (2007). The influence of land use on the urban heat island in Singapore. *Habitat International*, 31(2), 232–242.
5. Yuen, B. (2005, February). Romancing the high-rise in Singapore. Retrieved January 20, 2021, from [https://www.researchgate.net/publication/222648100\\_Romancing\\_the\\_high-rise\\_in\\_Singapore](https://www.researchgate.net/publication/222648100_Romancing_the_high-rise_in_Singapore)
6. Entrop, A. G., & Vasenev, A. (2017). Infrared drones in the construction industry: Designing a protocol for building thermography procedures. *Energy procedia*, 132, 63–68.
7. Dobler, G., Bianco, F. B., Sharma, M. S., Karpf, A., Baur, J., Ghandehari, M., & Koonin, S. E. (2021). The urban observatory: A multi-modal imaging platform for the study of dynamics in complex urban systems. *Remote Sensing*, 13(8), 1426.
8. Lane, J., Stodden, V., Bender, S., & Nissenbaum, H. (Eds.). (2014). *Privacy, big data, and the public good: Frameworks for engagement*. Cambridge: Cambridge University Press.
9. Tanaka, H., & Lee, Y. (1988). Stack effect and building internal pressure. *Journal of Wind Engineering and Industrial Aerodynamics*, 29(1–3), 293–302.
10. Borrmann, D., Elseberg, J., & Nüchter, A. (2013). Thermal 3D mapping of building façades. In *In Intelligent autonomous systems* (Vol. 12, pp. 173-182). Berlin, Heidelberg: Springer.

11. Wong, N. H., & Heryanto, S. (2004). The study of active stack effect to enhance natural ventilation using wind tunnel and computational fluid dynamics (CFD) simulations. *Energy and Buildings*, 36(7), 668–678.
12. Bruelisauer, M., Meggers, F., Saber, E., Li, C., & Leibundgut, H. (2014). Stuck in a stack-temperature measurements of the microclimate around split type condensing units in a high rise building in Singapore. *Energy and Buildings*, 71, 28–37.
13. Lovatt, J. E., & Wilson, A. (1995). Stack effect in tall buildings. *In Fuel and Energy Abstracts*, 4(36), 289.
14. Barrett, R. E., & Locklin, D. W. (1968). Computer analysis of stack effect in high-rise buildings. *Ashrae Transactions*, 74(Part II), 155–169.
15. Bruelisauer, M., Meggers, F., Saber, E., Li, C., & Leibundgut, H. (2013, November 23). Stuck in a stack-temperature measurements of the microclimate around split type condensing units in a high rise building in Singapore. Retrieved January 22, 2021, from <https://www.sciencedirect.com/science/article/pii/S0378778813007639>
16. Lee, S., Moon, H., Choi, Y., & Yoon, D. (2018, February 14). Analyzing thermal characteristics of urban streets using a thermal imaging camera: A case study on commercial streets in Seoul, Korea. A case study on commercial streets in Seoul, Korea. Retrieved January 22, 2021, from <https://www.mdpi.com/2071-1050/10/2/519>
17. Biljecki, F., & Ito, K. (2021). Street view imagery in urban analytics and GIS: A review. *Landscape and Urban Planning*, 215, 104217.