Energy 81 (2015) 213–221

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Viability of fuel switching of a gas-fired power plant operating in chemical looping combustion mode

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A R T I C L E I N F O

Article history:
Received 4 February 2014
Received in revised form
13 October 2014
Accepted 8 December 2014
Available online 8 January 2015

Keywords:
Fossil fuels
Carbon capture
Chemical looping combustion
Supercritical Rankine cycle
Fluidization
Power plant layout

A B S T R A C T

CLC (chemical looping combustion) promises to be a more efficient way of CO_2 capture than conventional oxy-fuel combustion or post-combustion absorption. While much work has been done on CLC in the past two decades, the issue of multi-fuel compatibility has not been addressed sufficiently, especially with regard to plant layout and reactor design. In the present work, it is shown that this is non-trivial in the case of a CLC-based power plant. The underlying factors have been examined in depth and design criteria for fuel compatibility have been formulated. Based on these, a layout has been developed for a power plant which can run with either natural gas or syngas without requiring equipment changes either on the steam side or on the furnace side. The layout accounts for the higher CO_2 compression costs associated with the use of syngas in place of natural gas. The ideal thermodynamic cycle efficiency, after accounting for the energy penalty of CO_2 compression, is 43.11% and 41.08%, when a supercritical steam cycle is used with natural gas and syngas, respectively. It is shown that fuel switching can be enabled by incorporating the compatibility conditions at the *design stage* itself.

1. Introduction

One of the main sources of carbon dioxide (CO_2) emissions is fossil fuel combustion which is also the principal route of electrical energy generation. Control of greenhouse gases, mainly CO_2, through CCS (carbon capture and sequestration), is being considered as a serious option to mitigate the global warming problem arising out of the use of fossil fuels for electrical power generation [1–3]. While renewable energy sources will play a more significant role in future energy scenarios [3,4], it is expected that fossil fuels will continue to be used in large quantities for the next few decades due to demand from countries such as India and China [5]. In this context, several CO_2 capture techniques have been proposed and are being investigated [6–11]; most of these have the disadvantage of requiring fairly large amount of energy for CO_2 separation resulting in a significant thermal efficiency penalty if CCS is implemented [12]. CLC (chemical looping combustion) [13] has been proposed by Ishida and co-workers [14,15] as a means of CO_2 capture with low energy penalty. Here, the combustion of a fossil fuel is split into two global reactions, namely, oxidation of metal by air in an AR (air reactor) and reduction of metal oxide in a FR (fuel reactor). Assuming that the metal/metal oxide used is Ni/NiO and that the fuel is methane, the redox reactions can be written as follows:

In the fuel reactor:

$$4NiO + CH_4 \rightarrow 4Ni + 2H_2O + CO_2 \quad \Delta H_{900^\circ C} = 133.6 \ \text{kJ/molCH}_4 \tag{1}$$

In the air reactor:

$$2Ni + O_2 \rightarrow 2NiO \quad \Delta H_{1000^\circ C} = -468.5 \ \text{kJ/molO}_2 \tag{2}$$

The net heat release by the entire system is the same as in conventional combustion of CH_4:

$$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2 \quad \Delta H_{1000^\circ C} = -803.4 \text{kJ/molCH}_4 \tag{3}$$

The oxidation of the hydrocarbon fuel occurs in the absence of nitrogen and the flue gas therefore consists primarily of CO_2 and H_2O and very little nitrogen. Since water vapour can be readily separated by condensation, the flue gas from the fuel reactor can be sent directly for compression for sequestration. Fig. 1 illustrates a typical CLC system; the arrangement consists of two major components: a CFB (circulating fluidized bed) type air reactor acting as a metal (Me) oxidizer, and a low velocity, bubbling bed type fuel

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http://dx.doi.org/10.1016/j.energy.2014.12.027
0360-5442/

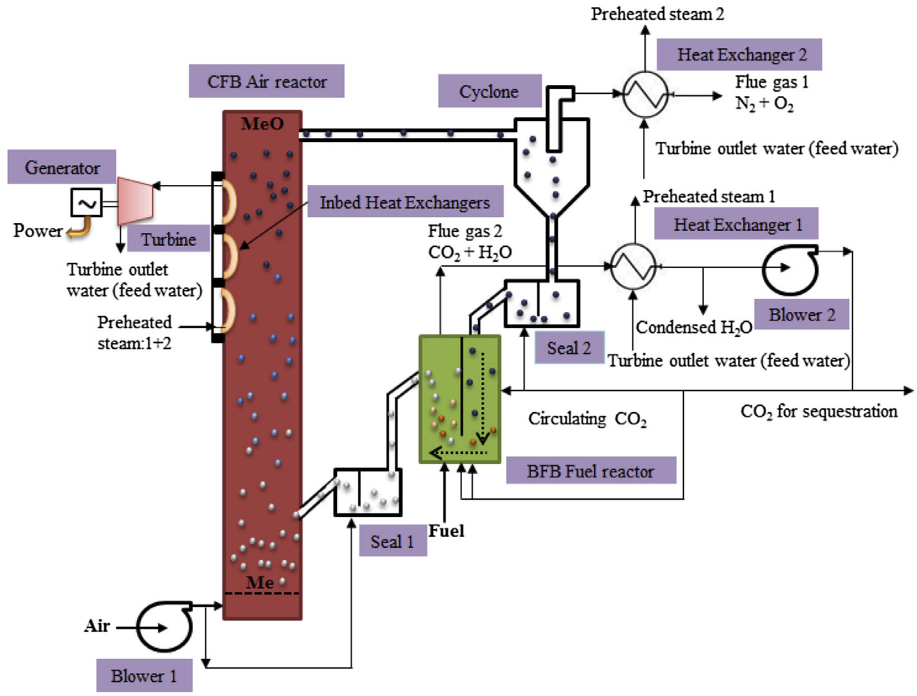

Fig. 1. General arrangement of equipment for chemical-looping combustion with a gaseous fuel.

reactor acting as a metal oxide (MeO) reducer. The reduction reactor system itself forms a large loop seal. Two small loop seals act as connectors of solid recycling between the air and the fuel reactors. These loop seals balance the system pressure and allow solids to flow from locations of lower static pressure to those of higher static pressure. The flue gas from the cyclone from AR is released into the atmosphere after extracting heat from it. Pure CO_2 can be obtained from FR exit flue gas by condensing the water. A part of this CO_2 is used as fluidizing stream along with fuel. A heat exchanger system can be installed in the AR to produce superheated steam for power generation.

A large amount of research has been carried out in the past couple of decades on CLC focussing on reactor configurations, oxygen carriers, fuels and plant layouts [16–28]. The motivation for the present work arises from the following considerations. Natural gas, being high in CH_4 content, can be considered as the most suitable fuel for power generation from cost, particulate emissions and emission of CO_2 per MW points of view. Thus, natural gas-fired CLC plants with CCS would make the best choice for a future energy generation scenario. However, for coal-rich and gas-deficient countries such as India and China, such a power generation scenario would not be sustainable in the long run. A fuel switch may also become necessary if some other gaseous fuel of hydrocarbon origin, for example, biogas or shale gas, becomes available for power generation. In such a scenario, a *future-compatible* plant layout must be designed a priori so that minimal changes need to be made when a switch-over becomes necessary or opportune.

While a switch-over from natural gas to syngas will not be much of a problem for conventional burners (some adjustments will indeed have to be made even in this case), the problem requires special considerations for a CLC plant. As far as oxygen carriers are concerned, research shows [20] that Ni/NiO can be equally effective as the oxygen carrier for methane and syngas. However, there are subtle differences in the two which impact on plant design. The first of these is thermodynamic. In the case of syngas, the two combustible components, namely, carbon monoxide and hydrogen, will react in the following way in the fuel reactor of the CLC plant [24]:

$$CO + NiO \rightarrow Ni + CO_2 \quad \Delta H_{927^\circ C} = -48\ \frac{kJ}{mol} CO \tag{4}$$

$$H_2 + NiO \rightarrow Ni + H_2O \quad \Delta H_{927^\circ C} = -15\ \frac{kJ}{mol} H_2 \tag{5}$$

Comparing these with reaction involving methane and NiO (Reaction 1), one can see that while the metal oxide reduction is endothermic if natural gas is used, it is exothermic in the case of syngas. This has a direct bearing on the fuel reactor; in the case of natural gas, heat is required to be added to the fuel reactor in order to carry out the endothermic reduction of NiO at a constant temperature while in the case of syngas, heat has to be removed from the fuel reactor in order to maintain a constant temperature. The amount of heat released in the air reactor will also be significantly different.

The second important aspect is the quantity of the fuel. Since the calorific value of natural gas is far higher than that of syngas, the flow rates of the gas will be different in the two cases. This may have an important bearing on the fluidization, heat transfer and carbon conversion aspects of the fuel reactor. Finally, the effective carbon content of the two fuels is different. Syngas generates more CO_2 per MWth and thus requires a higher amount of energy set aside for CCS. Thus, prima facie, it appears that a fuel switching between natural gas and syngas is not possible without major structural alterations to the plant layout.

In the present work, these aspects have been systematically analyzed to see if fuel switching can be enabled through an inclusive design. It is shown that thermodynamic limitations can be overcome by finding optimal operating conditions for each gas. The limitations arising out of rate processes such as heat transfer, residence time etc can be overcome by inclusive design, i.e. a sizing of the equipment which allows working with either fuel. Calculations supporting these are discussed below.