Heat Emissions from Buildings to Ambient Air

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Abstract

Heat emissions from buildings to ambient air are a crucial component influencing the urban microclimate. However, existing literature has very limited coverage of such research. This study developed a bottom-up approach to calculating heat emissions from buildings to the ambient air and implemented it in EnergyPlus. Simulation results of heat emissions from the small-sized office buildings in Chicago show the heat release from envelope convection is dominant over a year, accounting for 79% of the total annual heat emissions. Building releases the most amount of heat to the ambient air in summer, due to higher cooling loads, when heat rejected by condensers or cooling towers reaches the peak; during winter, HVAC system relief air and zone exfiltration emit a considerable amount of heat to ambient air (30% of winter heat emissions for the small office). Compared with the annual site energy use, the annual total heat emission is 3.7 times larger for the small office building.

Introduction

Heat emissions from buildings, transportation and industry are recognized as important factors influencing the urban microclimate, besides the factors of urban morphology and surface material property. Quantification of the heat emission to the urban atmosphere and its spatiotemporal distribution have significant implications and hence have been the focus of many related studies. Knowing how much heat is released into the atmosphere can help quantify the magnitude of its impact on urban microclimate, e.g., identifying and ranking the root source of urban heat island effect and climate change. Spatial and temporal distribution of heat emissions can further serve to locate hot spots in space and time for prioritizing resources to mitigate their environmental impact (Sun et al., 2018).

Three different approaches have been used in past researches to quantifying the heat emissions from building sectors, though they have some inherent limitations respectively (Sailor, 2011). Inventory method is a common approach to quantifying anthropogenic heat emission from different sectors (i.e., buildings, transportation and industry) in cities. It uses energy consumption from each sector as an approximation, given all consumed energy ultimately converts to heat and dissipates to the atmosphere. Previous studies have shown that the building sector is the largest contributor

especially in a metropolis. Based on energy statistics in Beijing, Sun et al. (2018) adopted the district GDP and population density as adjustment factors to calculate and allocate heat emissions to seven urban functional zones. They found that buildings account for 45% of urban heat emission, among which commercial buildings have the highest impact on urban climate. Study results of Hamilton et al. (2009) also conclude that heat emission from buildings in London could be 3 to 25 times greater than captured solar radiation in winter. The critical problem of inventory approach is that energy consumption is not equivalent to heat emission. It is particularly evident for buildings with HVAC systems, which reject more heat than energy consumption to offset thermal load from the enclosure and transmitted solar radiation in summer (Sailor, 2011). Another problem of the inventory method is the lack of fine-resolution energy data in time, which produces inaccurate temporal distribution.

Given the magnitude and complexity of heat emission from buildings, a bottom-up method with building energy models has been proposed to identify heat fluxes to outdoor from different building components. Hsieh et al. (2007) focused on heat rejection from air conditioning systems in summer, which can be represented by condenser side heat transfer to outdoor. They built EnergyPlus models for a building portfolio in Taipei city and derived diurnal heat rejection patterns with hourly EnergyPlus model output. Bueno et al. (2012) established a resistance-capacitance (RC) network model to represent the thermal interaction of buildings with their surroundings. They then used the RC model to investigate the impact of heat fluxes through the building envelope, exfiltration, and HVAC system heat rejection on outdoor air temperature. However, none of them encapsulates heat emitted from all possible building components, failing to quantify total heat emission from buildings and to deliver a complete picture of annual and seasonal variations.

The third approach, surface energy balance method, is the only method that utilizes field measurements to estimate anthropogenic heat emission in regions. The approximation of heat emission is the residual from the difference between measured net radiative heat flux and sensible/latent heat flux. Yet the requirement of expensive equipment and long-term measurement are prohibitive, in addition to the difficulty to split results into different sectors (i.e., buildings, transportation, industry, etc.) (Sailor, 2011).

To address the limitations of previous studies, the present study is dedicated to quantifying the total heat emissions from buildings with a more holistic bottom-up method.

Method

Heat emissions from a building include heat release to the ambient air, radiant heat to the sky, radiant heat to the ground, and radiant heat to the surrendering surfaces (neighbor building surfaces, water body) and objects (e.g., trees). This study focuses on heat directly discharged to the ambient air for urban climate research purpose.

A bottom-up approach is proposed to calculate heat emissions from buildings to ambient air, which can be adopted by any building energy modeling programs. The heat emissions from a building to ambient air include heat releases from three levels of building components: (1) building envelope – exterior surfaces' convective and radiative heat transfer to the ambient air, (2) zone - exhaust air or exfiltration from spaces to the ambient, and (3) HVAC system - relief/exhaust air and heat rejected by air-cooled or evaporative-cooled condensers or central plants, including cooling towers of water-cooled chillers, gas-fired boilers, furnaces and water heaters. All heat emission components are illustrated in Figure 1. It should be noted that any underground zones or envelope surfaces are excluded since the heat from those spaces is rejected to the ground instead of to the ambient air.

Figure 1: Building released heat compositions.

Figure 2: Envelope exterior surface heat balance.

Exterior surfaces of the envelope are crucial heat transfer elements of a building to ambient air. As shown in Figure 1, they emit heat to ambient air in the form of convection and long-wave radiation, which could be absorbed by particles and gas molecules in the ambient air. As

indicated by the heat balance of the exterior surface (illustrated in Figure 2), this part of emitted heat comes from both external source (i.e., solar radiation) and internal sources (internal heat gains and space heating or cooling). The internal sources change the outside surface temperature through envelope conduction, along with the incident solar radiation, and this triggers the heat exchange with the ambient air. The energy conservation between heat sources and envelope total emission holds for the annual aggregate results. However, since the heat radiated to the sky and ground is not considered as emissions to the ambient air, in this study, the calculated heat emissions should always be less than sum of the heat sources. The surface heat emission to ambient air is calculated as the sum of surface outside face convection heat gain rate and surface outside face thermal radiation to air heat transfer rate:

$$Q_{\text{emi, surf}} = (H_c + H_r) * A * (T_{\text{surf}} - T_{\text{out}}) \quad (1)$$

where H_c is the surface outside face convection heat transfer coefficient, H_r is the heat transfer coefficient of the surface outside face thermal radiation to the ambient air, A is the surface area, T_{surf} and T_{out} are the surface and outdoor air temperature.

Discharge air acts as the media carrying heat to outdoor as it leaves a building at indoor air temperature. It consists of three parts at two levels, including zone level - exfiltration, zone exhaust air and HVAC system level - system relief air. Exfiltration is the unintended airflow to outdoor through envelope cracks, as opposite to infiltration. Zones such as restroom, kitchen and laundry room are equipped with an exhaust fan for active venting. HVAC system releases part of return air from zones for mechanical ventilation purpose. With the discharge air temperature converging to the ambient air temperature, the contained heat is released into the ambient.

These items can be quantified by:

$$Q_{\text{exf, zone}} = m_{\text{exf}}(h_{\text{zone}} - h_{\text{out}}) \quad (2)$$

$$Q_{\text{exh, zone}} = m_{\text{exh}}(h_{\text{zone}} - h_{\text{out}}) \quad (3)$$

$$Q_{\text{exh, sys}} = m_{\text{exh}}(h_{\text{node_out}} - h_{\text{out}}) \quad (4)$$

where m_{exf} is the exfiltration air flow rate, m_{exh} is the exhaust air flow rate from the zone or system exhaust node, h_{zone} and h_{out} are the zone and outdoor air enthalpy, and $h_{\text{node, out}}$ is the system outlet air enthalpy.

While the HVAC system indirectly influences envelope heat emission through space heating or cooling, it also directly exchanges heat with ambient air via the refrigeration cycle and its energy usage. For gas-fired heating, waste heat is exhausted to outdoor with combustion byproduct. In order to provide space cooling, heat is removed from indoors and dumped to outdoor at the condenser side or corresponding cooling equipment, such as a cooling tower. Besides, energy consumed by outdoor equipment will directly dissipate as heat to the ambient air, such as compressor and condenser fan in packaged DX systems. Heat pump is a special case for heating, because it extracts heat from outdoors in heating seasons instead of releasing heat. In general, we assume the heat rejection is due to gas-powered combustion and

condensers of any type, and we calculated these items based on the system type:

1. Gas-powered combustion unit: Fuel generated heat – fuel heat supply;
2. Condensing unit:
 - a. Air-cooled: cooling rate + electric power of the condenser fan and compressor;
 - b. Water-cooled: total heat transfer rate with the outdoor air.

Detailed calculation of HVAC rejected heat varies with different HVAC object groups and component types. Details are documented in the EnergyPlus Engineering Reference Manual.

Implementation in EnergyPlus

EnergyPlus is an open source building energy simulation engine that can dynamically model heating, ventilation, air-conditioning, lighting, plug-loads, water use, renewable energy generation, and other building energy flows. Several new features were recently added to EnergyPlus to improve modeling buildings in urban context considering the interactions between buildings and between buildings and urban microclimate (Hong and Luo, 2018): (1) import and export of exterior shading schedules, (2) calculation of long-wave radiant exchange between buildings, and (3) use of urban microclimate conditions for heat transfer calculations in exterior surface convection and infiltration, as well as local outdoor air.

The heat emission calculations were implemented in EnergyPlus as a new feature. It is available in the EnergyPlus version 9.1 release in April 2019.

Two new choices, HeatEmissionsSummary and HeatEmissionsReportMonthly, are added to the object Output:Table:SummaryReports to specify the reporting of the annual and monthly heat emissions from buildings to the ambient in the EnergyPlus tabular summary reports. The reported heat emissions are broken down into the Envelope Convection (exterior surfaces, e.g., walls, roofs, windows), Zone Exfiltration, Zone Exhaust Air, HVAC Relief Air (from air handling units), and HVAC Reject Heat (from air-cooled condensers, cooling towers, and boiler combustion exhaust).

A dozen new report variables were added to enable the generation of the annual and monthly reports, as well as the reporting of time-step total, sensible and latent heat emissions:

- Zone, Average, Surface Outside Face Thermal Radiation to Air Heat Transfer Rate [W]
- Zone, Average, Surface Outside Face Heat Emission to Air Rate [W]
- HVAC, Average, Zone Exfiltration Heat Transfer Rate [W]
- HVAC, Average, Zone Exfiltration Sensible Heat Transfer Rate [W]
- HVAC, Average, Zone Exfiltration Latent Heat Transfer Rate [W]
- HVAC, Average, Zone Exhaust Air Heat Transfer Rate [W]

- HVAC, Average, Zone Exhaust Air Sensible Heat Transfer Rate [W]
- HVAC, Average, Zone Exhaust Air Latent Heat Transfer Rate [W]
- HVAC, Sum, Site Total Zone Exfiltration Heat Loss [J]
- HVAC, Sum, Site Total Zone Exhaust Air Heat Loss [J]
- HVAC, Sum, HVAC System Total Heat Rejection Energy [J]

Positive values of these report variables indicate heat released from the building to the ambient air, while negative values indicate the heat extracted by the building from the ambient air (i.e., the building absorbs heat from the ambient air).

Case Study and Results

Case study setup

As a simple case study to demonstrate the use of the feature in EnergyPlus and to gain a deep understanding of the heat emissions, we chose the small-sized office building models from the USDOE's commercial prototype buildings models suite (USDOE). The small office building uses packaged air-source heat pump for cooling and heating with a gas furnace for backup heat. The building meets the ASHRAE Standard 90.1-2014 efficiency requirements. Chicago is chosen as the typical climate with hot summer and cold winter.

Annual simulations were run. Results are first reported at 10-min time step, and then aggregated to monthly and annual summaries to demonstrate the temporal variations of building released heat.

Case study results

As shown in Figure 3, for the reference small office building, the annual net heat emission is 1180.26 GJ, which is 3.71 times of the annual site energy use of 317.91 GJ. Envelope heat emission to the ambient air via convection and long wave radiation is the dominant composition (82%), followed by the HVAC system heat rejection (9%), zone exfiltration (5%), and HVAC system relief air (4%).

Figure 3: Percentage of each composition of the annual total net heat emission of the small office building

Figure 4 and Figure 5 show the seasonal patterns of heat emissions. The seasons are defined as spring (March,

April, May), summer (June, July, August), autumn (September, October, November) and winter (December, January, February). The variation of the convective heat emission resembles seasonal solar radiation change: peaks in summer, continuously diminishes from fall to winter, and increases again in spring. The maximum HVAC heat rejection appears in summer, while the heat pump system absorbs heat from ambient air in winter (i.e., the negative value shown in Figure 4 & Figure 5). Heat rejected by the relief air shows a reverse pattern, which peaks in winter and carries cooling in summer. Long-wave radiation to air and zone exfiltration exhibit minimal seasonal variations. Except for the dominant convective heat emission across all seasons, HVAC heat rejection takes up 7% in summer while emission through zone exfiltration and HVAC relief air accounts for 16% in winter. In summer, the heat emission from the HVAC air system relief air is negative (meaning heat absorption due to the relief air having a lower temperature than the ambient/outdoor air) and is not plotted in the figures.

Figure 4: Seasonal net heat emission per floor area of the small office building

Figure 5: Percentage of each composition of the seasonal net heat emission of the small office building

Figures 6 and 7 show heat emissions during a typical summer and winter weekday, respectively. During daytime in summer, more heat is emitted by the envelope convection and the rejected heat from the air-cooled condenser, while the envelope absorbs heat during the night-time. In winter, the amount of heat emissions is much smaller (almost reduced by half compared with summer results), and the HVAC systems absorb heat rather than release heat due to the heat pump operation in

heating mode - moving heat from outdoor air to the indoor.

Figure 6: Heat emissions on a typical summer day

Figure 7: Heat emissions on a typical winter day

Among the heat emitted to the surrounding environment, we compared the heat emissions to the ground, sky and ambient air through the envelope. For the reference small office building, the annual heat emission through convection and radiation to air, radiation to the sky, and radiation to the ground are 964.2 GJ, 1401.5 GJ, and -144.7 GJ, respectively. In particular, the building absorbs heat from the ground in winter and releases heat in summer by long-wave radiation.

Overall the heat emissions from the small office building are dominated by the envelope convection heat transfer as the building has a much larger ratio of surface area to air volume. For buildings with more core area and less perimeter area, the amount of HVAC system related heat rises. On an annual basis, the small office building in Chicago emits a significant amount of heat to the ambient air of 3.71 times the total site energy consumed by the building. Again, this characteristic of heat emission will vary by building type, HVAC system type, efficiency level, and climate zones.

Conclusion

A new feature to calculate heat emissions from buildings to the ambient air was developed and implemented in EnergyPlus version 9.1. Simulated results of the small-sized office building show heat emissions from buildings

to the ambient air are dynamic and vary by day and night as well as by seasons. This feature enables a quantitative and deeper understanding of building heat emissions which is a key contributor to the urban heat island effect in dense urban areas. Future work includes verification of the simulated heat emissions using ideal EnergyPlus models, and applying the heat emissions feature in the urban building energy modeling tools (e.g., CityBES (Hong et al. 2016)) to enable the study of heat emissions from buildings in an urban context and how they influence the urban microclimate.

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