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Oxygen Supply for CO_2 Capture by Oxyfuel Coal Combustion

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1. Introduction

The air separation unit (ASU) is one of the key parts of an oxycombustion power plant with CO_2 capture. It must supply all the combustion oxygen as and when required, it consumes a significant percentage of the total generated power and it accounts for a sizeable proportion of the additional capital cost associated with CO_2 capture. Because of this, it is important that its design is optimised to give the right balance between power consumption, capital cost, flexibility and operability.

To achieve the maximum benefit, this design optimisation should not include the ASU alone, but should also investigate opportunities for integration with the rest of the plant. However, such integration leads to additional complexity, and the operation and flexibility of the integrated system under a variety of conditions also need to be considered to ensure that it remains close to optimal.

In previous papers, Air Products has given details of the factors that need to be considered in the specification and design of an ASU, and how these influence the final design. We have also listed the unique combination of these factors in the case of oxyfuel coal combustion and indicated how this provides a particular opportunity for reducing the power consumption of the ASU. Most recently, we have explained how the quoted power consumption of an oxygen plant can differ according to the basis used and provided examples to demonstrate this and assist in putting comparisons on a common basis. In addition we have presented a comparison of several different air separation process cycles and described the cycle and equipment chosen for Air Products' scalable reference ASU for oxyfuel coal combustion applications.

In this paper, we will summarise the results of these earlier studies and then go on to describe in more detail how the overall oxycombustion system can be optimised in two ways; firstly by integration of the ASU process with the rest of the system, and secondly by designing the ASU with operating flexibility to efficiently decouple its oxygen production rate from the required oxygen supply rate and so transfer power consumption from peak to off-peak periods. Air Products' has experience in the integration of ASUs with other processes and we will examine the thermodynamic benefits and practical constraints of heat integration between the power plant and the ASU and CO_2 purification plant including integration of heat of compression; preheating of oxygen, condensate and boiler feed water; and heating of waste nitrogen for ASU adsorber regeneration and potential power recovery. Air Products has designed air separation plants for other applications so as to minimise operating costs in the face of variable oxygen demands and variable power tariffs and we will illustrate how such a scheme could be suitable for an oxyfuel coal combustion power plant.

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2. Factors influencing ASU design

When designing an ASU, it is important to know certain key pieces of information about the products needed, the utilities available, the site location and the economics of the project. Firstly, and most importantly, the process conditions (temperature, pressure, flow, composition) of the feed air and desired products should be specified. It is also essential to identify the required operating range and demand profile of each product and whether it needs a back-up supply, as well as the availability and conditions of utilities such as power, cooling water and steam. The scope for integration with other processes should also be considered, for example whether heat of compression or waste nitrogen from the ASU could be used in an associated process. In addition, it is important to know certain details relating to the project execution, such as schedule, site conditions and limitations on the transport of large items of equipment to the site. Finally, to allow appropriate optimisation of the process, it is essential to understand the economic drivers, in particular the value of the utilities, normally expressed as the capital expenditure worthwhile to save one unit of utility (for example $/kW for power).

3. Comparison of quoted powers

The power consumption of an ASU for producing a given set of products from a given set of feeds under particular ambient conditions is made up of three components – compression, separation and refrigeration. When comparing powers, it important to understand, and if necessary correct for, any differences in ambient and cooling water conditions or additional products or product conditions. It is also important to determine what the power includes, for example it could be quoted at the electrical incomer, including all electrical losses and auxiliaries, or as just the shaft power of the main machines excluding auxiliaries and electrical losses. It might also be quoted as "separation power", and therefore also exclude the power of a hypothetical compressor from atmospheric pressure to the required product pressure. In a similar way, benefits from integration of exported heat may or may not be included in the quoted ASU power. Project-specific factors such as required operating range and level of integration could also affect the design point efficiency of the compressors, and hence the ASU power.

4. Air Separation Unit cycle comparison and nitrogen integration

Five different process cycles were compared; a conventional double column cycle, a three-column cycle operating at normal and elevated pressure and a dual reboiler cycle at normal and elevated pressure. The oxygen separation power at ISO conditions was calculated for each cycle, and the three-column cycle was found to have the lowest power at normal pressure (15% better than a conventional cycle with no nitrogen). Taking nitrogen at pressure from any of the cycles was found to reduce the oxygen separation power so long as a credit equal to the power to compress the nitrogen from atmospheric pressure could be applied to the total power. However, this is only possible if there is a use for the nitrogen. If there is no nitrogen requirement and power has to be recovered from the nitrogen by heating and expanding it, the benefit is reduced significantly unless the thermal efficiency of this Brayton power generation cycle exceeds that of the Rankine steam cycle. This is only true at temperatures in excess of 600°C, and to realise such a process novel machinery and boiler designs would be required.

5. Heat integration

In an oxyfuel coal power plant, the net fluegas flow from the boiler is significantly reduced compared to an air fired system, and the water concentration and dewpoint temperature in the fluegas are increased. Thus there is a substantial excess of low grade heat available from the fluegas condenser just below its dew point. So, if this heat can be recovered, there is no value in capturing heat from the ASU or CPU below this temperature. However, recovered heat above this temperature can be used instead of steam for preheating water in the steam cycle. This releases the steam for additional power generation. Intercooled compression of the air feed to the ASU can provide some useful heat, but partially-cooled or adiabatic compression can provide more heat, but at the cost of increased power consumption. Our results show a net benefit for heat integration up to a certain temperature, but above this the power penalty balances the benefit of the increased temperature; it is worth the modest power increase to convert the heat from waste to a useful temperature level, but not the additional penalty to upgrade it further. However, adiabatic compression does allow the heating of only part of the condensate and leaves scope for heating the rest with another heat source (for example in the CPU). So, in an optimal design, heating of oxygen, nitrogen or condensate should use heat from the fluegas condenser at low temperature, and heat from the ASU and CPU compressors above this temperature.

The start-up of an integrated scheme and its operation in different modes need careful attention. For example, relative changes in heat supply and heat demand must be considered, especially during start-up and at turndown when the heat supply from compressors on recycle may be more than the heat demand from the turned-down power generation process. Additional equipment such as coolers and heaters may be needed for these eventualities.

6. Electrical load management

Along with other industrial gas companies, Air Products has designed ASUs whose oxygen supply rate can change independently of their oxygen production rate by incorporating gaseous and/or liquid buffer storage. For example in steelmaking, where instantaneous oxygen rates are very high and there are short intervals where no oxygen is required, the variable demand can be satisfied by the ASU whilst its oxygen production rate is kept constant. Air Products has also designed ASUs to take advantage of variable power tariffs. In this case, the oxygen supply rate is constant but the oxygen production rate is adjusted to reduce the electrical load during peak periods and increase it during off-peak periods. In oxyfuel combustion applications, it is possible to turn up the ASU at times of reduced power output (and therefore reduced oxygen demand), and to turn it down at times of increased power output, so that the ASU can effectively store energy and swap it from one time period to another.

In the ASU cycles considered, liquid oxygen is produced from the distillation column system and evaporated against condensing air. So the supply of oxygen and the operation of the distillation columns can be decoupled by storing liquid oxygen and liquid air. The oxygen production can be supplemented when required from storage and the resultant liquid air sent to storage with no net refrigeration requirement or disturbance to the column system. All that is needed is an increase in air flow from the compression system to provide the extra air to be liquefied. If on the other hand the ASU is producing more oxygen than required, liquid air can be injected to provide refrigeration to produce liquid oxygen that can be stored rather than evaporated. In this case, less air has to be provided by the compression system, as part of the feed is provided as liquid air. Alternatively, the oxygen supply rate can be maintained whilst the ASU is turned down to reduce its power consumption during peak power demand periods and turned up during off-peak periods. The effective cost of the power provided to the ASU can therefore be reduced.

To design such a system, it is important to understand the likely operating profile of the plant so that the ASU and storage can be sized appropriately. For example, it may be worthwhile oversizing the ASU to allow load swapping at full oxygen output, or the system may be designed only to take advantage of reduced average production rates.

7. Conclusion

- Oxygen supply requirements for oxyfuel coal combustion are unique and enable the use of process cycles with particularly low power consumption. Even lower power consumption is possible by integration of the ASU and power plant, but operability of the integrated scheme must be ensured.
- Care is needed when comparing specific power consumption figures to make sure that they are comparable and attainable considering project-specific factors such as required operating range and level of integration.
- Several processes were evaluated as part of the Air Products reference plant development, and it was found that the triple column process proposed by Air Products had the lowest power in most cases.
- To realise a lower power consumption than Air Products selected process would require significant machinery development and modification of well-proven boiler equipment to enable high temperature expansion of pressurised waste nitrogen.
- Heat integration of the ASU with the boiler system can significantly lower the effective energy consumption of the oxygen plant, however the usefulness of the heat from the ASU depends on its temperature level and the configuration of the power generation cycle.
- It is possible to configure the ASU to effectively store energy by swapping electrical load from one time period to another. To design the system appropriately the expected average loading of the ASU and power plant must be considered and the benefits of increased stored energy weighed against additional ASU costs.
- Air Products has developed a state-of-the-art scalable ASU concept that uses an efficient and cost-effective three column cycle optimised to provide a low specific power for oxyfuel coal combustion applications whether or not it is integrated with the power generation cycle.