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The effect of district heating and cooling on anthropogenic heat mitigation in the Tokyo metropolitan area

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ABSTRACT

The consumer sector accounts for not a small portion of final energy consumption in major countries, and the growth over time is significant. For example, the energy consumption density in Tokyo, the capital of Japan, is about 10 times higher than the national average, and there is concern about the impact of anthropogenic heat by enormous energy consumption in the city on the atmospheric environment.

Therefore, this study will evaluate the effect of suppressing the amount of anthropogenic heat by operating high-efficiency equipment, taking advantage of economies of scale, for district heating and cooling which centrally managed heat source equipment.

We estimated the 5-minute cooling demand for consumer buildings in August based on GIS data and meteorological data. In addition, the study developed a model that reproduces the operation at five-minute intervals of a district heating and cooling system. We compared the amount of anthropogenic heat by district heating and cooling with the amount of anthropogenic heat by air-conditioning in individual buildings, and determined a large gap, indicating the suppression effect of district heating and cooling on the amount of anthropogenic heat. On the other hand, analysis of the regional distribution of anthropogenic heat revealed that anthropogenic heat is concentrated around district heating and cooling facilities, resulting in a large amount of anthropogenic heat, indicating the need for some measures to reduce the heat risk to pedestrians.

Keywords: Anthropogenic Heat, District Heating and Cooling, Cooling Demand, Air Conditioning Heat Source, Time Series Estimation.

Introduction

The consumer sector, which consists of the residential and tertiary industrial sectors, accounts for a substantial portion of the final energy consumption in major countries, and its growth over time is significant. For example, the energy consumption density in Tokyo, the capital of Japan, is approximately 8.4 times higher than the national average (Agency for Natural Resources and Energy 2020), and there are concerns regarding the effects on the

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atmospheric environment from the enormous energy consumption in the city. Energy consumption and anthropogenic heat are closely related, but their pathways and characteristics are diverse. Therefore, understanding the actual situation, including the qualitative breakdown of local anthropogenic heat from buildings and traffic, to evaluate its effect on the atmospheric environment is important (Ashie et al. 2004).

Various studies have been conducted both domestically and internationally regarding the quantification of heat hazards (Sailor 2011, Chen and Hu 2017, Jin et al. 2019, and Bautista et al. 2022). Furthermore, since air conditioning systems intervene in the process of generating heat exhaust from buildings, several studies that have analyzed the heat discharge characteristics of these systems have been published in the past, but the results are still insufficient (Kimura and Takahashi 1991, Ichinose et al. 1999, Li et al. 2019, Yuan et al. 2022). To evaluate the amount of air conditioning heat discharge from buildings in an area, it is necessary to understand the regional configuration of air conditioning systems in the area, estimate the cooling demand and operation of air conditioning equipment based on the usage of each building, and accumulate the heat discharge from each air conditioning system by also considering outdoor air conditions. The current situation of global warming and the increasing number of people living in urban areas seems to foresee a future in which heat risk reduction in urban areas will be considered in earnest.

Therefore, this study will evaluate the effect of suppressing the amount of anthropogenic heat by operating high-efficiency equipment, taking advantage of economies of scale, for district heating and cooling (DHC) which centrally managed heat source equipment.

Materials and Methods

Study design

We used a method for determining anthropogenic heat at five-minute intervals for each building using geographic information, human flow, and meteorological data. This method is based on that of a previous study (Ministry of Land, Infrastructure, Transport, and Tourism, Ministry of the Environment 2004) along with updated configuration for heating, ventilation, and air-conditioning equipment efficiency, load characteristics, and reflected weather data for the target year 2019. The estimation of anthropogenic heat is performed in three steps: cooling heat source equipment configuration, cooling demand estimation, and calculation of energy consumption and anthropogenic heat by cooling.

Our calculation target was district heating and cooling facilities in Tokyo. Tokyo is the capital of Japan, located at latitude 35°N and longitude 139°E. Tokyo receives approximately 1600 mm of precipitation per year, making it the most populous city in the world. Figure 1 shows the temperature and humidity in Tokyo for one week during the summer. Tokyo has a humid subtropical climate with hot and humid summers. Daytime temperatures rise to nearly 35°C and weekly relative humidity is almost always above 60%.

Ochanomizu area of Tokyo is a high-density commercial district where district heating and cooling are provided, and because of the large amount of anthropogenic heat emissions from air conditioning, the artificial heat emissions from consumer buildings were the subject of the study. Table 1 shows an overview of the DHC in the Ochanomizu area. It has three types of heat source equipments: Air source heat pump (AHP), Water source heat pump (WHP), and turbo refrigerator machine (TR). Figure 2 shows a piping diagram of the district heating and cooling system. Since the air-conditioning anthropogenic heat generated from residences in the target area is considered to be less than the air-conditioning anthropogenic heat generated from non-residences, only air-conditioning anthropogenic heat from non-residences is treated in this study.

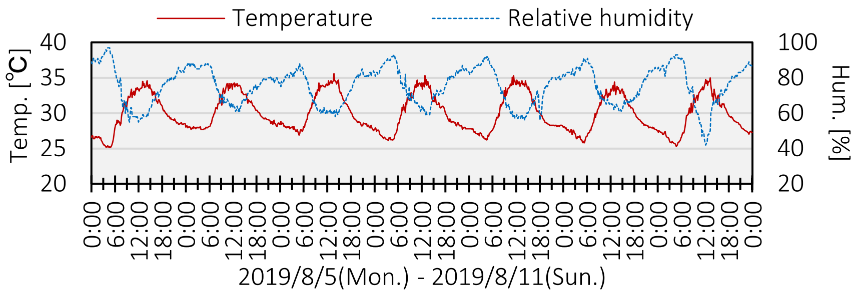


Figure 1. Temperature and humidity in Tokyo.

Table 1. Summary of the target DHC

Town and street [-]		3-chōme Kanda Surugadai, Chiyoda City, Tokyo
Number of demand buildings [-]		12
GFA of demand building [m^2]		231,000
Heat source equipments [MJ/h × unit]	AHP	1,710 × 8 and 1,542 × 8
	WHP	1,320 × 2
	TR	6,329 × 4

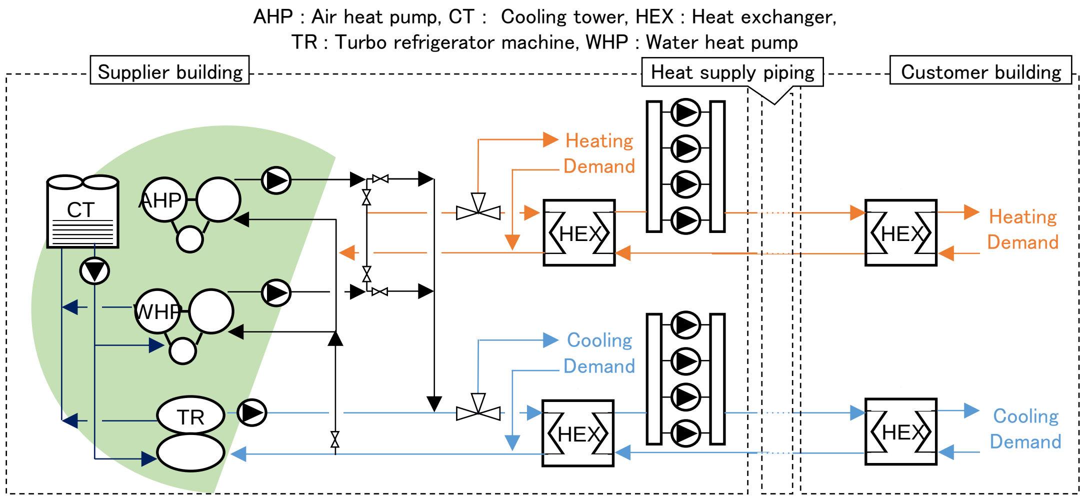


Figure 2. Piping diagram of the DHC.

Case study

Three cases were prepared for consumer building, one with cooling in each building (Individual case) and one with district cooling (DHC case), each with a different air-conditioning system configuration (Table 2). We calculated in each case the energy consumption and the anthropogenic heat.

Individual_0 case establishes the air conditioning heat source equipment configuration for each building based on the gross floor area and building use in the 2019 GIS data. The air-conditioning equipment in non-residential buildings in this study were defined as absorption chillers (RHA), AHP, and individually distributed packaged air conditioners (VRF). The cooling capacity of the heat source in each consumer building was obtained from the capacity intensity curves for the air-conditioning heat source equipment for each building use (Ueno et al. 2019) and the composition of the cooling heat source equipment by building use in a previous study (Ministry of Land, Infrastructure, Transport and Tourism, Ministry of the Environment 2004).

Table 2. Overview of cases

Case	Overview	Facility Configuration
Individual_0	Virtual individual building facilities corresponding to local DHC facilities	Conventional method
Individual_1	Virtual individual building facilities mainly for latent heat emission	Install water-source heat pumps in each building
Individual_2	Virtual individual building facility with sensible heat emission	Change absorption chiller/heater to air source heat pump
DHC_0	On-site DHC facilities	Actual facility configuration
DHC_1	Virtual DHC facility with mainly latent heat emission	All capacities are converted to electric turbo chillers
DHC_2	Hypothetical DHC facility with mainly sensible heat emission	All capacities are integrated into air-source heat pumps

Cooling demand

Based on the basic start and end times set for each building use, the start and end times for non-residential buildings were set based on the number of commuters passing by each sidewalk at different times of the day using the current population data. We used GIS software to calculate the distance between points and lines and select the sidewalk (line) with the shortest distance from each building (point), and the number of people passing by each building daily during the target period.

We then estimated the five-minute interval heat source cooling demand for each building using a method developed in a previous study (Ueno et al. 2019), classified non-residential buildings in the city block into seven building types—hospital, hotel, office, store, school, restaurant, and others—and calculated the following equation (1) for each building and time of the day to reproduce cooling demand fluctuations.

$$E_{Co\,(t)} = Ey_{Co} \cdot R_{Co(t)} / N_d \cdot A \cdot C(A) \cdot Ry \cdot R(temp) \tag{1}$$

where $E_{Co\,(t)}$ is the cooling demand (MJ), Ey_{Co} is the annual cooling demand (MJ/m^2/year) by industry, $R_{Co\,(t)}$ is the ratio of annual cooling demand to time demand, N_d is the number of days of the week by month, A is the gross floor area (m^2) of the building, $C(A)$ is the annual demand correction value by gross floor area, Ry is annual demand (MJ], and $R(temp)$ is the cooling demand blip factor with outdoor temperature.

The results of setting the start and end times of each building in this area based on human flow data indicated that there were some non-residential buildings in each area whose start and end times were approximately one or two hours ahead or behind the basic start and end times. Fig. 3 shows the results of the cooling demand estimation. By estimating the total daily district cooling demand in these areas, we confirmed that there were substantial differences between weekdays and holidays and between daytime and nighttime.

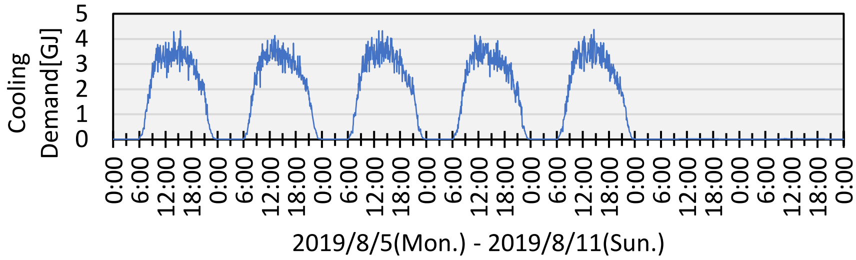


Figure 3. Five-minute interval cooling demand during a representative week.

Energy consumption

Based on the air-conditioning heat source equipment model in the Building Energy Conservation Law (Editorial Committee for the Commentary on the Energy Conservation Standard for Houses and Buildings 2013 (2014)), a model was constructed and used in this study to calculate the time-specific energy consumption of each building in the study area. The air-conditioning heat source equipment model first calculates the load factor of each air-conditioning heat source equipment based on cooling demand at five-minute intervals. Because the rated capacity during actual operation increases or decreases depending on the cooling water temperature and outdoor air temperature, a quadratic function equation was set for each heat source model as the rated capacity characteristics from moment to moment in this calculation model. Second, energy consumption with time was calculated by inputting the load factor into the load characteristic formula set for each heat source model and multiplying the calculation result by the rated energy consumption. In the calculations, the refrigerant temperature was set to 7 °C according to the Building Energy Conservation Law.

The DHC model also incorporates a submodel that reproduces the heat transfer from the supplier building to consumer buildings (hereinafter, the district heat transfer model). We used a model constructed in a previous study to supply heat from the building containing the heat source to the customer's building via a heat exchanger (exchange efficiency [-]: 1.0) and heat supply piping for both cold and hot water. As it is rare for pipes to be installed directly between buildings, the one-way length was set as the total distance based on the longitude and latitude differences between the DESS and the customer's building. The heat transfer power was calculated as the power consumption in 1 m of the heat supply pipe. The heat loss from the heat supply pipe was set to the same value in 1 m of piping (cold water: -0.004[MJ/m], hot water: 0.015[MJ/m]) for any pipe diameter.

Anthropogenic heat

The amount of anthropogenic heat transferred to the atmosphere by air conditioning was calculated from the air-conditioning energy consumption of each building in terms of sensible heat and latent heat. Fig. 4 shows the heat transport flow of the air-conditioning heat source. In the calculations, exhaust heat from the AHP, TR, WHP, and VRF were calculated as sensible heat, as it is derived from the power input and cooling demand. For the RHA, the amount of heat from the exhaust gas was estimated from the combustion efficiency of the boiler and divided into sensible heat and latent heat.

The heat transferred from the TR, WHP, and RHA to the cooling tower was calculated as sensible heat and latent heat using a cooling tower model based on a previous study (Ashie et al. 1999). The cooling towers were all open-type counter-current cooling towers, and the inlet/outlet water temperatures of the cooling towers were calculated based on the circulating water quantity, air flow rate, and atmospheric conditions, corresponding to changes in the cooling load. The quantity of circulating water was set for each building according to the capacity of the air-conditioning heat source equipment, and the airflow rate of the cooling tower was also set for each building based on the amount of circulating water and the water–air ratio. The cooling tower characteristics for each building were set using the results of calculations based on Chebyshev's formula according to the Japanese Industrial Standards (Japanese Standards Association 2008). To quantify heat loss from the cooling tower, the temperature difference between the cooling water inlet and outlet and the specific enthalpy of the outlet air were determined. Furthermore, the operating line was drawn on the T·h diagram and the U/N value was calculated using Equation (2). Subsequently, the combination of inlet/outlet temperatures of the cooling water that achieves the design value was obtained by iterative calculations based on the U/N value.

$$U/N = \int_{T_{l,out,t}}^{T_{l,in,t}} \frac{C_l \, dT}{h_s - h_l} \tag{2}$$

where U/N is the number of transfer units [-], $T_{l,in,t}$ is the temperature of cooling tower inlet water at time t [°C], $T_{l,out,t}$ is the tempera-ture of cooling tower outlet water at time t [°C], C_l is the specific heat of water (=4.217) [kJ/kg・K], h_s is the specific enthalpy of operating line [kJ/kg(DA)], h_l is the saturated specific enthalpy [kJ/kg(DA)].

: Anthropogenic heat : Energy consumption : The others

Q_l : Latent heat [MJ], Q_c : Cooling demand [MJ], Q_s : Sensible heat [MJ], E_{ele} : Electricity consumption [MJ], E_{gas} : Gas consumption [MJ] , G : Cooling tower airflow volume [kg/h], $h_{G,out}$: Specific enthalpy of cooling tower outlet air [kJ/kg(DA)], $h_{G,in}$: Specific enthalpy of cooling tower inlet air [kJ/kg(DA)], L : Cooling tower water volume [kg/h] , $T_{l,in}$: Temperature of cooling tower inlet water [°C], $T_{l,out}$: Temperature of cooling tower outlet water [°C], $T_{G,out,t}$: Temperature of cooling tower outlet air [°C], $T_{G,in}$: Temperature of cooling tower inlet air [°C].

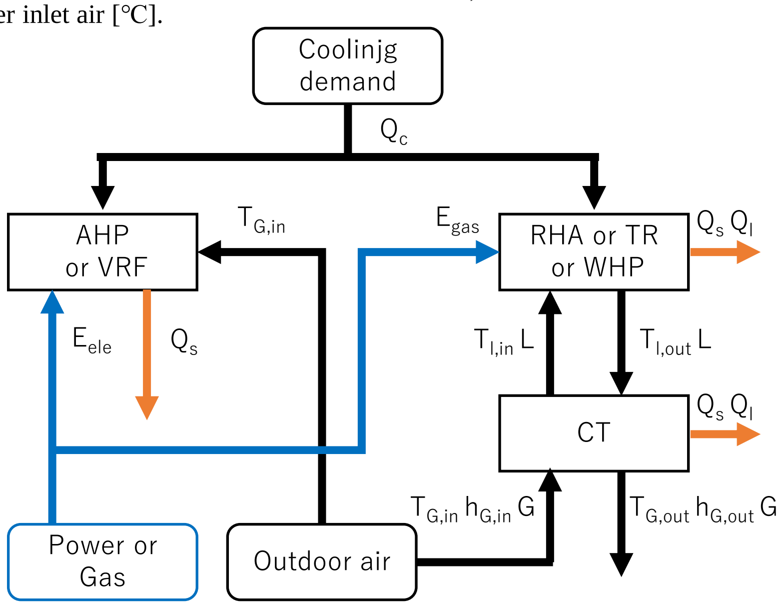


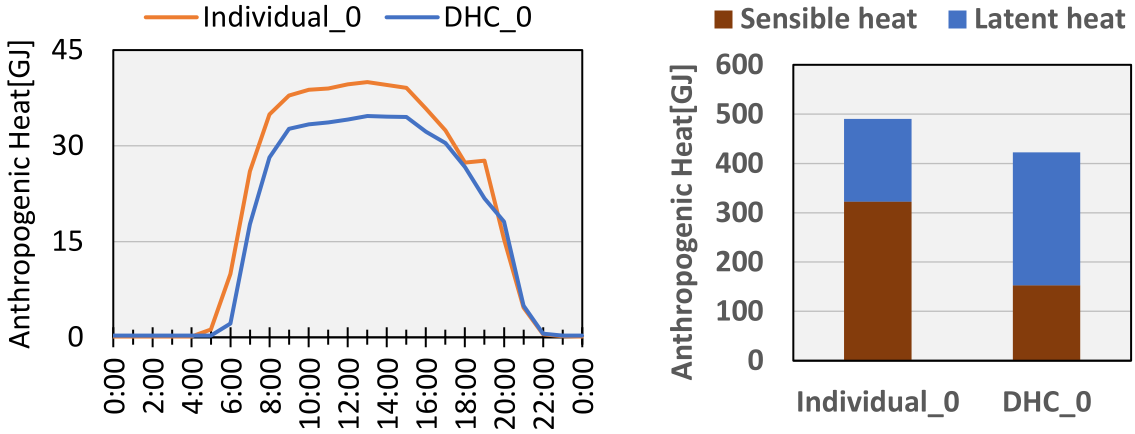
Figure 4. Heat transport flow of the air conditioning heat source.

Results and Discussions

Figure 5(a) shows a comparison of anthropogenic heat on a representative day in August between the case where each building is cooled for each consumer building (Individual_0) and the case where each building is cooled by district cooling (DHC_0). For the peak time (13:00), the DHC_0 case exhaust 34.7 GJ of anthropogenic heat, about 14% less than the 40.0 GJ in the Individual_0 case. To indicate a breakdown of sensible and latent heat in the daily total anthropogenic heat content, we summed the calculated values at each time for 24 hours for sensible and latent heat in DHC_0 and Individual_0. Figure 5(b) shows the breakdown of sensible and latent heat. The daily totals for the district heating and cooling cases are about 14% lower in the DHC_0 case than in the Individual_0 case. In addition, sensible heat is reduced by about 53% from the Individual_0 case, and latent heat is increased by about 60% from the Ind_0 case.

Figure 6 shows a comparison of the total artificial heat loss for a representative day in August in each case, calculated in the same way as in Figure 5(b). The case with the smallest daily anthropogenic heat was DHC_1. We determined that this was due to the improvement in operating efficiency resulting from the consolidation of capacity into turbo chillers which has high efficiency.

On the other hand, an analysis of the density of anthropogenic heat divided by the gross site area reveals that the DHC cases have larger values than the individual cases (Fig. 7). This indicates that the concentration of anthropogenic heat results in a larger amount of anthropogenic heat around district heating and cooling facilities, so some measures are needed to reduce the risk of heat for pedestrians.



(a) Anthropogenic heat on an average weekday in August.

(b) Total daily anthropogenic heat.

Figure 5. Comparison of anthropogenic heat results between Individual_0 case and DHC_0 case.

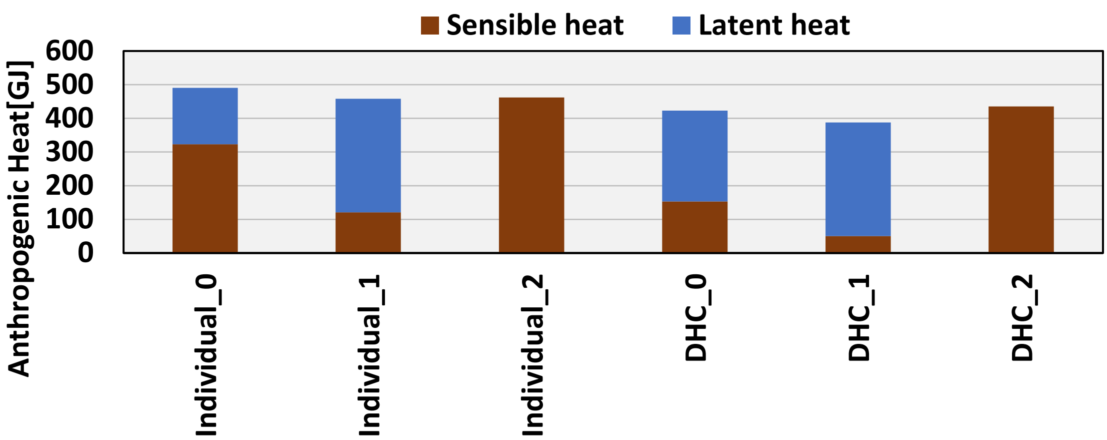


Figure 6. Comparison of sensible heat and latent heat.

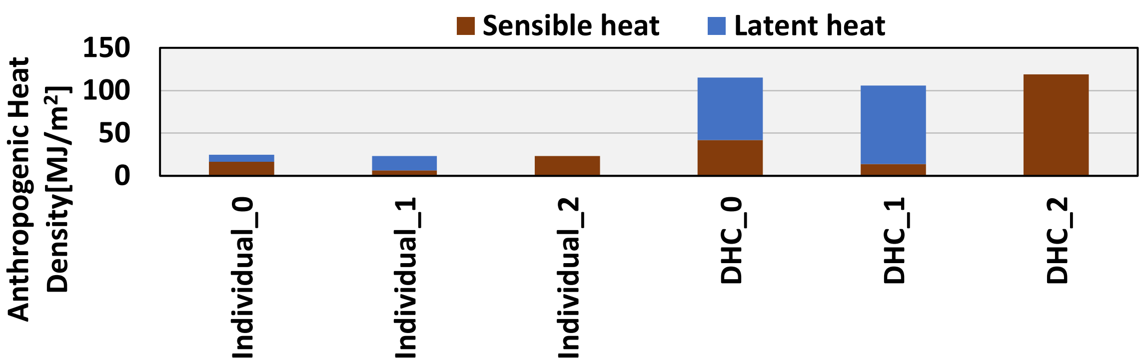


Figure 7. Comparison of density of sensible heat and latent heat.

Conclusions

We evaluated the effect of suppressing the amount of anthropogenic heat by operating high-efficiency equipment, taking advantage of economies of scale, for DHC which centrally managed heat source equipment. A comparison of the calculation results between district heating and cooling and air-conditioning in individual buildings showed significant gaps which indicate the mitigation effect of district heating and cooling on anthropogenic heat in the region. On the other hand, an analysis of the regional distribution of anthropogenic heat reveals that the concentration of anthropogenic heat results in a larger amount of anthropogenic heat around district heating and cooling facilities, so some measures are needed to reduce the risk of heat for pedestrians. These results are useful for assessing the summer heat risk in urban areas. In the future, we intend to assess anthropogenic heat due to road traffic. Based on the aforementioned results, we plan to develop a pattern of summer anthropogenic heat from traffic and incorporate it into a CFD-based thermal environment assessment tool to evaluate thermal risk considering artificial anthropogenic heat and to study measures to reduce exposure to anthropogenic heat, such as securing urban airways and building layouts and application of covering materials as heat stroke countermeasures for pedestrians.

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References

Ashie Y, Tanaka M, Yamamoto T (1999) Anthropogenic heat characteristics of air conditioning sys-tems of office buildings. Trans Soc Heat Air-conditioning Sanit Eng Jpn 24, 89–97. https://doi.org/10.18948/shase.24.75_89

Bonifacio-Bautista M, Ballinas M, Jazcilevich A, Barradas VL (2022) Estimation of anthropogenic heat release in Mexico City. *Urban Climate*, 43, 101158. https://doi.org/10.1016/j.uclim.2022.101158

Chen S, Hu D (2017) Parameterizing anthropogenic heat flux with an energy-consumption inventory and multi-source remote sensing data. *Remote Sensing*, 9(11), 1165. https://doi.org/10.3390/rs9111165

Editorial Committee for the Commentary on the Energy Conservation Standard for Houses and Buildings 2013 (2014) Methods of Calculation and Judgment in Accordance with the 2013 Energy Conservation Standards and Commentary, 2nd Edition, Tokyo, 149–261. “Heisei 25nen jutaku・kenchikubutsu no shoenerugikijun kaisetsusho henshu iinkai” (2014) “Heisei 25nen shoeneru-gikijun ni junkyoshita santei・handan no hoho oyobi kaisetsu Ⅰ hi-jutakukenchikubutsu (dai2han)”. “kabushiki kaisha rengo insatsu senta”, Tokyo, 149–261.

Ichinose T, Shimodozono K, Hanaki K (1999) Impact of anthropogenic heat on urban climate in Tokyo. *Atmospheric Environment*, 33(24-25), 3897–3909. https://doi.org/10.1016/s1352-2310(99)00132-6

Jin K, Wang F, Chen D, Liu H, Ding W, Shi S (2019) A new global gridded anthropogenic heat flux dataset with high spatial resolution and long-term time series. *scientific data*, 6, 139. https://doi.org/10.1038/s41597-019-0143-1

Kimura F, Takahashi S (1991) The effects of land-use and anthropogenic heating on the surface temperature in the Tokyo Metropolitan area: A numerical experiment. *Atmospheric Environment. Part B. Urban Atmosphere*, 25(2), 155–164. https://doi.org/10.1016/0957-1272(91)90050-o

Li X, Zhou Y, Yu S, Jia G, Li H, Li W (2019) Urban heat island impacts on building energy consumption: A review of approaches and findings. *Energy*, 174, 407–419. https://doi.org/10.1016/j.energy.2019.02.183

Ministry of Land, Infrastructure, Transport and Tourism, Ministry of the Environment (2004) “Heisei 15nendo toshi ni okeru jinkohainetsu yokusei ni yoru hitoairando taisaku chosahokokusho.” https://www.env.go.jp/air/report/h16-05/

Sailor DJ (2011) A review of methods for estimating anthropogenic heat and moisture emissions in the urban environment. *International Journal of Climatology*, 31(2), 189–199. https://doi.org/10.1002/joc.2106

Yuan C, Zhu R, Tong S, Mei S, Zhu W (2022) Impact of anthropogenic heat from air-conditioning on air temperature of naturally ventilated apartments at high-density tropical cities. *Energy and Buildings*, 268, 112171. https://doi.org/10.1016/j.enbuild.2022.112171

Ueno T, Takahashi K, Sumiyoshi D (2019) Estimation for energy demand fluctuation in commercial and business area by monte carlo simulation. *Journal of Environmental Engineering (Transactions of AIJ)*, 84(757), 291–301. https://doi.org/10.3130/aije.84.291