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The effect of heat recovery on near-source plume dispersion of a simple cycle gas turbine

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ABSTRACT

The waste heat recovery (HR) systems are employed to increase the overall thermal efficiency of electric generation units (EGUs). Although the emission factors (in terms of gram of pollutants per unit of thermal energy consumed or electric energy generated) generally decreases after installing HR systems, the emission rates in terms of grams of pollutants per unit of time remain unchanged. However, HR systems reduce stack exit temperature, resulting in lower effective emission heights, which lead to higher near-source ground level concentrations (GLCs) of air pollutants. In order to comprehensively evaluate the near-source air quality impact from deploying HR systems, we proposed a new modeling framework by integrating a computationally efficient Gaussian-based dispersion model (AERMOD) and a (relatively) more accurate computational fluid dynamics (CFD) model. As a demonstration of the proposed framework, we investigated the HR impact on NO_x concentrations near a simple cycle gas turbine located in Brentwood, NY. Specifically, we applied the AERMOD modeling system to screen the hourly GLCs over five years, and highest values (and the corresponding hours) were shown to cluster into two main meteorological conditions: the stable atmospheric boundary layer with relatively high wind speed (Stable, HW) and the unstable atmospheric boundary layer with relatively low wind speed (Unstable, LW). These two conditions were further simulated using a CFD model that have been extensively evaluated previously for detailed analysis. By setting different stack exit temperatures, the near-source air quality impact of different waste heat conversion rates was evaluated. We introduced a concept called the heat recovery amplified factor (HRAF), defined as the ratio between the maximum GLC with HR system and that without HR system, as an indicator of HR impact. HRAF was shown to be much more sensitive to temperature in the Unstable, LW condition than in the Stable, HW condition. Although the results were limited to a specific simple cycle gas turbine, the proposed modeling framework and HRAF can be used for evaluating the HR systems impact for other emission sources.

1. Introduction

According to the 2015 Annual Energy Review published by the U.S. Energy Information Agency (EIA, 2015), conversion losses, mainly in form of waste heat, account about 62% of the total primary energy consumed to generate electricity in the U.S. In the electricity sector, natural gas as a fuel source accounts for 43% of the fossil fuel primary energy consumption in the sector, and 33% of the total net electricity generation from all fuel types including nuclear and renewable. While combined cycle natural gas turbines plants can achieve thermal efficiencies as high as 60 percent, the thermal efficiency for simple cycle gas turbines typically range between 20 and 35 percent. The considerably large amount of wasted heat could be saved by using waste heat recovery systems (HR).

One option for HR is to utilize waste heat for on-site thermal process (e.g., preheating) or spacing heating (e.g., combined heat and power (CHP)) through district heating systems, which then reduce or replace fossil energy that would have otherwise been used. Many power generation facilities do not have a large demand for on-site thermal process, or space heating demand within reasonable distance (to reduce heat loss). Another option for HR is to convert waste heat to power. However, recovering waste heat for additional power generation from high efficiency gas turbines is challenging due to their low temperature exhaust gases ($< \sim 643$ K). The traditional steam Rankine cycle is not appropriate for low-grade ($< \sim 643$ K) HR because the working fluids, such as water, usually need to be superheated (Chen et al., 2010; Lecompte et al., 2015). Researchers proposed the organic Rankine cycle (ORC), which use organic substances as working fluids (Hung, 2001; Hung et al., 1997; Huppmann, 1983). Although the ORC is commonly accepted as a viable technology to convert low temperature heat into

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electricity, the large thermal mismatch between a pure working fluid and the heat source (referred to as the pinching problem) may occur in ORC counter current heat exchanger (Chen et al., 2006, 2011), which limits the adoption of ORC in HR applications (Chen et al., 2010).

Recently, supercritical CO_2 (s-CO_2) cycle has shown considerable potential as HR for converting low-grade waste heat into electricity. Comparing with the traditional Rankine cycle, supercritical CO_2 (s-CO_2) is more suitable for the small and medium size gas turbine (20–120 MW). The exhaust gas temperature from a gas turbine or general topping cycle is usually > 723 K. And the s-CO_2 cycle can potentially replace the steam Rankine cycle to further improve the thermal efficiency (Ahn et al., 2015) and the pinching problem can be avoided (Chen et al., 2006, 2011). CO_2 has a lot of advantages as a working fluid, such as relatively low critical point (critical temperature 304.25 K, critical pressure 7.39 MPa), and relative inertness. In addition, the high fluid density of s-CO_2 enables compact turbo-machinery designs and permits the use of compact heat exchanger technology (Sarkar, 2015).

One particular HR application that has drawn significant interests from the environmental research community is biomass-fueled CHP. Petrov et al. (2015) evaluated the health risk associated with a biomass CHP facility at a university campus using dispersion modeling and the intake fraction method. Tong et al. (2017) investigated the near-source micro-environmental air quality impact of a biomass CHP unit equipped with an electrostatic precipitator (ESP). Levy et al. (2017) conducted the health risks and cost-benefits analysis of the same unit studied by Tong et al. (2017) by quantifying the incremental contribution to population mortality and morbidity and assigning economic values to health outcomes.

By contrast, the air quality impact from waste heat to power applications has been rarely studied (Wu et al., 2014), which is the focus of our study. From this point forward, HR is referred to as waste heat to power heat recovery. A number of studies have reported the design and optimization of HR systems (Cayer et al., 2010; Shengjun et al., 2011; Wang et al., 2010), where the environment impact was usually not considered as a design factor. There are both benefits and disbenefits from HR in terms of air quality impact. The higher percentage of the waste heat can be recovered, the lower overall emission factor (g-pollutant/MWh_e) would be achieved. In other words, for the same amount of electricity (and heat) delivered, fewer fuels will be burned, and thus lower emissions. Therefore, it is expected that the wide deployment of HR systems could reduce emissions from the power sector, and thus improve regional air quality. On the other hand, the lower exit temperature and velocity as a result of HR may lead to lower effective emission heights, which may result in greater near-source impact. However, the extent of the near-source impact has not been quantified under realistic emission and environmental conditions. One of our main objectives is to bridge this gap.

In terms of quantifying the near-source impact of HR, there is also a need to develop better tools or integrate existing tools. Two major types of modeling tools have been employed in similar studies, i.e., Gaussian-based dispersion models (e.g., AERMOD, CALPUFF, etc.) and computational fluid dynamics (CFD) models. Gaussian-based dispersion models are widely used in regulatory applications. For instance, AERMOD is a steady-state Gaussian plume model that incorporates air dispersion based on planetary boundary layer turbulence structure and scaling concepts, including treatment of local meteorology, both surface and elevated sources, and both simple and complex terrain (Cimorelli et al., 2005). The performance of AERMOD is generally good for centralized power plants, but there are challenges when the plume is not much higher than the surroundings (Monbureau et al., 2018; Perry et al., 2016). Using more detailed mathematical and physical descriptions, properly configured computational fluid dynamics (CFD) models generally provide better concentration predictions than Gaussian-based dispersion models (Hanna et al., 2009; Mazzoldi et al., 2008, 2011), especially when the domain contains obstacle and/or complex terrain, which would significantly affect the dispersion pattern (Hsieh et al., 2013; Tauseef et al., 2011). One particular application is to analyze the near-source impact of distributed generation (DG) units (Tong et al., 2017; Tong and Zhang, 2015), which are located close to population centers. The advantage of CFD models over Gaussian-based models was also be found in simple, flat terrain cases. Tang et al. (2006) compared the simulation results between CFD and AERMOD against the measurement data capturing the condition of point source plume dispersion over flat terrains, which showed that CFD generally performs better than AERMOD at receptor locations closer to the source. Recently, researchers have utilized CFD simulations to improve the performance of AERMOD in modeling building downwash effect (Monbureau et al., 2018; Perry et al., 2016).

A dilemma that the modeling community is often facing is that Gaussian-based models are computationally efficient but may not be highly accurate, while well-configured CFD models are relatively more accurate but computationally expensive. A practice often adopted is to select a few prevailing wind conditions for CFD simulations. The main drawback of this approach is that the prevailing wind directions do not necessarily lead to the worse air quality, even though air quality assessments often require consideration of worse case scenarios. Another main objective of our study is to tackle this challenge.

In this paper, we proposed an integrated modeling framework to take advantage of both computationally efficient Gaussian-based dispersion models and relatively more accurate CFD models. As a demonstration of the proposed framework, we investigated the HR impact on NO_x concentrations near a simple cycle gas turbine (47 MW) located in Brentwood, NY, with and without an s-CO_2 HR system. The paper was organized as follows. First, we described the Brentwood facility and the surrounding environment. Then, we reported the model configurations for both Gaussian-based dispersion and CFD models. Next, the integrated modeling framework was elucidated. Finally, we discussed the modeling results and defined an indicator to represent the HR impact.

2. Modeling method

2.1. An integrated Gaussian dispersion-CFD method

As mentioned in Section 1, there is a need to develop better assessment tools to evaluate the near-source impact of HR systems. In our study, we proposed an integrated framework to take advantages of the computational efficiency of the Gaussian-based dispersion models and the accuracy of the CFD models in assessing the air quality impact of emission sources. Fig. 1 depicts the overall approach. In our modeling framework, a Gaussian-based dispersion modeling system, AERMOD,

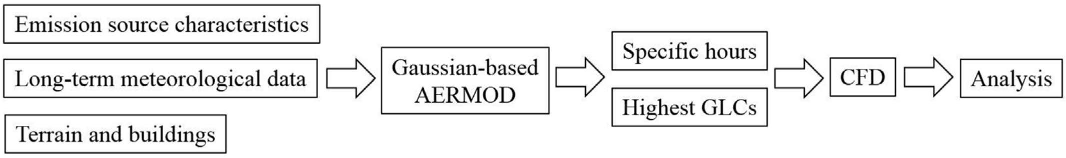

Fig. 1. A diagram that illustrates the proposed integrated modeling framework utilizing a Gaussian-based dispersion model, AERMOD, and a CFD model. GLC stands for ground level concentration.