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## Thermodynamic analysis of post-combustion inertial CO<sub>2</sub> extraction system

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### Abstract

The Inertial CO<sub>2</sub> Extraction System (ICES) represents a novel method of capturing CO<sub>2</sub> from flue gas. ICES makes use of the cooling effect of supersonic expansion to cool the flue gas stream, causing CO<sub>2</sub> in the flue gas to change phase to form a solid that can then be captured from the gas stream through an inertial separation. A first-principles thermodynamic analysis of this unique process is described and results of the analysis are reported.

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### 1. Introduction

There are many technical pathways that can be used for reducing the amount of carbon dioxide emitted to the atmosphere. Carbon capture and storage (CCS) from post-combustion flue gas from fossil-fired power plants is one of the major opportunities that is being pursued for reducing CO<sub>2</sub> emissions. Within the field of post-combustion CCS,

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several methods of capture have been proposed. The current largest scale projects are all aqueous solvent systems that use a liquid solvent to capture CO<sub>2</sub> from the flue gas and subsequently release it when heated to be compressed for transportation and storage or use. Other methods for capture have been explored including using non-aqueous solvents, phase change materials, membranes, solid sorbents, cryogenic processes, biological processes, or mineralization processes. Active development in these fields has led to robust understanding of many of the benefits and challenges that each of these classes of technologies faces. Novel technologies for CCS tend to cluster within these defined classes with changes to chemistry, equipment, process operation, and system optimization providing the major differences between the technologies.

Tools for understanding CCS systems have been developed that can evaluate or estimate the performance of solvent, sorbent, cryogenic, and membrane systems as well as hybrid systems. Biological and mineralization processes tend to be less easily described through modeling tools as they rely more on the fixation of CO<sub>2</sub> as opposed to the chemical separation processes. Advances within these fields can be benchmarked against metrics of performance of similar systems in order to rapidly evaluate and communicate the performance of different systems. For example, reporting only a single number for reboiler duty of an aqueous amine solvent system provides much of the information necessary to evaluate an aqueous amine process. This is because there are common flow sheets and known constraints for aqueous amine systems such as maximum temperatures of operation without causing solvent degradation, known cross heat exchanger efficiencies, assumed absorber efficiencies and geometries, and common equipment for CO<sub>2</sub> compression and processing. Similarly, different membrane properties may yield slight variations of common membrane flow sheets that have become accepted by the development community. Varying the permeability of a membrane, for example, is known to reduce the membrane area required while no other changes to the full process or energy consumption are necessary. In these cases, evaluating a single process parameter or chemical property can provide a general understanding of the system because of the accumulated knowledge of similar processes.

Truly novel technologies, however, rely on a different level of analysis in order to evaluate and compare to existing technologies. Instead of relying on an existing framework for analysis, such as the thermal load and compression energy for a solid-sorbent system that can be determined from the adsorption isotherms, a complete framework for evaluation must be created. This paper describes the creation of a framework for understanding a truly novel process that relies on the cooling effect of accelerating supersonic flow to cause CO<sub>2</sub> to form solid particles and the subsequent system analysis and results of such a model.

### *1.1. Inertial CO<sub>2</sub> Extraction process description*

The Inertial CO<sub>2</sub> Extraction System (ICES) was invented by Orbital ATK (formerly ATK) and ACENT Laboratories as a means of harnessing the cooling power of accelerating supersonic flow to solidify and capture CO<sub>2</sub> from post-combustion flue gas. At sufficiently low temperatures determined by the gas-solid phase behavior of CO<sub>2</sub>, 90% or any predetermined quantity of the initial CO<sub>2</sub> can be solidified. The solid CO<sub>2</sub> can then be separated from the remaining gas stream through turning the gas flow, which causes the solid particles to be inertially pushed against the outer wall in the turning duct. A knife-edge separator can then be used to capture the solid flow along with a small slip-gas stream. The solid particles can be further separated from the slip-gas stream in a cyclone. Meanwhile, the remaining CO<sub>2</sub>-lean gas in the main duct can be decelerated in a diffusor to increase the pressure to allow atmospheric discharge (Figure 1).

The solid CO<sub>2</sub> particles are pressurized by a process using solids pumping, heating to melt the CO<sub>2</sub> to become a liquid, and further liquid pumping and heating to make the CO<sub>2</sub> a supercritical fluid. As the solid CO<sub>2</sub> heating, melting, and liquid CO<sub>2</sub> heating take place at significantly sub-ambient temperatures, there is the possibility for thermal integration of this process to cool the incoming flue gas to facilitate the cryogenic capture. This capture process makes use of some process equipment that is common with other capture processes, such as the initial flue gas treatment and compression and solid CO<sub>2</sub> pressurization, but overall the capture process and capture mechanism is fundamentally different from all other capture processes as it does not rely on chemistry or any sort of separation medium.

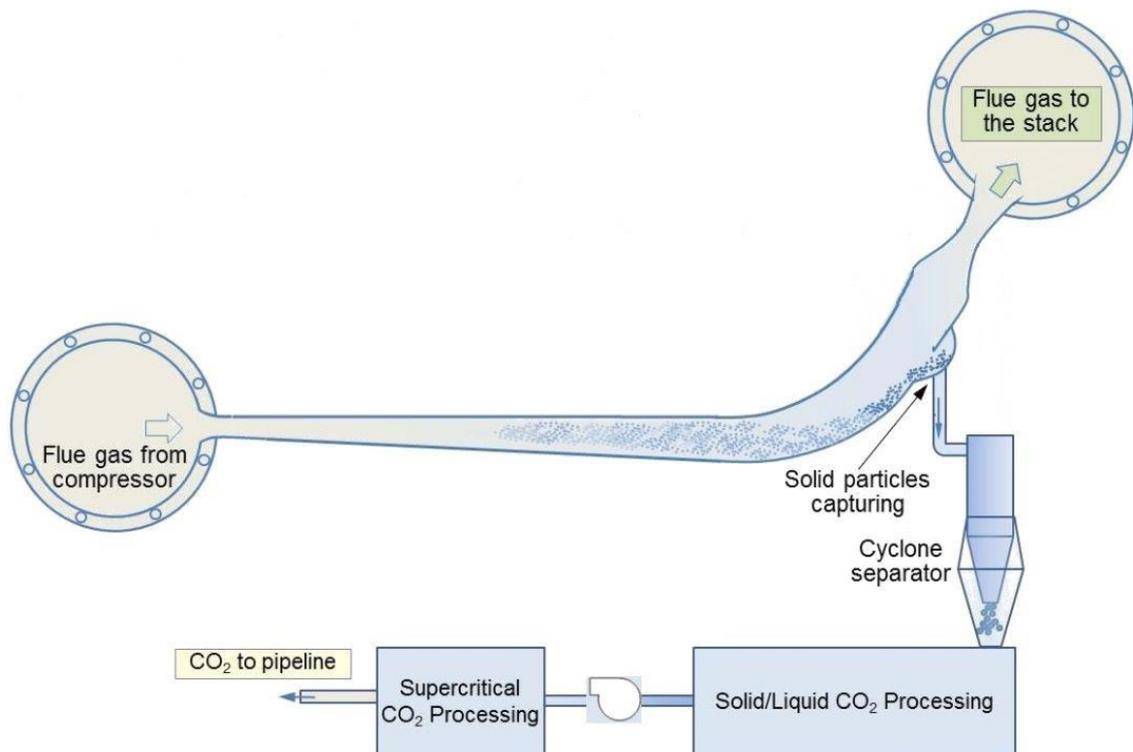


Fig. 1. Schematic of ICES process showing the converging-diverging supersonic nozzle for solid CO<sub>2</sub> particle formation, inertial CO<sub>2</sub> capture duct, and pressure recovery in gas diffuser before outlet to the stack

## 2. Method of evaluation

Evaluation of novel technologies requires an understanding of the fundamental forces governing system operation. For a system such as ICES, the governing parameters that must be understood are: the thermodynamic properties of CO<sub>2</sub> and flue gas as they are chilled, including phase equilibrium; evolution of temperatures, pressures, densities, and enthalpies as the two-phase gas + solid flow is accelerated, has the solids removed, and is decelerated; the effect of phase transition on the temperature, pressure, and velocity profiles of the system; flow dynamics of the two-phase gas + solid system as it goes through the ICES process; and particle nucleation and growth.

In this paper, an evaluation of the thermodynamic analysis will be described. While significant simulation and experimental effort has gone into understanding and describing the particle nucleation and growth [1] and an equal effort has been devoted to the CFD flow dynamics models, those are the subject of other works.

### 2.1. Principles of thermodynamic analysis

Thermodynamic analysis is the study of how energy flows within chemical and mechanical systems describe the operation of those systems. By examining the energy flows and possible energetic states that can result from a given starting condition, a fundamental understanding of a process can be determined. In any given process, the entropy of the full system cannot decrease and so the most efficient process is one in which the end result is achieved without

increasing entropy of the full system. This is referred to as an isentropic or reversible process because the starting and ending entropy are identical making it theoretically possible for the process to proceed in either the forward or the backward direction.

In order to understand the limitations and benefits of novel systems, thermodynamic analysis that initially assumes isentropic behavior is useful for two reasons. First, it provides a bounding condition on the performance given ideal behavior of every component. Second, by comparing isentropic results to more realistic results, either simulated or experimental, the impact of component inefficiencies can be quantified and the process can be optimized. For these reasons, this initial evaluation of the ICES process involves an isentropic description of the process. Primary causes for irreversibilities within this system relate to the conversion of mechanical energy to thermal energy such as through friction, shocks, fluid stresses, and heat transfer across thermal gradients. For this analysis, we will initially ignore these terms and assume isentropic, uniform flow conditions.

## 2.2. Isentropic supersonic flow effects

The basic premise of the ICES process is that accelerating gas yields lower temperatures, as seen in the isentropic, ideal gas equation for temperature as a function of Mach number:

$$\frac{T_0}{T} = 1 + \frac{k-1}{2} M^2 \quad (1)$$

Where  $T_0$  is the stagnation temperature,  $T$  is the temperature at the given Mach number,  $k$  is the ratio of specific heats, and  $M$  the Mach number or ratio of the velocity to the speed of sound at the evaluation point. As the velocity increases Mach number increases and temperature decreases for a given stagnation temperature. Similarly, the pressure decreases as velocity increases as described for an isentropic, ideal gas by the following equation:

$$\frac{P_0}{P} = \left[ 1 + \frac{k-1}{2} M^2 \right]^{k/k-1} \quad (2)$$

Where  $P_0$  is the stagnation pressure and  $P$  is the pressure at the given Mach number. Through these equations, it is possible to understand the temperature and pressure profiles of an ideal gas as it accelerates or decelerates in an isentropic nozzle or diffuser. The other equations necessary to understand the behavior of the system are the relationship between pressure, velocity, and density or the equation of state (EOS). For an ideal gas, the ideal gas equation of state  $P = \rho RT$  can be used. By applying these equations, a full understanding of single phase, isentropic fluid flow can be determined from only the velocity and initial conditions of the process. However, in non-ideal conditions, the assumption of a constant ratio of specific heats no longer holds and, especially as multi-phase region is entered, the velocity, momentum, density, temperature, and pressure relations all differ significantly from the ideal equations above. In order to accurately capture the full effect on a system undergoing phase change, an understanding of the full equation of state for the gas + solid system must be developed.

## 2.3. Equation of State for CO<sub>2</sub>

Equations of state describe the full thermodynamic state of a substance from a subset of its thermodynamic properties. While these are well developed for most gases and liquids of interest, equations of states for solids and solid+gas systems are less commonly deployed for process evaluation. However, in order to understand the behavior of CO<sub>2</sub> as it undergoes gas-to-solid phase transition in a cooling fluid, a description of the gas-solid transition is necessary. Specifically, the solid-vapor equilibria, heats of sublimation, densities, and specific heats of each phase are required to determine the entropy and enthalpy of the system at any given condition.

An extended Peng-Robinson EOS for CO<sub>2</sub> properties developed by Martynov, et al. at the University College of London [3] was implemented in order to describe and model the behavior of CO<sub>2</sub> in the region of interest region. This EOS provides the P-v-T relationship for gas and solid phases, and all other thermodynamic properties including enthalpy, entropy, and ratio of specific heats can be derived from that relationship along with the ideal gas specific heat. A code set including derivations of enthalpy, entropy, pressure, and temperature from any two of those properties in the gas, solid, and two phase regions of interest was developed in Matlab to assist in the calculation of specific state points and thermodynamic analysis of this process.

For gas properties, including CO<sub>2</sub> that was not on the sublimation line, REFPROP, a commercially available software package, was used [4]. REFPROP was developed by the National Institute of Standards and Technology (NIST) using multi-parameter equations of state that generally capture the full behavior of gas and liquid fluid properties to within the margin of error of the measurements provided.

For mixed gas properties in the 2-phase region, a combination of these two property methods is used with REFPROP being used for the non-CO<sub>2</sub> components of the flue gas and the extended Peng-Robinson EOS used for the gaseous and solid CO<sub>2</sub> properties. Ideal gas mixing laws are used to combine the CO<sub>2</sub> and non-CO<sub>2</sub> components of the gas phase to calculate mixed-gas and multi-phase properties.

#### 2.4. Modeling two-phase supersonic flow

The ideal gas supersonic flow effect equations described above are useful for determining the properties of a single-phase ideal gas system. However, in multi-phase flow the ideal gas assumptions are no longer applicable. Instead, a numerical simulation is utilized to calculate fluid conditions as a function of the gas velocity. In most supersonic flow modeling, the discretization variable is the cross sectional area of the flow. By varying the cross sectional area, the velocity, pressure, and other flow properties can be calculated. This is useful in the design or evaluation of real physical systems. However, for our thermodynamic analysis that assumes ideal components, we algebraically eliminate the cross sectional area from the equations and use velocity as the discretization variable. The assumptions for the two-phase flow are that the system is isentropic and that the temperatures and velocities of each phase are in equilibrium.

The solving method is a marching solver that uses the results of the previous velocity step in order to compute the pressure, temperature, enthalpy, and phase equilibrium at each given velocity. Given an initial condition of the temperature, pressure, and inlet concentration, a velocity profile is assumed that starts at 0 m/s and advances in 2m/s increments in the single phase region and 0.5m/s increments in the two-phase region. At each velocity increment, a gas enthalpy is calculated from the definition of stagnation enthalpy in isentropic flow (3) and the pressure is calculated from the momentum equation (4).

$$h_0 = h_1 + \frac{v_1^2}{2} = h_2 + \frac{v_2^2}{2} \quad (3)$$

$$P_2 = P_1 + \rho \frac{(v_1^2 - v_2^2)}{2} \quad (4)$$

Where  $P$  is the pressure,  $\rho$  the density,  $v$  the velocity,  $h$  the enthalpy and  $h_0$  the stagnation enthalpy of the gas stream. The density used in equation (4) is determined as the average of the density at point 1 and the estimated density at point 2. The estimated density at point 2 is determined by numerically computing  $\frac{d\rho}{dv}$  and then estimating the density as  $\rho_2 = \rho_1 + \Delta v \frac{d\rho}{dv}$ . Without using the density estimation, the simulated results experience significant pressure deviation from analytically calculated results during simulation verification. With the density correction, pressure results are consistent across multiple types of verification. Once the pressure and enthalpy are determined, the previously implemented EOS is used to solve for the temperature, density, and vapor fraction of the CO<sub>2</sub> in the flow. By treating the gas and solid as a single flow, complex effects from density changes, apparent heat addition or removal from phase change, and pressure effects are all treated consistently and internally.

For isentropic single-phase or two-phase flow, the stagnation temperature and pressure remains constant as the flow is accelerated. However, the associated properties such as the static temperature and pressure of the flow will increase significantly for the two-phase compared to the single-phase flow. This is due to two main factors. The first is that the phase change has an associated heat of sublimation that is released from the solid phase into the vapor phase when the CO<sub>2</sub> becomes a solid. This apparent heat addition has the same effect as Rayleigh flow in the gas phase, which is to increase the apparent stagnation temperature and lower the apparent stagnation pressure of the gas stream. Because the heat addition is reversible with phase change of the CO<sub>2</sub> back into the vapor phase, the overall stagnation pressure is not effected. This apparent heating does still affect the static temperature and pressure properties for the full flow. The other main factor is the kinetic energy transfer from the gas to the solid phase. While gases accelerate in nozzles, solids do not experience any acceleration on their own due to area effects. This means that for solids to accelerate, they must be absorbing the kinetic energy from the gas they are entrained in. This has the effect of lowering the kinetic energy of the gas and transferring it to the solids. While the solids and gas remain in the same flow, this entire process is reversible. However, when the solids are separated out of the flow, the apparent loss in stagnation pressure, increase in stagnation temperature, and loss in kinetic energy from the gas phase become real losses and gains in the stagnation conditions.

### 2.5. Isentropic modeling of the full process

The full system model is simulated by calculating the system conditions during acceleration, solids removal, and subsequent deceleration. From a given set of initial conditions including gas composition, temperature, and pressure, the flow is numerically accelerated until the solid CO<sub>2</sub> fraction matches a target level. At that point, the flow is computationally separated into a product stream with a specified fraction of the solid and specified slip gas component, and a CO<sub>2</sub>-lean gas streams that contains the remainder of the flow. By specifying the percent of the solids captured and the percent of CO<sub>2</sub> solidified, a specified CO<sub>2</sub> capture fraction can be achieved. The remaining CO<sub>2</sub>-lean stream can then be numerically decelerated to stagnation in order to recover pressure for atmospheric discharge. The assumptions made for the two phase flow are that: 1) the temperature of the gas is equal to the temperature of the solid, which is also equal to the sublimation temperature at the partial pressure of CO<sub>2</sub> in the gas stream, and 2) that the velocities of the gas and solid particles are the same.

The dominant effect of introducing two-phase flow to the system is that the latent heat of sublimation has to be adsorbed by the vapor stream. Phase change from vapor to solid phase has an associated heat release that acts on the gas stream similar to Rayleigh flow effects for heat addition in supersonic flow. While heat addition in a subsonic (converging) nozzle accelerates the flow towards the speed of sound, heat addition in a supersonic (diverging) nozzle decelerates the flow velocity towards the speed of sound and decreases the stagnation pressure. The higher the velocity when the heat addition is applied, the greater the reduction in the stagnation pressure. However, because the enthalpy released during CO<sub>2</sub> anti-sublimation during acceleration could be re-adsorbed by the solid CO<sub>2</sub> sublimating at the same velocity in decelerating flow, the entire process is reversible and no change in stagnation pressure for the two-phase system is observed when there is no mass removal from the processes. This is shown in figure 2b as the plot of pressure at the 0% CO<sub>2</sub> capture rate has the same initial and final values.

This heat release also increases the temperature in the fluid relative to the single phase flow case. The increased temperature decreases the amount of CO<sub>2</sub> that will solidify at a given velocity, and the velocity at which the target CO<sub>2</sub> solid fraction is achieved is significantly higher than would be calculated by the single phase flow calculations alone. The onset of temperature release is visible as the kink in the temperature plot of figure 2a occurring around 520 m/s, which represents the point of incipient solid CO<sub>2</sub> formation for the modeled inlet conditions. While the 0% solids removal case shows the temperature profile during the deceleration mirroring that of the accelerating flow, any quantity of solids removal alters the temperature profile as less solid CO<sub>2</sub> is available to change phase during deceleration to buffer the temperature rise expected in a purely gas system. Similarly, in the pressure profile, removing the kinetic energy in the solid particles and increasing the temperature of the system yields lower pressures in the diffuser and decreases the pressure recovery.

## 2.6. Modeling particle recycle

Another factor in the behavior of the ICES process is the particle growth rate in order to form particles of sufficiently large size that they can be inertially separated from the remaining gas stream. Because the residence time in the supersonic nozzle and turning duct is too short to form larger particle agglomerations, solid CO<sub>2</sub> recycle particles have been explored as a means of seeding particle growth and nucleation. In this particle seeding, solid CO<sub>2</sub> particles are assumed to be present in the gas stream from the entrance to the reactor. In order to model the behavior of the particles, the surface pressure of the particle is taken to be the same as the partial pressure of CO<sub>2</sub> in the gas stream. The temperature of the particle is then calculated to be along the saturation line at the partial pressure of CO<sub>2</sub> calculated. Because the residence time of the solid particles in the gas stream is very short prior to the expanding and turning duct, it is assumed that no solid CO<sub>2</sub> sublimation would occur. While this is not entirely valid in real-world applications, it provides a framework and limiting case from which to perform analysis.

The target solid CO<sub>2</sub> fraction for determining the maximum velocity achieved is calculated based on the fraction of the inlet gas CO<sub>2</sub> that becomes a solid. The effect of solid CO<sub>2</sub> inlet to the reactor and subsequent removal at the solids capture duct is a net reduction in the kinetic energy of the remaining gas stream. This is because the solid CO<sub>2</sub> is not accelerated on its own in the nozzle: it is only accelerated by kinetic energy transfer from the gas particles. When the solid CO<sub>2</sub> particles are removed, the total amount of kinetic energy left in the gas stream is less than it would have been had no solid CO<sub>2</sub> been injected at 0m/s and removed at the maximum velocity.

## 3. Results

Results from the simulations of the nozzle, solids removal, and diffuser of the ICES system described above are shown below. All results shown assume frictionless, uniform, isentropic flow, which would not be the case in actual operation. However, by simulating the thermodynamic ideal operation, we can understand the limiting behavior of this system and identify the potential of the CO<sub>2</sub> capture system. While the ICES process will also need to include balance of plant equipment and process simulation for flue gas compression, cooling, heat integration, possible dehydration, potential gas or solid recycling, potential air dilution, solid and liquid CO<sub>2</sub> compression, and other process steps, these results focus exclusively on the converging-diverging nozzle, supersonic solids removal duct, and subsequent diffuser.

### 3.1. Simulated ICES process results

The simulations described in Section 2 provide a marching solving methodology for evaluating process conditions along the ICES supersonic reactor. The results from three simulation runs representing different solids capture efficiencies are presented as temperature, pressure, Mach number, CO<sub>2</sub> gas fraction, enthalpy, and density profiles in Figure 2. The three different runs represent capture rates of 0%, 45%, and 90% of the total solids fraction. The inlet conditions are 2.5 bar at 300 K and 14% CO<sub>2</sub> by mole in a balance of dry N<sub>2</sub>. The maximum velocity is determined by the point at which 90% of the inlet CO<sub>2</sub> is solid and occurs at 765 m/s for these inlet conditions. This coincides with the solids removal and occurs at the point of maximum Mach number, minimum temperature, minimum pressure, minimum density, and the discontinuity in enthalpy and gas fraction

For the 0% solids capture rate simulation, all of the profiles are symmetrical with the decelerating portion being an exact mirror of the accelerating profile for all variables. This changes with the 45% and 90% solids capture rate. For the 45% capture rate, the temperature and pressure profiles closely follow the 0% capture rate profiles from inlet through solids removal until all solid CO<sub>2</sub> that remains in the gas stream has been sublimated to become vapor. After the last solids remaining in the gas stream are vaporized, the temperature increases and the pressure decreases beyond what would be expected from the 0% capture case due mainly to the apparent heat addition compared to the case where solid CO<sub>2</sub> changing phase is absorbing the latent heat of vaporization. In the 90% solids capture rate, the onset of increased temperature and decreased pressure is very close to the capture location as only a small quantity of solid CO<sub>2</sub> remains in the gas stream to moderate the temperature rise.

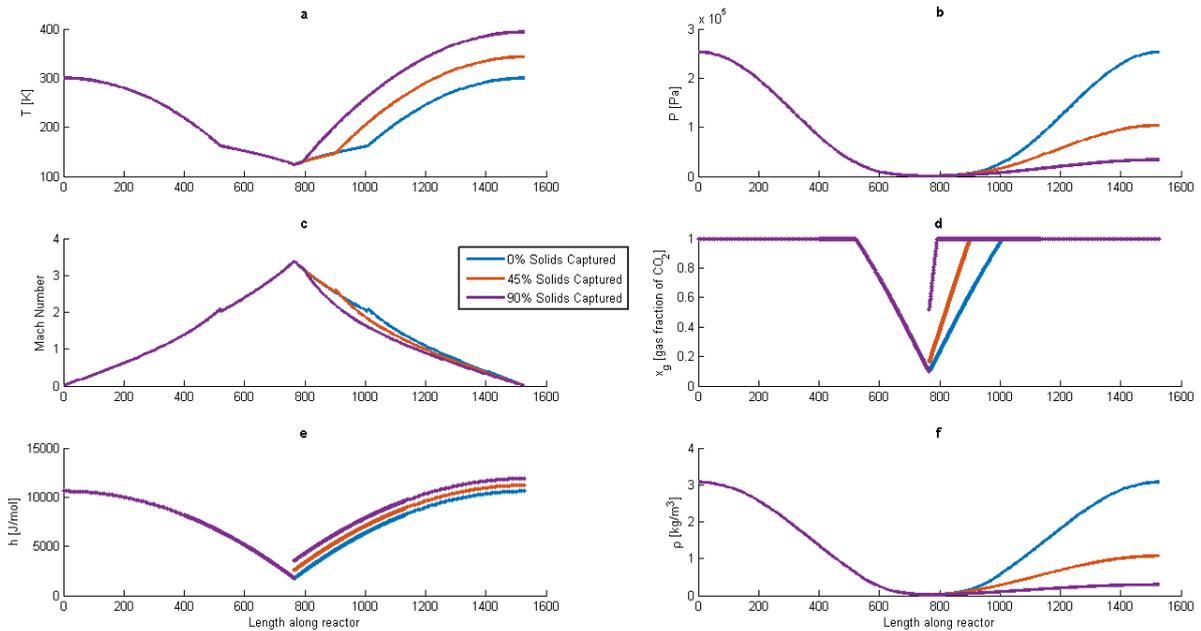


Fig. 2. Results from simulation of ICES process with no solids capture (blue), 45% solids capture (red), and 90% solids capture rate (purple). The x-axis represents the length along the reactor measured in increments of 1 m/s: velocity increases from 0 to 765 m/s and then decreases down to 0 m/s at coordinate 1530. (a) Temperature profile showing higher final temperature for higher CO<sub>2</sub> capture rate. When no CO<sub>2</sub> was removed from the stream, the final temperature is the same as the initial temperature; (b) Pressure profile showing higher pressure recovery for lower CO<sub>2</sub> capture rate; (c) Mach number profile in the gaseous phase of the process showing increasing and decreasing velocity; (d) Profile of fraction of CO<sub>2</sub> in the gaseous phase. Discontinuity occurs at solid CO<sub>2</sub> removal point; (e) Profile of average enthalpy of the system. Removal of solids yields higher average enthalpy; (f) Density profile showing low final density after CO<sub>2</sub> solids removal.

### 3.2. Results including particle recycle

With particle recycle, the temperatures and pressures in the accelerating portion of the nozzle change significantly. This is in large part due to the extra mass of the solid CO<sub>2</sub> added to the accelerating stream. While gases undergo acceleration in nozzles, the solid component of the flow only accelerates by imposing drag on the gas stream it is entrained within. This means that the percent of the kinetic energy of the system retained in the gas phase decreases as the proportion of solids in the flow increases. As the stagnation pressure of a flow is a combination of the static pressure and the contribution from the kinetic energy  $P_0 = P + \frac{1}{2}\rho v^2$ , the lowered velocity has an immediate impact on the stagnation pressure of the system. This is seen in Figure 3 as the recycled (dashed) CO<sub>2</sub> streams have significantly lower pressure recovery than do the simulated cases with no CO<sub>2</sub> recycle (solid). For this figure, all flows have inlet concentration of 14% CO<sub>2</sub> in N<sub>2</sub>, target CO<sub>2</sub> solidification of 90% and capture 90% of the solids in the capture duct.

Figure 3 shows the effect of inlet pressure and temperature on the outlet pressure recovery. For atmospheric discharge, an outlet pressure of at least 1 bar must be achieved. With no CO<sub>2</sub> recycle, this can be achieved for isentropic flow assumptions by either initially compressing the flue gas to slightly below 10 bar at 300K, 6 bar at 250K, or 4 bar at 200K. The reason that lower inlet temperatures decrease the required inlet pressure is that the 90% CO<sub>2</sub> solidified condition occurs at a lower velocity because less temperature decrease is required for the full system. At lower velocities, the impact of heat addition on stagnation pressure is decreased as seen by the increase in  $\frac{\partial h}{\partial s}$  for the Rayleigh flow line at increasing Mach numbers in the supersonic regime.

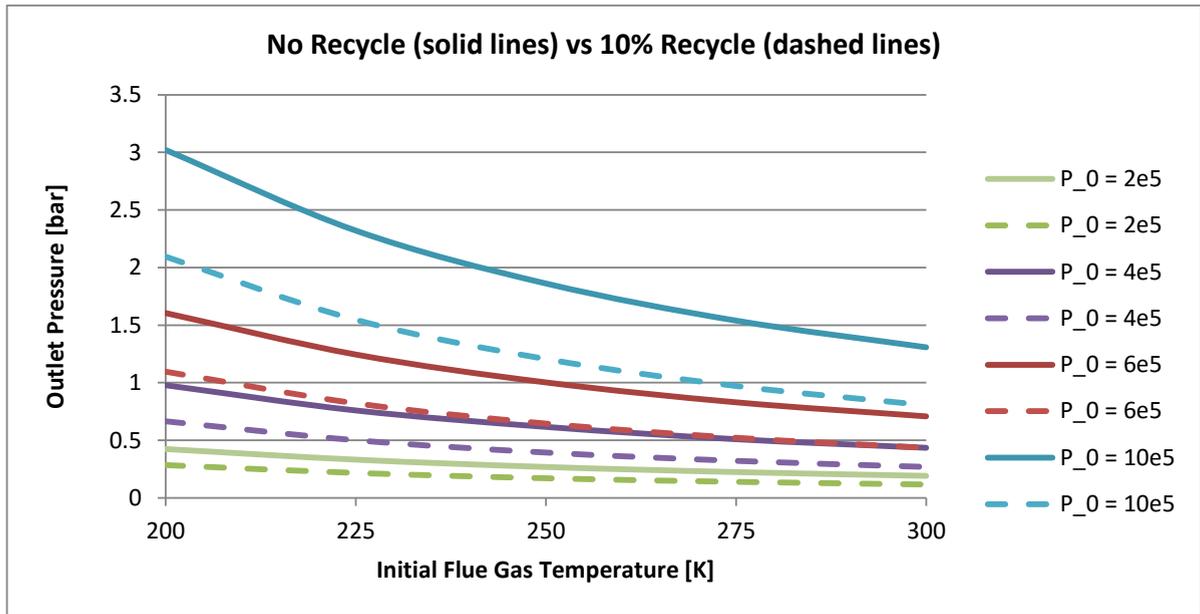


Fig. 3. Effect of inlet temperature, inlet pressure, and CO<sub>2</sub> recycle rate on outlet pressure for ICES capture process. Cases with 10% solid CO<sub>2</sub> recycle (dashed) show significantly less pressure recovery than cases with no solid CO<sub>2</sub> recycle (solid lines)

#### 4. Conclusions

Previous work on the ICES system had estimated that inlet conditions of 300K, 2.5 bar, and 14% CO<sub>2</sub> in N<sub>2</sub> would allow 90% CO<sub>2</sub> capture and atmospheric discharge [5]. However, the current analysis has shown that this initial condition would result in an outlet pressure of approximately 0.3 bar, even assuming isentropic flow and no solid CO<sub>2</sub> particle recycle. This indicates that additional initial conditioning will be required at the flue gas inlet to achieve atmospheric discharge. This can take the form of increased flue gas pressure, decreased temperature, or both. The addition of solid CO<sub>2</sub> recycle will further reduce the pressure recovery of the process. To overcome this additional pressure impact either the inlet flue gas has to be compressed even more or the inlet temperature has to be even lower.

For a real process, the thermodynamic modeling here should act as a benchmark and limiting case. The simulation should also help provide an understanding of the process and its benefits and limitations. For any supersonic cryogenic system, the heat of CO<sub>2</sub> phase change from the vapor phase to the solid phase will have to be accounted for. This generally takes the form of apparent heat addition to the remaining gas once the solids are extracted, which has the same impact on stagnation pressure as Rayleigh flow heat addition. Further, the acceleration of the particles and subsequent extraction at the solids removal duct has the impact of removing kinetic energy from the gas stream, which reduces the stagnation pressure of the remaining flow. While the results from this study have confirmed the major principles of ICES operation, the combination of these factors yields the reduced outlet pressures calculated and presented in Figures 2 and 3.

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