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The Water-Injected Compressors as a Potential of Energy Saving for Small Oxyfuel Combustion Unit

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The energy required for air compression is the largest cost item for oxygen separation from air by pressure swing adsorption technology (PSA). This paper aims to demonstrate the potential of water-injected compressor technology for energy savings for small oxyfuel combustion units that use PSA technology as an oxygen source. Additionally, the utilization of waste heat from the compressor was further examined for the dewatering of biomass. Based on the performance data presented for available commercial water injected compressors, 2 % of electrical energy can be saved compared to oil lubricated single compression as a reference case. The waste compression heat released was capable of drying the burned wood and saving 10.4 % of the wood to obtain the required thermal load.

1. Introduction

The combustion using oxygen instead of air (oxyfuel combustion) enables increasing the CO_2 concentration in flue gases and, in this way, to affect the CO_2 separation and purification costs. Furthermore, oxygen is used in steam-oxygen gasifiers for the production of advanced 2nd generation biofuels from different biomass residues (Kurkela et al., 2016) or for the treatment of the aqueous phase by wet oxidation (Silva Thomsen et al., 2022).
Small coal- or biomass-fired heat and power generation units are typical examples of decentralized power supply units where oxygen supply by pressure swing adsorption can be recommended. The oxyfuel process requires oxygen purity of at least 95 %. The oxygen of the required purity can be obtained by cryogenic air separation (ASU) or pressure swing adsorption (PSA). For PSA technology, the energy required for air compression is the largest cost item.
Air can be compressed by oil-injected compressors (OIC) when the oil cools and lubricates the compressor moving parts; thus, it decreases energy consumption. In cases where oil contamination becomes critical, dry-type oil-free compressors with lower energy efficiency are used. The next generation of oil-free compressors introduces water-injected compressors (WIC). Injected water cools and lubricates the moving parts, and practically isothermal compression could be reached. The compression heat released is mainly absorbed by water evaporation.

1.1 Water-injected compression

20 % energy savings could be potentially obtained by reaching isothermal compression (MultiAir Italia, 2022). Venu Madhav and Kovačević (2015) analyzed the economy of designed water-injected screw compressors in the 15-315 kW power range and delivery pressures of 6-10 bar. They compared WIC performance data estimated using SCORPATH software developed at City University London with OIC data of OICs presented by various manufacturers. The averaged specific compressor power of 5.41 and 5.71 kW (m^3 min)$^{-1}$ can be estimated from Figure 7 for WIC and OIC, respectively, at 7 bar (g) discharge and 100 kW power input.
Based on these data, the 5 % energy savings could be achievable. The higher corrosion resistance required for WICs increases the purchase price by 20-30 % compared to OICs. The WIC is a single-stage screw compressor equipped with a single- or single-screw rotor and directly driven by an electrical motor without a gearbox.

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1.2 The potential for energy savings

Šulc and Ditl (2021a) identified the highest potential of energy savings for dual compression and utilization of low-grade waste compression heat for fuel drying. 10 % of the electrical energy can be saved using dual compression. The utilization of low-grade waste compression heat for fuel drying was able to reduce fuel consumption depending on fuel moisture. This contribution aims to analyze the potential of air compression using oil-free water-injected compressors for the oxygen supply by PSA technology under the same conditions as used by (Šulc and Ditl, 2021a), i.e. compression of ambient air, compressed air with a pressure dew point of +3°C at an outlet temperature of 30 °C and an outlet pressure of 750 kPa (a) at the PSA unit inlet, air factor of 10 $Nm^3\ Nm^{-3}$ for 95 % purity (INMATEC Ltd., 2020), thermal power load of 0.5 MW, the flow rate of 95 % oxygen (GOX) of 101 $Nm^3\ h^{-1}$. In addition, the utilization of lost waste heat from the compressor was further examined for biomass dewatering.

2. Methodology

We formed the following model to calculate the electric power supply needed for the required oxygen production. When the inlet temperature of the water injected T_{WI-in} is higher than the air inlet temperature T_1, the reversible adiabatic compression is assumed until the air temperature is equal to the inlet temperature of the water injected. The power input for reversible adiabatic compression is calculated as follows:

$$P_{ad-rev} = p_1 \cdot \dot{V}_{air1} \cdot \frac{\kappa}{\kappa - 1} \cdot \left[1 - \left(\frac{p_2}{p_1} \right)^{(\kappa-1)/\kappa} \right], \tag{1}$$

where P_{ad-rev} is the power input for reversible adiabatic compression (kW), p_1 is inlet air pressure (kPa), $V^{\bullet}_{air1}$ is the air flowrate ($m^3\ s^{-1}$) under the inlet conditions (temperature t_1, pressure p_1), p_2 is the air pressure (kPa) at the which actual compressed air temperature reached the inlet temperature of water injected, and κ is Poisson constant (-). The air pressure p_2 is calculated using the adiabatic p-V law assuming the ideal gas law as follows:

$$p_2 / p_1 = \left(T_{WI-in} / T_1 \right)^{\kappa/(\kappa-1)}, \tag{2}$$

where T_{WI-in} is the input temperature of water injected (K). When the actual temperature of compressed air reached the inlet temperature of the the water injected, irreversible polytropic compression was assumed until the required outlet air pressure was reached. The power input for reversible polytropic compression is calculated as follows:

$$P_{poly-rev} = p_2 \cdot \dot{V}_{air2} \cdot \frac{n}{n-1} \cdot \left[1 - \left(\frac{p_3}{p_2} \right)^{(n-1)/n} \right], \tag{3}$$

where $P_{poly-rev}$ is the power input for reversible polytropic compression (kW), p_2 is an initial air pressure for polytropic compression (kPa), $V^{\bullet}_{air2}$ is the actual air flowrate ($m^3\ s^{-1}$) at initial conditions for polytropic compression (temperature t_2, pressure p_2), p_3 is an ending air pressure for polytropic compression corresponding to the required outlet pressure (kPa), and n is a polytropic exponent (-).
The heat duty released during reversible polytropic compression $Q^{\bullet}_{poly-rev}$ (kW) is calculated as follows:

$$\dot{Q}_{poly-rev} = \frac{\kappa - n}{\kappa - 1} \cdot p_2 \cdot \dot{V}_{air2} \cdot \frac{1}{n-1} \cdot \left[1 - \left(\frac{p_3}{p_2} \right)^{(n-1)/n} \right]. \tag{4}$$

The polytropic exponent is estimated using the polytropic p-V law assuming the ideal gas law as follows:

$$p_2 / p_1 = \left(T_3 / T_2 \right)^{n/(n-1)}, \tag{5}$$

where T_3 is the required outlet temperature (K) of compressed air for the required outlet pressure p_3 after compression (kPa). The required power input and heat duty released for irreversible polytropic compression are calculated as follows, respectively:

$$P_{poly-irrev} = P_{poly-rev} / \eta_{c-poly}, \tag{6}$$

and

$$\dot{Q}_{poly-irrev} = \dot{Q}_{poly-rev} + (P_{poly-irrev} - P_{poly-rev}). \tag{7}$$

When water injected serves as sealing and lubrication medium, the power of liquid pumping could be taken into account. The power needed for pumping of water-injected P_{pump} (kW) is estimated as follows:

$$P_{pump} = (1/2)\cdot(\dot{V}_{WI-inlet} + \dot{V}_{WI-outlet})\cdot(p_1 - p_3)\cdot \quad (8)$$

where $V^{\bullet}_{WI-inlet}$ and $V^{\bullet}_{WI-outlet}$ are volumetric flowrates of water injected at the inlet and outlet of the compression chamber, respectively ($m^3\ s^{-1}$). The total electrical power input is calculated as follows:

$$P_M = -\frac{f_P}{\eta_{GB}\cdot\eta_{EM}}\cdot(P_{ad-rev} + P_{poly-irrev} + P_{pump}), \quad (9)$$

where P_M is the compressor electrical power input (kW), η_{GB} is mechanical efficiency of the gearbox (-), η_{EM} is electromechanical efficiency of the electrical motor (-), f_P is the power factor representing the power input of the compressor accessories (-).
The outlet temperature of compressed air, which has usually been reached in standard compressor units, is approx. 10° C above inlet air temperature. To ensure temperature difference for heat transfer we assume installation of compressed air/cooling water cooler (A/CW cooler) for waste heat extraction and compressed air/ambient air cooler (A/A cooler) for compressed air cooling onto expected outgoing temperature. The cooling capacity is calculated as follows:

$$\dot{Q}_c = \dot{m}_{d.a.}\cdot(h^{air}_{in}(t_{in}, x_{in}) - h^{air}_{out}(t_{out}, x_{out})), \quad (10)$$

where $Q^{\bullet}_c$ is the cooling capacity of the cooler (kW), h^{air}_{in} (t_{in}, x_{in}) is the wet air enthalpy (kJ kg^{-1}) at the cooler inlet at inlet conditions (temperature t_{in}, humidity x_{in}) and h^{air}_{out} (t_{out}, x_{out}) is the moist air enthalpy (kJ kg^{-1}) at the cooler outlet at outlet conditions (temperature t_{out}, humidity x_{out}). The enthalpy of moist air is calculated as follows:

$$h^{air} = c_{pd.a.}\cdot t + x_{water}\cdot(c_{pwv}\cdot t + l_{water}) = 1.010\cdot t + x_{water}\cdot(1.840\cdot t + 2500), \quad (11)$$

where h^{air} is the enthalpy of wet air (kJ kg^{-1}), t is the air temperature (°C), $c_{pd.a.}$ is the specific heat capacity of dry air (kJ kg^{-1} K^{-1}), $c_{pwv.}$ is the specific heat capacity of water vapors (kJ kg^{-1} K^{-1}), and l_{water} is the latent heat of water (kJ kg^{-1}).
The heat released during compression is absorbed by the water injected into the compression chamber. The enthalpy balance of the water injected is given as follows:

$$\dot{m}_{WI-in.}\cdot h^{WI}_{in}(t_{WI-in}) + \dot{Q}_{g-l} + \dot{m}_{cond}\cdot h^{c/v} = \dot{m}_{vap}\cdot h^{c/v} + \dot{m}_{WI-out.}\cdot h^{WI}_{out}(t_{WI-out}), \quad (12)$$

where $m^{\bullet}_{WI-in}$ is the entering mass flow rate of water injected (kg s^{-1}), $m^{\bullet}_{WI-out}$ is the outgoing mass flow rate of water (kg s^{-1}), $m^{\bullet}_{cond}$ is the mass flow rate of water vapor condensed from moist compressed air (kg s^{-1}), $m^{\bullet}_{vap}$ is the mass flow rate of water vapor evaporated to compressed air if the water evaporation occurs (kg s^{-1}), and $Q^{\bullet}_{g-l}$ is the heat duty transferred from the gaseous phase to liquid phase. The enthalpy of the liquid phase h^{WI} (kJ kg^{-1}) at the liquid phase temperature t_{WI} (°C) is calculated:

$$h^{WI} = c_{pwater.}\cdot t_{WI} = 4.18\cdot t_{WI}\cdot \quad (13)$$

The enthalpy of condensed or evaporated water vapor $h^{c/v}$ (kJ kg^{-1}) is calculated as follows:

$$h^{c/v} = (c_{pwv}\cdot t_3 + l_{water}) = 1.840\cdot t_3 + 2500, \quad (14)$$

where t_3 is the required outlet temperature of compressed air (°C) for the required outlet pressure p_3 (kPa) after compression (kPa). The mass balance of the liquid phase is given as follows:

$$\dot{m}_{WI-in.} + \dot{m}_{cond} = \dot{m}_{vap} + \dot{m}_{WI-out}\cdot \quad (15)$$

The compression heat released is absorbed by the injected which serves simultaneously as a sealing and lubrication medium. Depending on the actual mass driving force, some part of the water evaporates into compressed air. The evaporated water is removed from compressed air by condensation in air coolers.
The heat absorbed by liquid water is removed by the water cooler, and the cooled water is injected into the compression chamber again. To ensure the temperature difference for heat transfer, we assume installation of a water-injected/cooling water cooler (WI/CW cooler) for waste heat extraction and a water/ambient air cooler (WI/A cooler) for water cooling onto expected outgoing temperature. The cooling capacity is calculated as follows:

$$\dot{Q}_{c-WI} = \dot{m}_{WI-out.} \cdot (h_{out}^{WI}(t_{WI-out}) - h_{WI-in}^{WI}(t_{WI-in})), \quad (16)$$

where $Q^{\bullet}_{c\text{-}WI}$ is the cooling capacity of the water cooler (kW), h^{WI}_{in} ($t_{WI\text{-}in}$) is the water enthalpy (kJ kg^{-1}) at the cooler input at inlet conditions (temperature $t_{WI\text{-}in}$) and h^{WI}_{out} ($t_{WI\text{-}out}$) is the water enthalpy (kJ kg^{-1}) at the cooler outlet at outlet conditions (temperature $t_{WI\text{-}out}$).

3. Results and discussion

3.1 Air compression by water-injected compression

The electrical power input of the compressor was calculated for an intake air temperature of 20 °C, the pressure of 100 kPa and a humidity of 70 %, an inlet temperature of water injected of 30 °C, and κ = 1.4. The electrical efficiency η_{EM} was estimated according to EN 60034-2-1 for a 4-pole asynchronous electrical motor of the IE3 class. The water-injected screw compressor is driven directly by an electrical motor, thus the gearbox efficiency η_{GB} = 1. The power input of accessories (fans, pumps) was taken into account by a factor of 1.03. Water evaporation or condensation during air compression were taken into account depending on the actual mass driving force. The pressure losses of 10 kPa and 2 kPa were assumed for the air/oil cooler, and the air/air cooler respectively. The air temperature after compression and the water injection rate (WIR) are not directly reported in the manufacturer´s datasheets. Some manufacturers present air temperature after compression from 40 °C (Mitsui Seiki Kogyo, 2022) to 60 °C (ALMIG, 2022). For prototype screw compressors, temperatures in the range from 50 °C to 60 °C (Li et al., 2009) are reported. The WIR values are reported to be up to 6 % (Wang et al., 2018) or 15 % (Nikolov and Brűmmer, 2018). It was found that to achieve these data, the required specific compression power could be lower than reported by manufacturers.

Table 1: Air compression – single-stage water-injected compression

Description	Unit	Case 1	Case 2	Case 3
Temperature after compression [*1]	°C	100	100	85
Pressure after compression [*1,2]	kPa	762	762	762
Polytropic exponent	-	1.1218	1.1218	1.0955
Polytropic efficiency	-	0.77	0.9	0.77
A/CW cooler – outlet air temperature	°C	40	40	40
A/A cooler – outlet air temperature	°C	30	30	30
Water injected – inlet/outlet temperature	°C	30/90	30/90	30/80
Water injection rate	kg_{WI} $kg_{d.a.}^{-1}$	0.25	0.132	0.573
Cooling water – inlet/outlet temperature	°C	30/80	30/80	30/75
WI/CW cooler – outlet WI temperature	°C	40	40	40
WI/A cooler – outlet WI temperature	°C	30	30	30
Water condensed from air	kg/h	76.8	72.5	47.6
A/CW cooler – heat duty	kW	76.9	73.7	49.3
A/A cooler – heat duty	kW	6.13	6.13	6.13
WI/CW cooler – heat duty	kW	15	6.3	32.9
WI/A cooler – heat duty	kW	3	1.26	8.22
Compressor power input [*1,2,3]	kW	104	89	100.4
Specific compressor power input	kW (m^3 min^{-1})$^{-1}$	5.646	4.848	5.469

Note: [*1] ambient air: temperature of 20 °C, pressure of 1 bar (a), relative humidity of 70 %.
Note: [*2] Compressed air: outlet temperature 30 °C, outlet pressure of 7.5 bar (a).
Note: [*3] Electrical efficiency: η_{EM} = 0.952, gearbox efficiency η_{GB} = 1.

Therefore, the following three cases were analyzed:

- Case 1: Outlet temperatures of 100 °C and 90 °C were estimated for compressed air and water injected, respectively. The polytropic efficiency was fitted to the compressor power input of 104 kW and the specific compression power input of 5.646 kW (m^3 min^{-1})$^{-1}$ overtaken from the the Compair D-series compressor datasheet (Compair, 2022).
- Case 2: The influence of polytropic efficiency was analyzed. Increasing the efficiency from 0.77 to 0.9, the compressor power decreases by 14 % and the required WIR is 13.2 %.
- Case 3: Outlet temperatures of 85 °C and 80 °C were estimated for compressed air and water injected, respectively. The polytropic efficiency of 0.77 is assumed. In this case, the water evaporation is insufficient to absorb the released compression heat. Some part of compression heat has to be removed by liquid water

as a sensitive heat which is indicated significantly by high WIR value and low water amount condensed from compressed air.

The calculated data are summarized in Table 1.

3.2 Total electrical power input

The total electrical power input for the cases analyzed is presented in Table 2. The electrical power input of the PSA unit is declared 0.15 kW by the manufacturer. The cooling capacity of dryer $Q^{\bullet}_{c\text{-}DR}$ without heat regeneration was calculated analogously using Eqs. (10) and (11). The electrical power input of the dryer calculated using the procedure described by Šulc and Ditl (2021b) is presented in Table 2. Data for oil lubricated single and dual compression calculated in our previous work (Šulc and Ditl, 2021b) are presented for comparison. Based on the performance data presented for available commercial water injected compressors, 2 % of electrical energy can be saved only compared to single compression as a reference case. With increasing polytropic efficiency, the potential for energy savings grows.

Table 2: Air compression – total electrical power input

Description	Unit	Oil lubricated		Water lubricated		
		Single compression	Dual compression	Single compression		
				Case 1	Case 2	Case 3
Compressor power input	kW	106.6	96.1	104	89	100.4
Refrigeration dryer power input*1	kW	3.4	3.4	3.4	3.4	3.4
PSA unit	kW	0.15	0.15	0.15	0.15	0.15
Total electrical power input	kW	110.2	99.7	108	93	104
Specific energy consumption	$kWh\ Nm^{-3}{}_{GOX}$	1.091	0.987	1.069	0.921	1.030
Specific energy consumption	$kWh\ kg^{-1}{}_{O2}$	0.805	0.728	0.788	0.679	0.759
Energy saving	%	-	-9.5	-2	-15.6	-5.6

Note: *1 Dryer: compressed air: pressure dew point of +3 °C. Coolant scroll compressor (Ingersoll-Rand, 2020).
Note: *2 Oil-lubricated single compression: temperature after compression 250.5 °C (Šulc and Ditl, 2021a).
Note: *3 Oil lubricated double compression: pressure after compression 1st stage 315 kPa, temperature after compression 133.7 °C (Šulc and Ditl, 2021a).

3.3 Dewatering of biomass

Assuming that water entering the PSA unit outflows into the waste PSA stream, the mass flow rate of the 1,158 $kg\ h^{-1}$ of dry waste PSA stream and humidity of 0.0007 $kg_{H2O}\ kg_{d.g}{}^{-1}$ can be obtained by mass balance. To utilize the waste compression heat, the ambient air and the mixture of ambient air and waste PSA stream were considered for wood dewatering. The specific drying capacities and available drying capacities for three drying media calculated assuming the ideal isenthalpic drying and fully saturated outgoing drying medium are presented in Table 3.

Table 3: Drying capacity utilizing waste compression heat for various drying gases

Description		Unit	Air *1	Waste PSA *2	Mixture
	Drying gas humidity – inlet *3	$kg_{H2O}\ kg_{d.g.}{}^{-1}$	0.0103	0.0007	0.0067
Case 1: 80 °C/30 °C *4	Heater – duty	kW	91.9	16.7	91.9
	Specific drying capacity	$kg_{H2O}\ kg_{d.g.}{}^{-1}$	0.0163	0.0187	0.0169
	Drying capacity	$kg_{H2O}\ h^{-1}$	104.7	21.6	106.1
Case 2: 80 °C/30 °C *4	Heater – duty	kW	80	16.7	80
	Specific drying capacity	$kg_{H2O}\ kg_{d.g.}{}^{-1}$	0.0163	0.0187	0.0169
	Drying capacity	$kg_{H2O}\ h^{-1}$	91.1	21.6	92.7
Case 3: 75 °C/30 °C *5	Heater – duty	kW	82.1	15	82.1
	Specific drying capacity	$kg_{H2O}\ kg_{d.g.}{}^{-1}$	0.0147	0.0172	0.0153
	Drying capacity	$kg_{H2O}\ h^{-1}$	93.8	19.9	95.3

Note: *1,2 Molar weight ($kg\ kmol^{-1}$) of drying gas (on dry basis): 28.968 for air*1, 28.595 for PSA waste stream*2.
Note: *3,4,5 Drying gas: inlet conditions*3: 20 °C,100 kPa, temperature after preheating : 70 °C*4, 65 °C*5.
Note: Drying gas from a dryer: relative humidity φ = 100 %.

For drying of raw wood of 50 wt. % moisture and LHV of 8.074 $MJ\ kg^{-1}$ to 20 wt. % moisture and LHV of 14.418 $MJ\ kg^{-1}$ which is suitable for combustion (Gebreegziabher et al, 2013) the drying capacity of 86.5 $kg_{H2O}\ h^{-1}$ is required for 500 kW of thermal load. The waste compression heat is capable of drying raw wood. Using pred-dried wood reduces fuel consumption by 10.4 % of the wood to obtain the thermal load required.

4. Conclusions

This paper aimed to analyze the potential of integrating water-injected compressor and PSA technology as an oxygen source for the oxy-fuel combustion unit for saving of consumed energy to reach more friendly processing. In addition, the utilization of lost waste heat from the compressor was further examined for biomass dewatering.

The following conclusions can be drawn from the technical analysis presented in this paper:

- Based on the performance data presented for available commercial water injected compressors, 2 % of electrical energy can be saved only, and the specific energy consumption decreases from 0.805 kWh kg_{O2}^{-1} to 0.788 kWh kg_{O2}^{-1} compared to oil lubricated single compression as a reference case.
- The polytropic efficiency and the water injection rate significantly influence the potential of energy saving. Increasing polytropic efficiency from 0.77 to 0.9 the energy savings grows up to 15 % for analyzed case, leaving other conditions the same.
- The low-grade waste compression heat used for fuel pre-drying is capable of drying raw wood from 50 wt. % moisture to 20 wt. %. The pre-drying reduces fuel consumption by 10.4 % of wood for reference fuel conditions to obtain the thermal load required.

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