River Project, An Innovative Way to Reduce Pollution on Riverboats

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Abstract. Considering the EU environmental standards for non-road mobile machinery (NRMM), reducing pollutant emissions from inland waterway vessels is becoming increasingly important. The RIVER research project aims to find solutions to achieve nitrogen-free combustion in waterways transportation systems while also emitting zero CO_2 emission. RIVER addresses these issues using Carbon Capture and Storage (CCS) technology and Oxy-fuel combustion (OFC). The project is co-financed by the European Union, as part of the Interreg North-West Europe program. There are ten partners involved in this project (FR, UK, GE, NL, LU). In OFC technology, pure oxygen is used instead of air. Due to the absence of N_2 in the intake charge, NOx emissions will be eliminated. Consequently, the only products of combustion are CO_2 and water vapor. To have a stable combustion process and avoid overheating problems caused by using pure oxygen, some part of the exhaust CO_2 will be recirculated to the engine to create an oxygen-CO_2 mixture for being fed into the engine. A detailed CFD simulation carried out in this project has revealed that 21% oxygen and 79% carbon dioxide is the ideal mixture for the engine to run at maximum efficiency. The remaining CO_2 from the exhaust is collected. It is then condensed, compressed, and stored in a tank to be valorized later. It will be transformed into cosmetics, skincare products, and formic acid. These types of acids are used by the medical sector as an anti-rheumatic product. River's final demonstration will take place in Crewe, UK in July 2022.

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1 Introduction

The global warming problem has been significantly exacerbated by greenhouse gas emissions (GHG) over the last few decades (Kanniche et al. 2010; Wang et al. 2015). The transportation sector consumes twenty percent of global fossil fuel production which puts it second in terms of emission of carbon dioxide (CO_2) and consequently, contributes to alarmingly increasing levels of atmospheric CO_2 and associated greenhouse gases. The European Union has set a target of less than 59 g/km of CO_2 tailpipe emissions in 2030, meaning that a 37.5% reduction is required through this decade. Discussions are underway to further reduce the target to align it with the European Green Deal, which is aiming for net-zero greenhouse gas (GHG) emissions by the year 2050. There have been several initiatives proposed to deal with the deteriorating climate crisis, including carbon neutrality (Figueroa et al. 2008; Li et al. 2021, 2022).

In 2017, the European Union adopted regulations requiring limits on carbon emissions and certification of internal combustion engines used in nonroad mobile machinery (Directive 97/68/EC). As a result, inland waterways (IW) vessels must now comply with more strict emission standards. In project RIVER, the goal is to find solutions to achieve nitrogen-free combustion in waterways transportation systems while also emitting zero carbon dioxide (Aitouche 2022).

It has been proposed that oxygen enriched combustion and oxy-fuel combustion (OFC) are an efficient way to increase engine efficiency and reduce pollutant emissions. OFC combustion uses pure oxygen for combustion instead of air. Due to the absence of N_2 in the intake charge, NOx emissions will be eliminated. As a result, carbon dioxide and water vapor are the only products of combustion. Studies to date have been mainly focused on applying oxy-fuel or oxygen enriched combustion technologies to gas turbines and coal-fired power plants. The utilization of OFC and CO_2 capture for IC engines has been gaining a lot of attention during the last few years. Research on oxygen-enriched combustion shows that a slight increase in oxygen reduces smoke emissions as well as the amount of CO and unburnt hydrocarbons but increases the amount of nitrogen oxides (NOx). Various technologies have been used to decrease NOx and particulates, such as exhaust gas recirculation (EGR) and optimum injection strategies. Research conducted recently has drawn attention to oxy-fuel and nitrogen-free combustion because of the benefits it brings to vehicles and is being used to make huge improvements to the efficiency of internal combustion engines and to achieved zero NOx emissions. As is known, over-high peak pressures and peak pressure increases can easily appear in engine cylinders in oxygen-enriched conditions. An increase in combustion flame temperature is expected if oxygen is used instead of air. To minimize overheating problems due to overheating, it is crucial that the fuel injection flow rate be accurately controlled in order to eliminate unexpected temperature rises in the premixed and diffusion combustion. Further, the diluent ratio and intake charge temperature have a meaningful impact on controlling in-cylinder temperature and combustion process (Giorgi et al. 2021).

Homogeneous Charge Compression Ignition (HCCI) is one of the low-temperature combustion regimes being researched for internal combustion engines. The HCCI concept has been widely studied as a promising concept since it produces emissions comparable to those of a SI engine while achieving thermal efficiency comparable to diesel engines with direct injection. As a result of the auto-ignition occurring nearly simultaneously over the entire combustion chamber, HCCI engines have limited power density. The rapid energy release leads to a large pressure rise in the combustion chamber under high load, causing pressure oscillations. Additionally, HCCI combustion often suffers from the lack of proper combustion phasing. HCCI combustion is initiated by chemical kinetics: the high propensity of diesel fuel to auto-ignite combined with the high compression of diesel engines results in combustion starting before top dead center, very rapid pressure raises rates, short combustion durations.

The current project, which is part of a European project called RIVER (funded by Interreg North-West Europe), aims to examine how different intake charge temperatures may affect oxy-fuel combustion in HCCI mode.

2 River Project Proposed Technology

Equation (1) and Eq. (2) present the chemical reaction process of conventional air combustion (CAC) and OFC, respectively. Unlike with the CAC, the main feature of OFC is oxygen replaces air to react with fuel directly, leading to the chemical products merely contain CO_2 and H_2O.

Moreover, compared to nitrogen of air, the main discrepancies in physicochemical properties for CO_2 can be found in Table 1, which would affect the combustion characteristics of OFC under some specific conditions (Wall et al. 2009; Chen et al. 2012). Regarding molecular weight, CO_2 is 57% higher than that of nitrogen. Hence, under the conditions of OFC, the combustion temperature will be adversely affected due to the higher heat capacity on mole basis of CO_2. In addition, under OFC, chemical reaction rates at early combustion stage would be potentially reduced owing to the low thermal diffusivity and oxygen diffusion of CO_2.

$$\mathrm{C_xH_yO_z} + \left(x + \frac{y}{4} - \frac{z}{2}\right)(\mathrm{O_2} + 3.773\mathrm{N_2}) \rightarrow x\mathrm{CO_2} + \frac{y}{2}\mathrm{H_2O} + 3.773\left(x + \frac{y}{4} - \frac{z}{2}\right)\mathrm{N_2} \tag{1}$$

$$\mathrm{C_xH_yO_z} + \left(x + \frac{y}{4} - \frac{z}{2}\right)\mathrm{O_2} \rightarrow x\mathrm{CO_2} + \frac{y}{2}\mathrm{H_2O} \tag{2}$$

Table 1. Physicochemical properties of CO2 and nitrogen at 1000 k and 0.1 MPa

Property	CO_2	Nitrogen
Molecular weight	44	28
Density (kg/m^3)	0.5362	0.3413
Kinematic viscosity (m^2/s)	7.69e−5	1.2e−4
Specific heat capacity (kJ/kg K)	1.2343	1.1674
Thermal conductivity (W/m K)	7.057e−2	6.599e−2
Thermal diffusivity (m^2/s)	1.1e−4	1.7e−4
Mass diffusivity of O2 (m^2/s)	9.8e−5	1.3e−4
Prandtl number	0.7455	0.7022
Emissivity and absorptivity	>0	~0

The RIVER project's primary goal is to eliminate NOx emissions from inland boat engines as well as to capture and store carbon emissions from these engines. These issues are addressed through the use of Carbon Capture and Storage (CCS) technology and OFC in RIVER. A summary of the RIVER technology can be seen in Fig. 1.

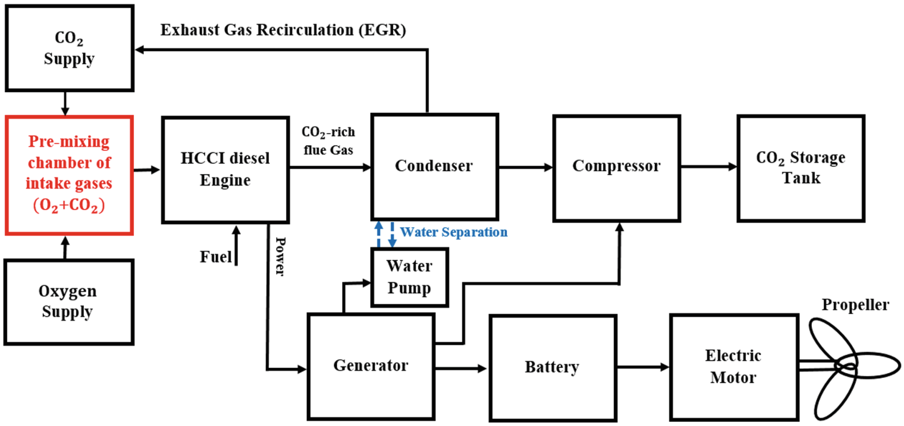


Fig. 1. An overview of RIVER technology

As shown in Fig. 1, power is supplied to the boat by a diesel generator. The engine operates in HCCI mode. There are three components involved in oxyfuel combustion: the oxygen supply system, the exhaust gas recirculation system, and the carbon capture system. Oxygen is provided by a commercial high-pressure oxygen cylinder. CO2-rich exhaust gases are condensed in the condenser, followed by the separation of water from it. Following recirculation, a portion of the remaining CO2 is recirculated back into the engine through EGR and mixed with oxygen prior to being used. Meanwhile, the rest of the CO2 is compressed and stored. It is predicted that this technology will eliminate NOx emissions while storing 100% of carbon dioxide. Optimizing oxy-fuel HCCI combustion requires using an appropriate oxygen concentration and EGR ratio. The authors examined how oxygen and carbon dioxide percentages affected combustion characteristics and engine operating conditions of OFC under HCCI mode. In the current study, the effect of intake charge temperature is discussed. This goal has been accomplished by studying the effects of five different intake charge temperatures on engine operating conditions for diluent strategies. The proposed idea in this study to apply oxy-fuel provides a significant advantage over previous studies in that the diluent strategy is integrated with HCCI combustion to control OFC process instead of water, which can eliminate problems associated with water injection such as lubrication and corrosion.

Because CO_2 is released at the outlet of the engine, no CO_2 is present during startup. It is being proposed to start the engine with an air mixture and wait a few cycles before switching to an oxygen/CO_2 mixture. Alternatively, install a tank in which CO_2 will be stored and solely used for starting. Both techniques have been tested, and both are effective. We will carry out tests under real conditions to see which works best. The ideal solution would be to use CO_2, as we don't take the risk of producing nitrogen oxide, which will mix with the CO_2.

Many boats in recent years have been equipped with exhaust gas recirculation (EGR) valves, making their installation of this technology much easier. However, this equipment must be added to older boats. All engines must be also equipped with oxygen supply valves. On smaller boats, oxygen can be provided by cylinders, but on larger boats, it should be produced on-site due to the large quantities needed. It must be noted the way to produce oxygen is much simpler than to produce hydrogen: Furthermore, oxygen does not have to be pure like in fuel cells, even 95% pure oxygen can be used.

The effect of different diluent strategies on in-cylinder cylinder pressure, and in-cylinder temperature are shown in Fig. 2 and Fig. 3, respectively, under a constant intake temperature and intake pressure.

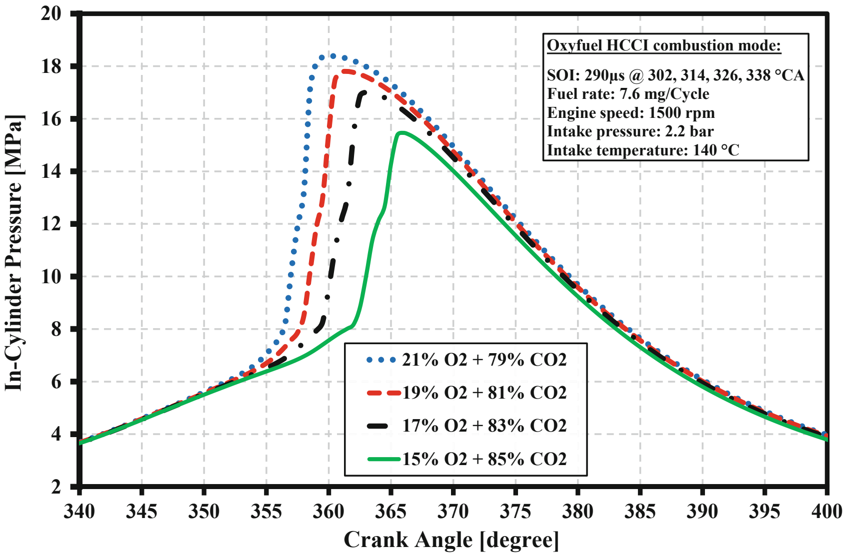


Fig. 2. Effect of different diluent strategies on in-cylinder pressure

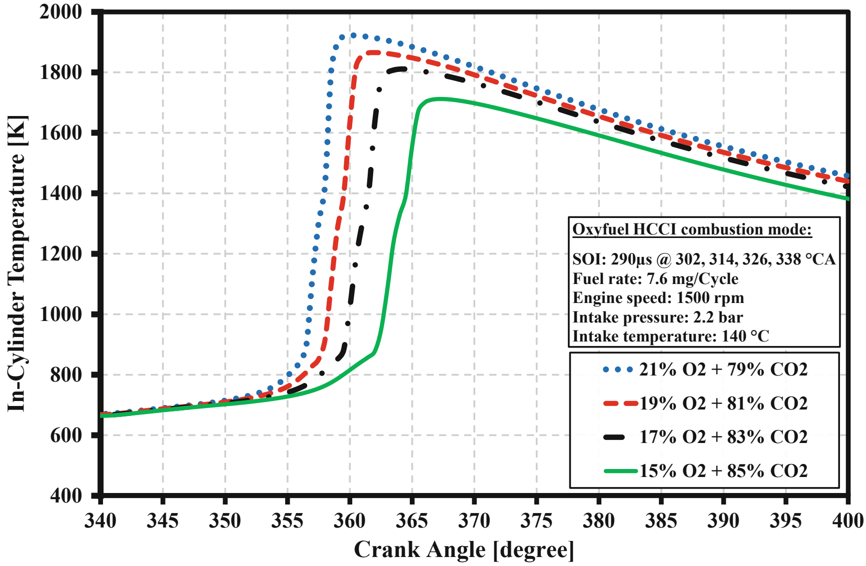


Fig. 3. Effect of different diluent strategies on in-cylinder temperature

As illustrated in Fig. 2 and Fig. 3, the increase of intake-air oxygen content from 15% to 21% results in a significant increase of peak in-cylinder pressure and peak in-cylinder temperature after TDC. In addition, it tends to advance peak pressure location and peak temperature location due to a significantly advanced main combustion process. Highest values of peak in-cylinder pressure and in-cylinder temperature are observed for the highest oxygen percentage (21%v/v). Applying oxy-fuel HCCI combustion instead of conventional HCCI combustion leads to acceleration of the combustion process which results in a shorter ignition delay period. In addition, premixed combustion is minimized while diffusion combustion is maximized. With the heat release rate dramatically increased, it takes a much shorter time to complete the entire heat release process. Subsequently, with such a high heat release rate, the in-cylinder temperature and in-cylinder pressure have increased.

In Table 2, it shows the amount of CO and PM emissions. The results indicate that the oxy-fuel HCCI combustion has brought the CO and PM emissions to a very ultra-low level while the NOx emission has been eliminated using the oxy-fuel combustion. In Table 1, Lambda_{O2} is defined as follow:

$$\text{Lambda}_{O2} = \frac{\text{ActualO}_2 - \text{fuelratio}}{\text{O}_2 - \text{fuelratio for stoichiemetriccombustion}} \tag{3}$$

Table 2. Effects of different strategies on PM and CO emissions

Applied diluent strategy	$Lambda_{O2}$ [-]	PM [gr/kg.fuel]	CO [gr/kg.fuel]
23% O_2 + 77%CO_2	2.38	1.92E−04	59.25
21% O_2 + 79%CO_2	2.18	1.17E−04	72.57
19% O_2 + 81%CO_2	1.97	3.66E−05	86.14
17% O_2 + 83%CO_2	1.77	3.88E−05	161.8

In addition, Fig. 4 and Fig. 5 shows the design and technical drawings of the whole after-treatment system in RIVER project. The system mainly involves a two-stage heat exchanger, water/gas separator, CO_2 compressors, CO_2 tank, required valves, controller, pipes, etc. The excess CO2 exhaust gas can be captured and stored in a storage tank to achieve zero carbon emissions. Furthermore, based on some initial simulation work in advance, the system would provide a good cooling capability, effectively reducing the exhaust temperature from around 800 K to 330 K before entering into the CO_2 tank.

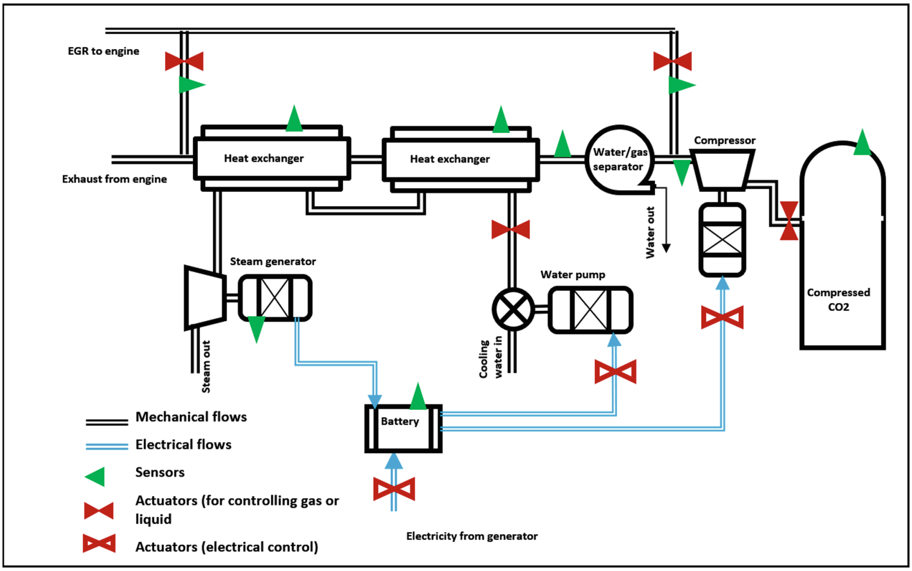
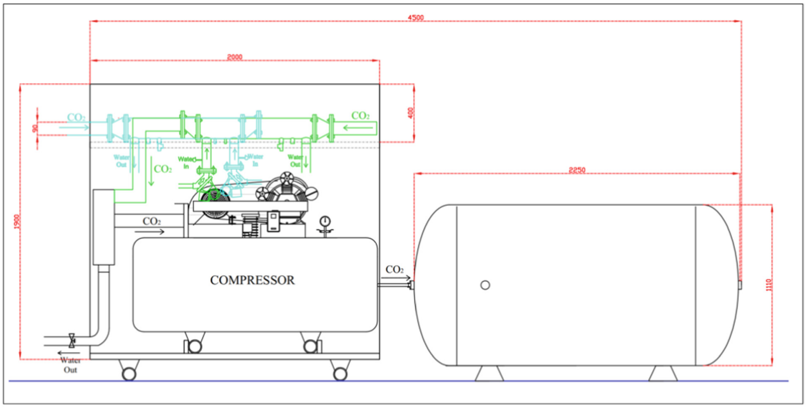
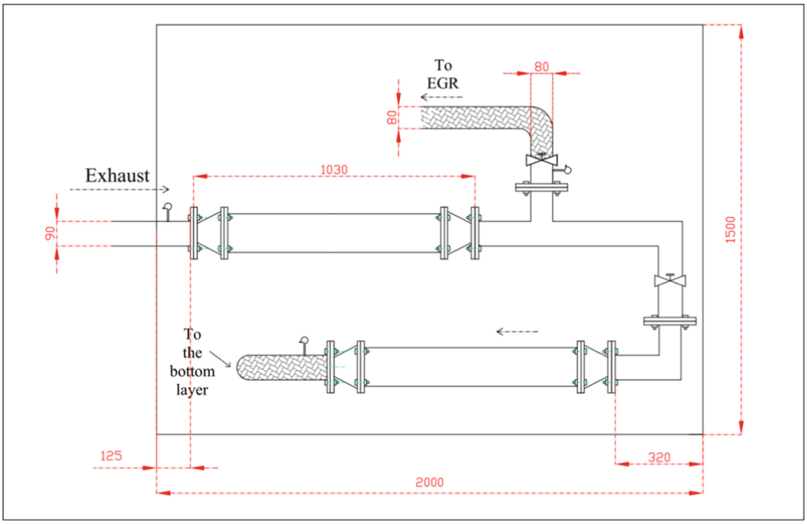


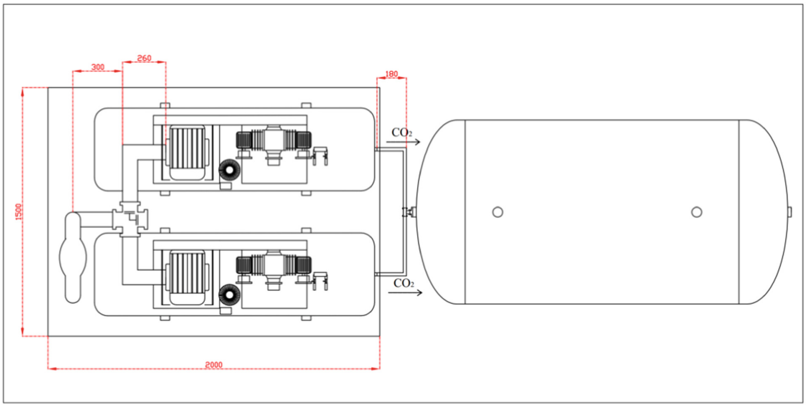
Fig. 4. Design of the after-treatment system in RIVER project



(a) Front view of the whole system



(b) Top view of the top layer



(c) Top view of the bottom layer and receiver

Fig. 5. Technical drawings of our after-treatment system

3 Conclusions

A technology has been proposed by the RIVER project to eliminate pollutant emission for the water transportation systems using CCS and OFC techniques. An advanced CFD simulation using detailed chemistry has been applied to explore the effect of different strategies on engine performance and the amount of pollutant emissions. Besides, a novel design and technical drawings of the after-treatment system of OFC has also been presented. The following conclusions may be drawn:

– Because no nitrogen is present in the intake charge of an oxy-fuel combustion, nitrogen oxides are eliminated. Consequently, combustion reactions produce CO2-rich emissions. In all cases investigated, PM emissions were very low (<0.0004 gr/kg.fuel) and NOx emissions were eliminated when using OFC HCCI.
– The proposed application of oxy-fuel in this study offers a significant advantage over previous studies in that a diluent strategy is used to control oxy-fuel combustion instead of water, thus eliminating problems associated with water injection such as lubrication and corrosion.

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