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Modelling of greenhouse gas emissions from the steady state and non-steady state operations of a combined cycle power plant located in Ontario, Canada

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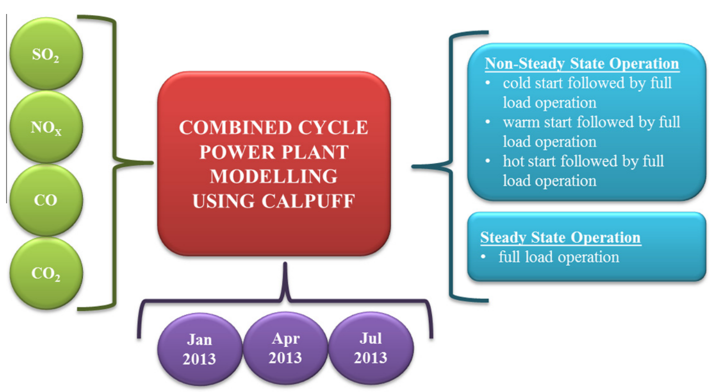
HIGHLIGHTS

- Modelling the greenhouse gas concentrations from the steady state operations.
- Modelling the greenhouse gas concentrations from the non-steady state operations.
- Concentrations of some pollutants were found higher during non-steady state.
- It is recommended to consider emissions from both states.
- The impacts of emissions should be assessed based on the worst case scenario.

GRAPHICAL ABSTRACT



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ABSTRACT

Although often neglected, the non-steady state operations of power plants are more likely to result in increased emissions and process safety incidents compared to steady state operations. There are multiple challenges in predicting non-steady state emissions. Firstly, it is difficult to collect accurate data during such events due to their dynamic process variables and shorter time span. Additionally, many manufacturers do not have emissions data available for start-up and shut-down events. Also, the U.S. EPA does not provide method tests applicable for dynamic processes. Furthermore, developing and processing facility emission models are more challenging and expensive for dynamic processes. Moreover, integrating coupled process functions, such as reaction and heat transport operations, complicates the prediction of non-steady state emissions. In this study, the dispersion of greenhouse gas emissions from steady state and non-steady state operations of a future combined cycle power plant were modelled using CALPUFF. The natural gas fired plant consists of a turbine generator that exhausts through a heat recovery steam powered generator. The main source of emissions is the stack of the heat recovery generator. Nitrogen oxide, carbon monoxide, carbon dioxide and sulphur dioxide were modelled under full load operation, cold start followed by full load operation, warm start followed by full load operation and hot start followed by full load operation. The results showed that nitrogen oxide and carbon monoxide emissions were significantly higher under non-steady state operation. This may be because during start-up operations, the low temperature will not activate any control technology operations that may be in place. Sulphur dioxide emissions did not change significantly with operating scenarios. Carbon dioxide emissions were higher under steady state operation, likely due to higher fuel consumption. Based on the results of

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this study, air quality impact assessments are recommended to consider emissions from both, steady state and non-steady state operation to ensure that impacts are assessed based on the worst case scenario.

1. Introduction

The air permit framework in Ontario and the United States (U.S.) is based on defining and enforcing limits on the concentrations of contaminants that are emitted from a facility to the environment [1,2]. Guidance provided by regulatory agencies in calculating emissions relies heavily on the use of the emission factors listed under AP-42, Compilation of Air Pollutant Emission Factors, developed and published by the United States Environmental Protection Agency (U.S. EPA) [1–3].

However, it should be noted that these emission factors were developed based on data collected from the testing of emissions under normal process operating conditions, such as steady state operation. Furthermore, these emission factors do not account for short-term fluctuations in the process conditions, such as those encountered under non-steady state operation [4]. Thus, it can be concluded that the use of these emission factors in assessing worst case scenario emissions from a facility does not capture emissions generated by the facility when it is operating under non-steady state conditions.

Thus, more accurate approaches need to be developed and investigated to predict emissions of contaminants from the facility when it is not operating under steady state conditions. Non-steady state conditions can include process start-ups and shut-downs, as well as process fluctuations where the operating conditions deviate from the normal operating conditions [5].

Due to the lack of clearly defined methods of quantifying and regulating emissions generated during start-up and shut-down events, the approaches taken by the states to limit and regulate these emissions have been inconsistent. Some states allow facilities to use six to twelve months of Continuous Emissions Monitoring System (CEMS) data to develop site-specific emissions limits for start-up and shut-down events. In other states, emission limits remain applicable to normal operating conditions only [1]. Furthermore, some states restrict the length of time that a facility takes during start-up and shut-down events to limit excess emissions during such events [6].

In response to a petition filed by a U.S.-based environmental organization called the Sierra Club, the U.S. EPA proposed a rule in February 2013, necessitating that the states develop plans to require that all industrial facilities comply with air pollution rules during plant start-ups, shut-downs and malfunctions [7].

There are multiple challenges in predicting emissions that are generated during non-steady state operations, such as start-up and shut-down events. Firstly, it is difficult to collect accurate and representative data during such events due to their relatively short time span and their dynamic process variables. Additionally, many manufacturers do not have emissions data available for start-up and shut-down events. Also, the U.S. EPA does not provide method tests that can be applied for dynamic process situations [5]. Furthermore, developing and processing dynamic models for facilities is often more challenging and costly than developing models that only represent normal operating conditions. Moreover, the integration of multiple process functions, such as reaction and heat transport operations, within the same process unit further complicates the prediction of emissions under non-steady state conditions [8].

Despite the challenges in predicting emissions from start-up and shut-down events, investigating methods to predict these emissions is essential in ensuring that a facility does not adversely impact human health or the environment. Oftentimes, emissions are higher during the start-up and shut-down of a facility, compared to its steady state operation under normal operating conditions [6,9]. Additionally, most incidents that are related to the process carried out at the facility occur when the plant is operating at an unsteady state [8]. Furthermore, as emission limits become more stringent with time, it is more important to investigate methods of predicting emissions associated with non-steady state events, to ensure that resources are adequately allocated to minimize emissions and thus to achieve compliance with these limits [1].

The Environment Agency in 2011 developed a protocol to describe criteria that should be taken into account during start-up and shut-down events for gas turbines [9]. As part of the start-up protocol, the percent loading on the turbine is systematically increased to above 70%, at which point normal operating conditions are attained. The protocol states that, at less than 70% load, there is an increase in the air–fuel ratio and a decrease in the temperature of the flame, which can ultimately lead to an increase in carbon monoxide emissions [9].

Bivens [6] investigated the nitrogen oxides emissions generated from the start-up and shut-down events of combined-cycle combustion turbine units, by predicting these emissions based on manufacturer's data and CEMS, and ultimately comparing them against emission limits. The study concluded that nitrogen oxide emissions varied greatly with the make and model of the turbine units, and that the emissions for start-up events, calculated based on manufacturer's data, exceeded the applicable emission limits.

The Ohio Environmental Protection Agency in 2006 developed an emissions inventory for the Great Bend IGCC power plant, located in Ohio, USA, whereby potential emissions associated with start-up, shut-down and normal operations were estimated for the facility [10]. U.S. EPA AP-42 emission factors were used to assess the emissions. The results showed that the emissions of nitrogen oxides, particulate matter and volatile organic compounds were higher for start-up and shut-down events, compared to normal operation.

The California Puff Model, CALPUFF, is one of the models that the U.S. EPA recommends for the prediction and modelling of the dispersion of airborne contaminants that are emitted from a source [11]. The U.S. EPA specifically recommends the use of this Lagrangian puff model when assessing impacts on receptors that are located over 50 km away from the emission source. Thus, it is considered a long-range transport model [12]. A non-steady state model, CALPUFF has several advantages, including its allowance for non-straight line trajectories, its consideration of a non-uniform atmosphere across the domain, its accuracy in calm conditions, and its ability to retain the memory of contaminant emissions from previous hours.

Many studies have used CALPUFF to simulate the dispersal of contaminant emissions and assess their impacts at receptors within a domain. CALPUFF has been used to model the dispersion of the emissions of sulphur dioxide from a flare located at an oilfield, sulphur dioxide from various refineries, nitrogen oxide from the operation of a power plant that converts biomass into energy,