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DEVELOPMENT OF A SYSTEM APPROACH FOR ADAPTATION OF CURRENT AND DESIGN OF NEW COMBUSTION EQUIPMENT FOR LOW-CARBON AND SUSTAINABLE ENERGY

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Abstract: *The transition to low-carbon and sustainable energy is essential for reducing greenhouse gas emissions and ensuring energy security. This study introduces a system approach for adapting existing and designing new combustion equipment under new conditions. A thermodynamic analysis based on the T-Q diagram highlights key differences when implementing low-carbon and sustainable fuels, including increased thermal loads in hydrogen-based fuels and lower flame temperatures in biomass co-firing. An initial formulation of a structured system approach is proposed, identifying four critical areas: fuel preparation and transport, combustion process, heat transfer changes in the radiation chamber and convection section and waste heat utilization. Each area requires consideration and/or computational validation to address various risks. The findings emphasize the necessity of a systematic evaluation to maintain safe and reliable operation under new combustion conditions. The proposed framework provides a foundation for future studies in which the system approach should be perfected.*

Keywords: Low-carbon and sustainable energy, thermodynamic analysis, combustion equipment

1. Introduction

With growing concerns about climate change impacts, low-carbon and sustainable energy sources are becoming a key target of global efforts for sustainable development. Transforming the energy sector is necessary not only to reduce greenhouse gas emissions to achieve climate neutrality by 2050 but also to ensure long-lasting security and stability of the energy sector. When replacing fossil fuels with greener alternatives, it is essential to assess the impact of this transition on energy and process equipment, both in terms of heat transfer (the overall thermal power) and strength analysis and lifetime estimation.

This study aims to propose an initial formulation of a *"system approach".* The term system approach refers to a systemic set of testing, experimental or computational tools and methods for adaptation of current or design of new equipment for modern combustion conditions. The goal of this system approach is to quickly and effectively identify and address problematic technical issues in combustion equipment to ensure safe and reliable operation. The system approach is being developed within a work package dealing with the adaptation of current and design of new energy equipment in conditions of modern low-carbon and sustainable energy, as part of the project "Technical solutions for low-emission energy" of the program "National Center for Energy II".

From the perspective of adapting current and designing new combustion equipment, it is necessary to distinguish between the commonly used terms *low-carbon energy* and *sustainable energy* because each of these energy fields requires a specific approach to combustion equipment. The term low-carbon energy in the context of combustion equipment particularly refers to the implementation of new and advanced hydrogen-based fuels, respectively fuels with higher hydrogen content in the fuel mixture (for example the current trend of replacing natural gas with a mixture of natural gas and hydrogen in an appropriate ratio or,

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in extreme cases, completely replacing natural gas with pure hydrogen). The term sustainable energy in the context of combustion equipment then refers to replacing coal with other solid fuels and fuels mixtures, such as biomass including waste from biomass products (Kalak, 2023), or energy recovery from waste including medical waste, sewage sludge, non-recyclable plastics and solid recovered fuels among others.

2. Thermodynamic analysis of combustion equipment for low-carbon and sustainable energy

The aspects of the adaptation of current and the design of new combustion equipment for modern low-carbon and sustainable energy conditions can be illustrated using an elemental thermodynamic representation of combustion equipment known as the T-Q diagram (or the flue gas line model). This diagram is widely used not only during the conceptual design phase of combustion equipment to verify operational requirements but also for evaluating the environmental impacts of combustion equipment (Jegla et al., 2023). The T-Q diagram, along with a schematic of general combustion equipment, is shown in Fig. 1 a). The process stream (e.g. water) heated in the combustion equipment from temperature T_1 to temperature T_2 is represented in the T-Q diagram by a dark blue line. The red line represents flue gas generated by the combustion, cooling from the theoretical flame temperature T_{TFT} to the ambient temperature T_O. The relation between the T-Q diagram and actual energy equipment is clarified on the right side of Fig. 1 a), which presents a simplified schematic of combustion equipment where the temperatures are indicated. The abbreviation RC denotes the radiation (combustion) chamber, while CS represents the convection section. The flue gas produced from the combustion of a generic reference fuel exits the equipment at the stack temperature T_{STACK} while the temperature T_{BW} represents the flue gas temperature at the exit of the radiation chamber. The heat released during fuel combustion is labelled as Q_F, the unused waste heat of the flue gas as Q_L, and the heat transferred to the heated stream as Q_H, which is further divided into heat transferred in the radiation chamber (Q_{RC}) and heat transferred in the convection section (Q_{CS}).

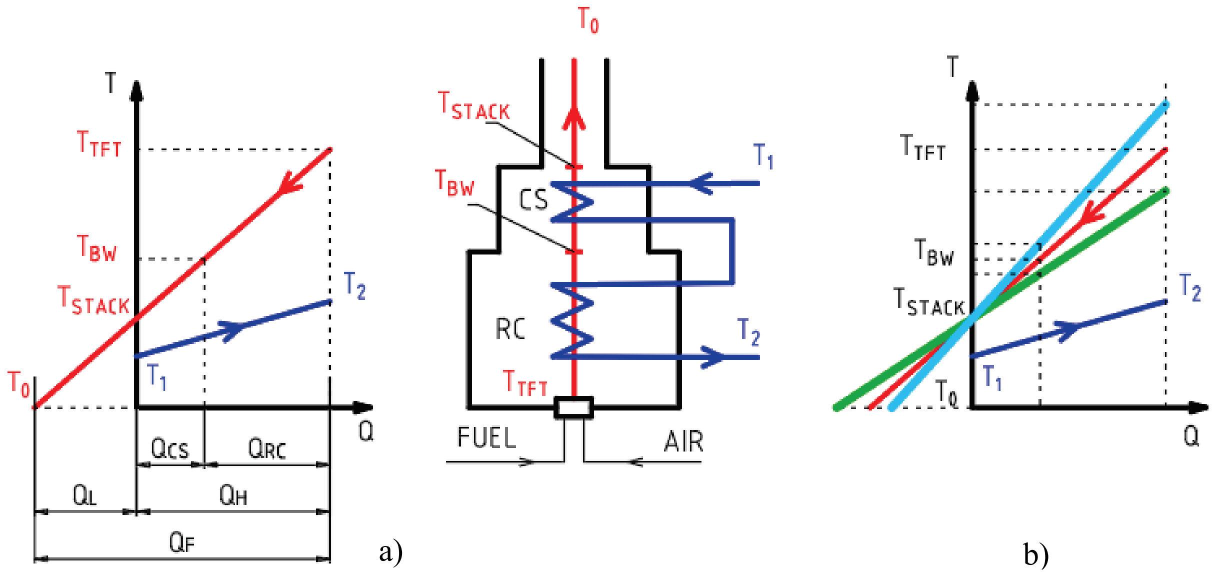

Fig. 1: T-Q diagram of combustion equipment: a) for a reference fuel along with a schematic, b) for implementation of new fuels or fuel mixtures (light blue line stands for low-carbon energy, green line denotes sustainable energy)

Although the T-Q diagram describes the combustion equipment in a simplified way (especially in high-temperature region of RC), it well indicates thermodynamic changes related to fuel change. Fig. 1 b) illustrates how the implementation of new fuels (represented by different colored lines) affects the position of the flue gas line with the assumption of maintaining the equipment exit temperature T_{STACK}. The light blue line represents the typical transition to low-carbon energy – if the red line corresponds to flue gas generated by natural gas combustion, then the light blue line represents flue gas from combustion of natural gas–hydrogen blend. The theoretical flame temperature of hydrogen is higher than that of natural gas (Green & Southard (2019) report an adiabatic flame temperature of 2 213 K for natural gas and 2 318 K for hydrogen). On the other hand, the green flue gas line in Fig. 1 b) typically represents the transition to sustainable fuel mixtures – if the red line corresponds to flue gas generated by coal combustion, then the green line represents flue gas from co-firing coal with biomass. This process typically results in lower flame temperatures and lower fuel heating values (Kalak, 2023). Overall, Fig. 1 b) demonstrates that a change of fuel or fuel mixture will lead to variations in thermal loads within different parts of the combustion equipment (i.e. RC and CS). The transition to low-carbon energy is particularly challenging since individual components of the combustion equipment will experience higher temperatures (higher thermal load), and that can, for example, lead to potentially reducing the creep lifetime of heat exchange surfaces.

3. Initial formulation of the system approach

The thermodynamic analysis provides a foundation for the initial formulation of the system approach illustrated in Fig. 2. This approach identifies four key areas that require computational validation when transitioning to alternative fuels to verify the existing state or the need for potential adjustments of combustion equipment.

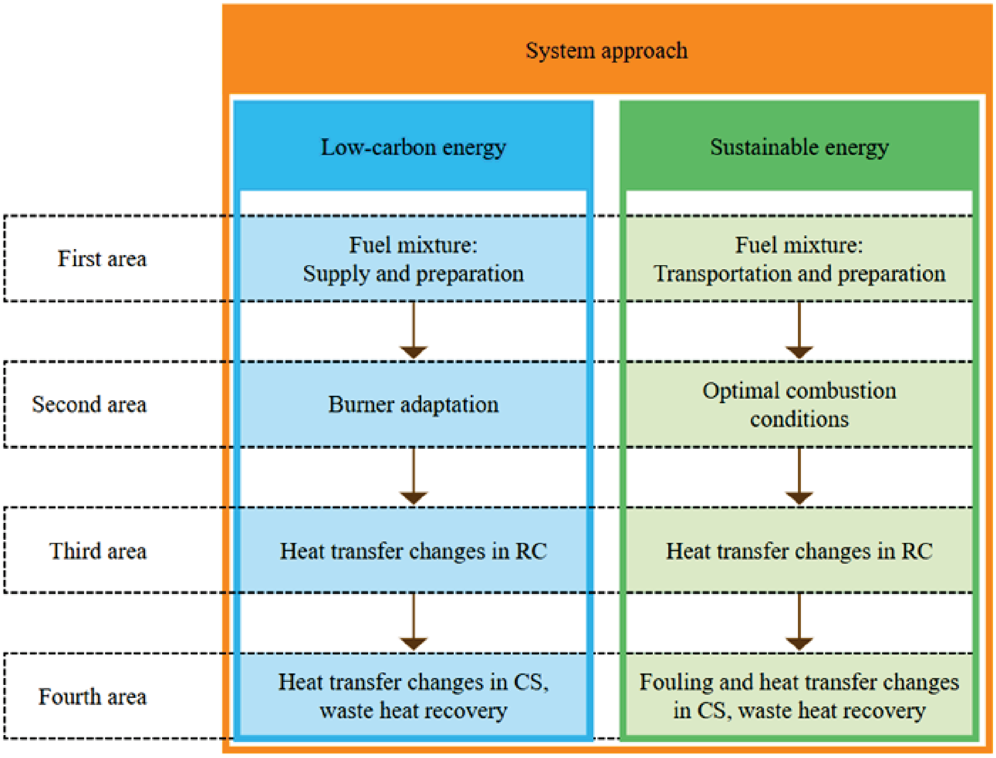

Fig. 2: Initial formulation of system approach

The first area consists of the fuel mixture preparation and transport system. For example, transitioning from natural gas to a hydrogen blend requires an assessment of material compatibility within the transport infrastructure involving both steel components and non-metallic sealing elements, to ensure resistance to hydrogen degradation mechanisms. Additionally, gaskets and flange joints or pipe fittings must be replaced or re-sealed to maintain sufficient tightness. The issue of hydrogen-related leakage and flange joint tightness has been previously examined by authors (Michálková et al., 2024). Maintaining the same energy flow rate may require an increase in the volumetric fuel flow rate, leading to higher flow velocities and pressures in the system. Green & Southard (2019) report that the lower heating value of hydrogen is 10.2 MJ/m^3, roughly three times lower than that of natural gas (29–38 MJ/m^3). In the case of co-firing coal with solid recovered fuels or biomass, the suitability of the conveyor system must be evaluated, potentially requiring a different design. For instance, while coal-fired grate combustion commonly employs a combined feeder and spreader system, biomass combustion requires separate units due to higher volume and lower heating values (Rayaprolu, 2009).

The second area concerns the combustion itself, where modifications to the burner may be necessary when using hydrogen-rich gaseous fuels. This is due to the significantly different flame speeds – methane burns at 0.45 m/s, while hydrogen has a flame speed of 2.83 m/s (Green & Southard, 2019), increasing the risk of flashback. In solid fuel mixtures, establishing optimal combustion conditions is critical, especially the ideal amount of combustion air and its distribution to respective stages (primary, secondary, etc.).

The third and fourth areas involve heat transfer changes in the RC and CS of the combustion equipment along with associated challenges. The implementation of new fuels alters the thermal load distribution across the different parts of combustion equipment. Hydrogen blending increases flame temperature, so combined with an altered flue gas composition, it potentially alters its temperature, leading to variations in heat transfer within both the RC and the CS. Higher temperatures also relate to higher stress, accelerating corrosion and reducing lifetime. These effects must be verified through appropriate calculations.

Biomass combustion presents additional risks, including fouling and slagging of heat exchange surfaces leading to deposit formation, and higher susceptibility to corrosion and erosion due to fly ash particle impacts. The exact mechanism of material degradation depends on fly ash composition and physical state, which significantly vary based on biomass type. Biomass-derived fly ash rich in sodium and potassium is more prone to slagging because such ash has a low softening temperature (Rayaprolu, 2009). These deposits then significantly decrease heat transfer efficiency and shorten the equipment lifetime. Sodium and potassium originate from soil nutrients (fertilizers) absorbed during plant growth. Key corrosive elements in flue gas include mainly chlorine and sulfur. For example, Montgomery et al. (2011) studied high-temperature corrosion in Danish straw-firing power plants concluding that corrosion rates were significantly higher than in coal-fired plants due to chloride-rich deposits, which become even more aggressive at steam temperatures exceeding 540°C due to increased volatility.

Finally, waste heat utilization must also be considered. As shown in Fig. 1 b), the implementation of different fuels alters the heat released (Q_F), unutilized waste heat (Q_L), and therefore overall efficiency. Waste heat can be recovered using additional heat exchangers for preheating any of the available process streams. Waste heat is typically utilized for combustion air preheating or boiler feedwater preheating (Jegla et al., 2023). Following a fuel change, it is essential to verify whether available waste heat remains sufficient for its intended purpose.

4. Conclusions

The transition of the energy sector towards low-carbon and sustainable energy is a critical step toward achieving climate neutrality. Implementation of “green” fuels poses complex technical challenges requiring a structured approach to identify and address them. This study presents an initial formulation of the system approach which aims to systematically and clearly guide the transformation of combustion equipment and to highlight key areas that demand computational verification of existing combustion equipment and offer insight into potential necessary modifications. The concepts and recommendations outlined for each area in this study will be further investigated and refined in future research.

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