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Energy Procedia 63 (2014) 243 – 252

Energy Procedia

GHGT-12

CO_2 capture from off-shore gas turbines using supersonic gas separation

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Abstract

CO_2 capture from gas turbine based off-shore application face challenges such as size (foot-print), weight and stability (wave motion) in addition to the challenges faced by on-shore industry. Space- and weight challenges are given priority, and the size of the capture installations will be of importance when selecting capture technology rather than process efficiency alone. In this work, CO_2 capture from an FPSO turbine exhaust gas using a supersonic separator is investigated. To assess the operational performance of the capture process, a Laval nozzle (converging-diverging geometry) model is implemented and successfully integrated in a steady-state process flow sheet simulator. The model includes equilibrium thermodynamics describing freeze-out of dry ice from a gas mixture containing CO_2. To determine under which conditions this process is thermodynamically and fluid dynamically feasible, different boundary conditions are explored. By integrating the supersonic separator unit in a flow sheet model, the interaction between the capture and the rest of the process is studied. The results indicate that supersonic expansion is a viable strategy for capturing CO_2 from off-shore gas turbines.

Peer-review under responsibility of the Organizing Committee of GHGT-12

Keywords: Carbon capture; Process modelling; High speed flow; Thermodynamics, Gas-solid equilibrium, Laval nozzle

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Peer-review under responsibility of the Organizing Committee of GHGT-12
doi:10.1016/j.egypro.2014.11.026

Nomenclature

A	Area
c	Speed of sound
f	Efficiency factor
h	Enthalpy
n	Molar flow rate
P	Pressure
S	Entropy
T	Temperature
u	Velocity
W	Power consumption
μ	Chemical potential
ρ	Density

Subscript

d	Dry ice
g	Gas
l	Liquid
Out	Outlet of nozzle
Ref	Refrigerant system

1. Introduction

CO_2 capture from gas turbine based off-shore application face challenges such as size (foot-print), weight and stability (wave motion) in addition to the challenges faced by on-shore industry. Typically, space- and weight challenges are given priority and the size of the capture installations will be of importance when selecting capture technology rather than process efficiency alone. In the BIGCCS Centre [1], various alternatives are being evaluated based on these principles for off-shore CO_2 capture applications. The focus is on identifying processes that do not require large quantities of steam and those without a gas-liquid interface. Some of the options considered are high temperature dual phase membranes that operate in the range 415-600°C, novel oxy-combustion cycles and the use of supersonic nozzles for CO_2 capture. The reference case is an MEA based post-combustion capture option that requires significant steam consumption and has a large footprint. In this work, the applicability of the supersonic gas separation process for CO_2 capture from off-shore gas turbines is studied.

Supersonic gas separation has been studied extensively for compact water removal systems from raw natural gas streams at high pressure [2-5]. This method has been proposed and is being investigated for CO_2 capture from the exhaust of a coal fired power plant as part of the United States Advanced Research Projects Agency – Energy (ARPA-E) [6, 7].

Karimi [4, 8], built an integrated process model in Aspen HYSYS, including a steady-state supersonic nozzle unit model. The case investigated was water removal from natural gas on a predefined nozzle geometry. Their nozzle model was validated against CFD simulations with ANSYS Fluent. In this work we do not assume fixed nozzle geometry; rather we assume that a nozzle with the desired characteristics can be constructed.

The principle of supersonic CO_2 separation is visualized in Fig. 1. Gas containing CO_2 is sent to a Laval (convergent-divergent geometry) nozzle. Due to the expansion, the gas is cooled and the CO_2 freezes-out and create dry ice. Due to the large density difference between dry ice and gas, the dry ice can be separated due to inertial forces in a cyclone. The solid-to-gas density ratio depends on the capture pressure and the molecular weight of the gas, but will be in the magnitude of thousands. A swirl is induced at the entry to enable separation through the slits at the outer rim. As the separation occurs at supersonic velocities, there is expected to be no deposition of solid CO_2 particles in the nozzle. The CO_2 depleted gas will, due to its supersonic velocity, recover some pressure. Depending on the inlet and outlet pressure levels a shock may occur in the diverging section, accompanied by energy dissipation.

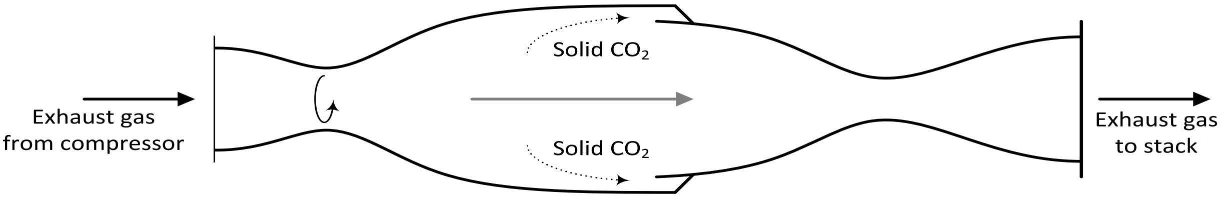

Fig. 1. Principle of the Laval nozzle for supersonic gas separation.

Depending on the area of the slits, and the flow area in the nozzle, some gas will escape through the slits. This slip gas must be separated from the dry ice in a cyclone and is sent to the exhaust gas stream. The remaining dry ice must be sublimated and compressed. The dry ice can self-compress by being sublimated in a fixed space, as is also illustrated by [7].

2. Modelling

The purpose of this work is to evaluate whether supersonic separation is a viable CO_2 capture technology for capture from off-shore gas turbines. The FPSO gas turbine exhaust gas is tabulated in Table 1 and is used for all simulations in this work.

Table 1. FPSO gas turbine exhaust gas.

Component	Composition (*mol %*)	Amount (*kg/h*)
CO_2	2.98	11,146
N_2	75.10	178,966
O_2	14.36	39,091
Ar	0.90	3,051
H_2O	6.67	10,255

To assess the operational performance of the capture process, a steady state flow sheet model must be made for the entire process. The process simulation tool of choice is Aspen HYSYS [9]. To perform these simulations, an in-house code of the Laval nozzle model with dry ice deposition and gas-solid separation is integrated as a unit model in HYSYS.

The supersonic unit modelling can be modelled to great detail with CFD, including the swirl of the flow, shock capturing, etc. [10]. In this work a more simplistic steady state model, with the same level of detail and accuracy as the other unit models in HYSYS, is used. This is deemed adequate for our feasibility study, and process models assembled from unit models with different accuracy, will be limited by the least accurate unit model. The detailed CFD modelling would be subject to the results of the feasibility study performed as part of this work.

2.1. Phase equilibrium

In order to describe the formation of dry ice in the supersonic unit, a set of thermodynamic models are required. The thermodynamic gas properties are calculated using the Peng-Robinson (PR) [11] equation of state (EOS). To describe the dry ice, the Gibbs free energy function of Jäger and Span [5] is used. The dry ice Helmholtz energy model of Trusler [12] could also be applied, but is not used in this work.

The pure CO_2 saturation line predicted by the PR EOS is slightly offset from the experimentally determined triple point. The model triple point is therefore calculated as the saturation pressure at the experimental triple point temperature. As described in [5], the dry ice model reference levels are aligned to the reference levels of the PR

EOS model, by adjusting the Gibbs energy to match the PR EOS Gibbs energy at the triple point. Further the entropy of the dry ice model is adjusted to get the correct melting entropy at the triple point.

The method of Michelsen [13] is used to calculate the phase equilibrium at constant pressure and temperature. In addition, the phase equilibrium must be calculated at specified pressure and entropy. This is achieved using a state function approach described by Michelsen [14]. Solid formation for a fast expansion will typically occur from a sub-cooled meta-stable state. To model the non-equilibrium thermodynamic phenomenas associated with this process is difficult without experimental data. Full equilibrium (mechanical, thermal and chemical) is therefore assumed.

Water is removed from the flue gas before it enters the supersonic separation unit. The phase diagram for the remaining components of Table 1 is plotted in Fig. 2. Iso-mass lines for dry ice show how the CO_2 concentration of the flue gas changes with temperature. As the pressure is reduced, the iso-mass lines come closer together. Fig. 2 also shows that the solid appearance line predicted by our model is similar to the predictions by HYSYS.

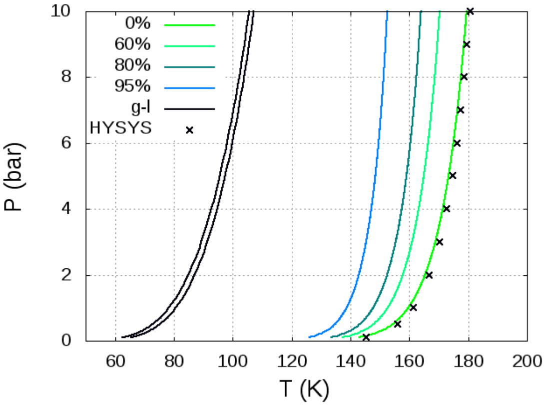

Fig. 2. Phase diagram: Single phase gas to the right of the solid appearance line (0%). As a model sanity check, the solid appearance line predicted by HYSYS is plotted as point values (x). Iso-mass lines for dry ice is also included, as well as a narrow gas-liquid envelope (g-l) to the left. The envelope is close to the pure nitrogen saturation line.

2.2. Supersonic nozzle model

A steady state homogeneous equilibrium model (HEM) is used to describe the flow in the nozzle. Further, the flow is assumed to be adiabatic and ideal, with no friction or gravity effects. This is identical to the model described in Chapter 7 of [15]. Depending on the pressure levels at the inlet and outlet to the nozzle, 7 different flow regimes for the diverging part of the nozzle is identified [15]. These regimes are not modelled in detail, but a simple model is included to dissipate energy and model deviation from ideal (isentropic) pressure recovery, induced from turbulence and over a possible shock.

The steady state model, with isentropic conservation of mass and conservation of energy (Bernoulli equation) then becomes,

$$\begin{aligned} &\rho u A = \text{const}, \\ &\frac{1}{2}u^2 + h = \text{const}. \end{aligned} \tag{1}$$

The capture pressure is given as a parameter to the model. In the simulations, the capture pressure must be optimized for performance of the supersonic nozzle. Specifying the mass flow of exhaust gas and boundary conditions (pressure, temperature and composition), the required nozzle flow areas can be calculated from equation (1).

The slits of the capture section of the nozzle, together with the swirl and the large density difference between solid and gas, allow for separation of the solid. This capture is not possible without some gas escape, as the slits might clog. The ideal amount of gas escape must be addressed in the design phase, and possibly experimentally determined. A parameter is included that allows for a fixed fraction of gas, relative to the overall gas flow, to escape. The pressure of the dry ice and escaped gas is set equal to the gas pressure at the outlet of the nozzle. Gas-solid equilibrium is assumed at this pressure, sublimating some of the dry ice.

To include some energy dissipation in the diverging part of the nozzle, a fixed parameter, $f_{Recovery}$, is used to scale the pressure recovery form capture to the outlet of the nozzle,

$$P_{Out} = P_{Capture} + f_{Recovery}\left(P_{Out,Ideal} - P_{Capture}\right). \tag{2}$$

The temperature at the outlet is then determined from the stagnation enthalpy and the outlet pressure. Wen [16] report a maximum of 78% recovery and Karimi [8] report 76% pressure recovery for natural gas nozzles. They reported recovery as $P_{Out}/P_{Out,Ideal}$. Based on this recovery ~75% can be assumed.

Fig. 3 shows the isentropic expansion paths for the Laval nozzle leading to 90% capture at four different capture pressures. The figure illustrates how inlet conditions and capture pressure relates.

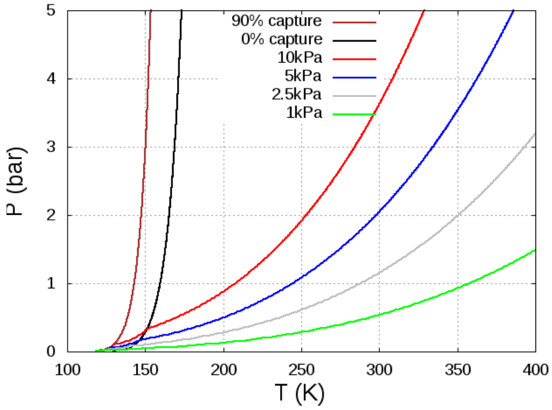

Fig. 3. Four isentropes for an FPSO gas turbine exhaust gas are shown. The capture pressure is set to 1 kPa, 2.5 kPa, 5 kPa and 10 kPa, and the capture is set to 90%. Both the solid appearance line (0%) and the 90% CO_2 deposition line are included.

Assuming capture at 0.1 bar in the divergent section of the nozzle, the theoretical capture limit from the off-shore gas turbine exhaust gas is plotted as a function of inlet temperature for 4 different pressures in Fig. 4. It is seen that elevating the inlet pressure and lowering the inlet temperature will give a higher conversion of gaseous CO_2 to dry ice. Lowering the pressure of capture will increase the freeze-out percentage of CO_2, but the trade-off will be an increased flow area.

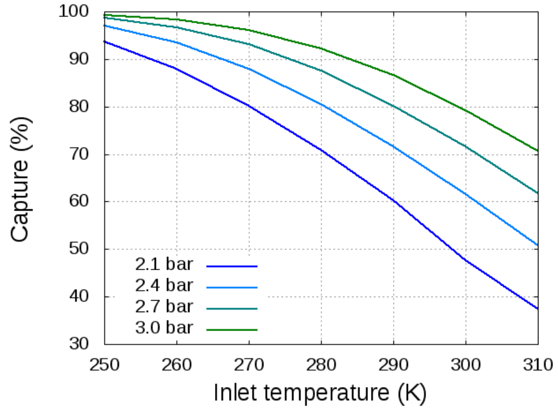

Fig. 4. Theoretical capture limit for supersonic expansion of FPSO gas turbine exhaust gas. Capture is set at 0.1 bar.

2.2.1. Speed of sound

The speed of sound in the single phase region, c_g, is given as

$$c_g = \sqrt{\left(\frac{\partial P}{\partial \rho}\right)_S} . \tag{3}$$

The speed of sound in the dry ice-gas region, $c_{\mathrm{d,g}}$, is subject to an additional equilibrium condition, $\mu_{\mathrm{g,CO2}} = \mu_{\mathrm{d,CO2}}$. By setting up a Jacobian for an isentropic-isochoric system at equilibrium, $c_{\mathrm{d,g}}$ is calculated without the use of numerical perturbations. The procedure for a solid-gas system is described by [17]. For multiphase systems, the speed of sound becomes a combined thermodynamic and fluid mechanic property. The full equilibrium condition used here, introduces a discontinuity in the speed of sound at the solid appearance line [18]. This is also seen for the speed of sound along an isentropic depressurization path, as plotted in Fig. 5. Fig. 5 also shows the fluid velocity calculated from equation (1) and indicates the sonic point, $u = c$.

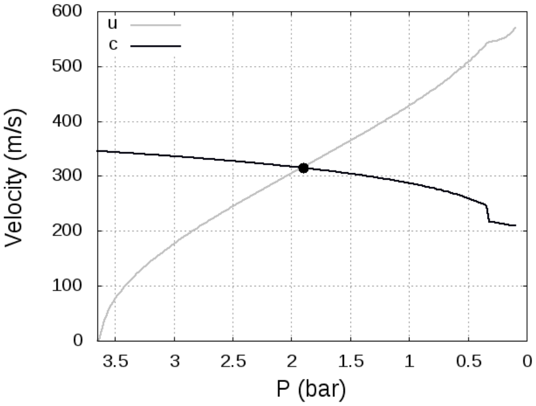

Fig. 5. Speed of sound plotted as a function of pressure along a depressurization path. A discontinuity in the speed of sound can be found at approximately 0.3 bar. The fluid velocity according to equation (1) is also plotted. The intersection, the sonic point, is plotted as a dot.

The sonic point is located when solving the Laval nozzle model, to ensure supersonic flow in the diverging geometry.

2.3. Process model

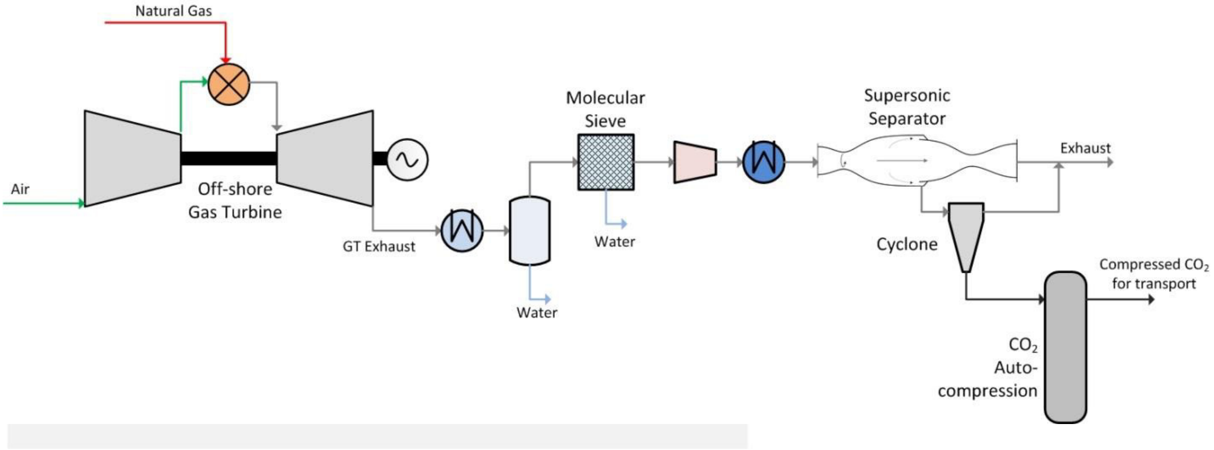

Fig. 6. Process flow diagram of the supersonic separation for CO_2 capture from an FPSO gas turbine.

The selected boundary conditions and parameters used when optimizing the performance of the supersonic capture unit will affect the performance of the upstream gas turbine. In order to address these interactions, the model is integrated in Aspen HYSYS. Steady-state flow sheet analysis is then conducted to study process model interaction and effect of the various model parameters on the overall process performance.

The supersonic unit model in HYSYS is interfaced with one input stream for the feed gas and two exit streams that interact with other unit models. The module has one exit stream for the CO_2 depleted gas stream, and one for the gas escaping with the solid. The dry ice is not readily transferred and handled in HYSYS, and is therefore only handled inside the unit model, and is not appearing in any streams exiting the module.

The nozzle parameters/variables made available in the HYSYS model is the pressure recovery factor, $f_{Recovery}$, gas escape fraction, and capture pressure. The capture pressure is a variable that needs to be optimized for performance, while the two former parameters will be constants, adding energy penalty to the overall process.

The transferred variables from HYSYS to the unit model are component molar flow rates, pressures and temperatures. The supersonic unit model and the HYSYS flowsheet can then interact without using the same reference state for the thermodynamic potentials. The thermodynamic model in HYSYS is set to Peng-Robinson.

3. Results and discussion

Three different case configurations are optimized, using the HYSYS internal optimizer, with overall power consumption as objective function. Only the main power consuming components are considered. The assumptions common for all three cases are:

- 90% capture of CO_2 ($n_{CO2,d}/n_{CO2,Nozzle,Inlet} = 0.9$).
- 80% adiabatic efficiency is assumed in all expander and compressor calculations.
- Sufficient sea water is available for cooling.
- The pressure recovery in the supersonic nozzle is set to 100%.
- The escape gas from the nozzle is ignored.
- Energy required for water removal is assumed to be small for technologies such as molecular sieve and is ignored.
- Self-compression of produced solid is possible, therefore the compression power for CO_2 is ignored.

- 1% pressure drop for all gas streams in heat exchangers, 200 kPa for cooling water.

The variables of all the simulation are the pressure at the nozzle inlet, $P_{Nozzle,Inlet}$, the temperature at nozzle inlet, $T_{Nozzle,Inlet}$, and the capture pressure, $P_{Capture}$.

3.1. Case A description

The exhaust gas from the FPSO turbine is precooled against the CO_2 depleted product from the supersonic separator. Further the gas is cooled to 30°C in a water heat exchanger. The water is removed from the exhaust gas before cooling the gas further and feeding the gas to the separator. The CO_2 depleted gas exiting the nozzle is then heated by the exhaust gas before it is expanded to atmospheric conditions in an expander.

The power consumers in this case are the pump power for the water circulation, W_{Pump}, and the power consumption in the refrigeration system at the nozzle inlet, W_{Ref}. The expander taking the purified product stream to atmospheric pressure will produce power, $W_{Expander}$. In addition the loss of power, due to elevated outlet pressure, from the gas turbine must be included, $W_{Turbine}$. The objective function is the sum of these power consumers. The exit pressure from the nozzle is in this case restricted to be above atmospheric pressure, $P_{Nozzle,Exit} \geq 1\text{atm}$.

3.2. Case B description

The exhaust gas from the FPSO turbine is cooled to 30°C in a water heat exchanger. The water is removed from the exhaust gas before cooling the gas further and feeding it to the separator. The CO_2 depleted gas exiting the nozzle is compressed to atmospheric conditions.

The power consumers in this case is the is the pump power consumption for the water circulation, W_{Pump}, the refrigeration system at the nozzle inlet, W_{Ref}, and the compressor taking the CO_2 depleted product stream to atmospheric pressure, $W_{Compressor}$. Again, the loss of power from the gas turbine must be included, $W_{Turbine}$. The objective function is the sum of these power consumers.

The nozzle exit pressure is in this case restricted to be below atmospheric pressure, $P_{Nozzle,Exit} \leq 1$ atm. This ensures positive compression power, $W_{Compressor} \geq 0$. The nozzle inlet pressure is limited to be above atmospheric pressure, $P_{Nozzle,Inlet} \geq 1$ atm.

3.3. Case C description

This case is similar to case B. The main difference is that the gas compression is moved to the feed side of the supersonic nozzle, after the water removal. The exit pressure from the gas turbine is fixed at 102 kPa, with the consequence that no turbine power will be lost. The nozzle exit pressure is in this case restricted to be at atmospheric pressure, $P_{Nozzle,Exit} = 1$ atm.

3.4. Results from process optimization

Table 2 shows the variables from the optimization of all three cases, together with outlet pressure and capture area in the supersonic nozzle. Table 3 show the power consumption in all three cases. W_{Pump}, includes all pump power used to cool turbine and compressor products to 30°C.

From Table 3, it is seen that the main drawback with Case A is the loss of work from the gas turbine. Because of the water removal, the expander is not able to compensate this loss. This motivated the alternative configurations of Case B and C, where atmospheric pressure at the gas turbine exit removes the turbine power penalty. For Case B Table 2 shows that the exhaust gas pressure takes its minimum value and no loss of turbine power (Table 3). Here the main power consumer is the compression of the CO_2 depleted exhaust gas. This is also the case for Case C.

Table 2. Results from optimizing case A, B and C.

Variable	Case A	Case B	Case C
$P_{Nozzle,Inlet}$	157 kPa	101.3 kPa	163 kPa
$T_{Nozzle,Inlet}$	-4.23°C	-4.44°C	6.1°C
$P_{Capture}$	4.88 kPa	2.47 kPa	3.65 kPa
$A_{Capture}$	0.77 m^2	1.40 m^2	0.93 m^2
$P_{Nozzle,Exit}$	102 kPa	63.1 kPa	101 kPa

Table 3. Optimal power consumption for case A, B and C.

Power consumer [kW]	Case A	Case B	Case C
W_{Pump}	91.8	267.8	297.1
W_{Ref}	250.3	488.3	211.0
$W_{Turbine}$	6019.6	0.0	0.0
$W_{Expander}$ or $W_{Compressor}$	0.0	3310.1	3562.5
$W_{Overall}$	6361.7	4066.2	4070.6

The optimal capture pressure found in all there cases are similar, and ranges between 2.47 kPa and 4.88 kPa while the capture area ranges from 0.77 to 1.40m^2. The case study shows that the loss of turbine power by increasing the pressure at the turbine exit dominates, and must be avoided. Compression before or after the supersonic separator is favored, compared to a process configuration without compression.

The efficiency penalty of the supersonic separator compares favorably to that that of a post-combustion MEA process where the penalty is in the range of 4.5-5 MW. However, the MEA process requires steam and hence a heat recovery steam generator must be installed downstream of the gas turbine to generate steam (and power). This would lead to a large foot-print in addition to the already large absorber and desorbed required for the process.

The pressure recovery was assumed to be 100% and is not achievable in practice. This was used in this work mainly to identify the most optimistic energy penalty numbers and check if they fall in the range of competing technologies. The effect of reducing the pressure recovery in the supersonic nozzle to ~75% should be investigated. Also, it should be noted that the power consumed for refrigeration at the inlet of the nozzle could be reduced by integrating the sublimation energy of dry ice.

4. Conclusion

CO_2 capture from an FPSO turbine exhaust gas using a supersonic separator is investigated. To assess the operational performance of the capture process, a Laval nozzle (converging-diverging geometry) model is implemented and successfully integrated in the steady state process flow sheet simulator Aspen HYSYS. The model includes equilibrium thermodynamics describing freeze-out of dry ice from a gas mixture containing CO_2.

Three different process configurations are investigated. To determine under which conditions this processes are thermodynamically and fluid dynamically feasible, a pressure and temperature optimization is performed. The results indicate that supersonic expansion is a viable strategy for capturing CO_2. However, more simulation as well as experimental work is required to enable this technology.

Acknowledgements

This publication has been produced with support from the BIGCCS Centre, performed under the Norwegian research program *Centres for Environment-friendly Energy Research (FME)*. The authors acknowledge the following partners for their contributions: Aker Solutions, ConocoPhillips, Det Norske Veritas, Gassco, Hydro, Shell, Statoil, TOTAL, GDF SUEZ and the Research Council of Norway (193816/S60).

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