SHOCKWAVECO2

Ultra low-cost skid-based shockwave technology to turn waste CO2 into carbon products

Vertical prototype of CO2 system in TX

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carbon capture journal

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IEA CLEAN COAL CENTRE

Shockwave-tech clean coal plant in China

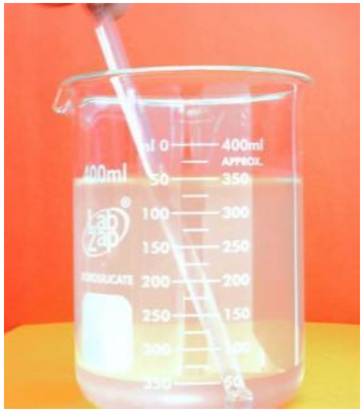
Simple Instruction Manual

1. Connect Shockwave CO2 system to CO2-rich stack gas
2. Input excess trona or Nahcolite brine, carbonate, or hydroxide liquid
3. Push the “ON” button (open compressed air valve + turn on liquid reagent pump)
4. When pH of liquid in tank drops to 12.0 or 9.0 respectively, pump carbonate or bicarbonate product for further processing (drying, packaging, or heating)

Make <u>more product</u> using <u>excess or wasted resource</u> for little cost!

5 System Requirements

1. CO2 stack gas conditioned to 75°-85°F (23°-30°C)



2. Chemical liquids to absorb CO2

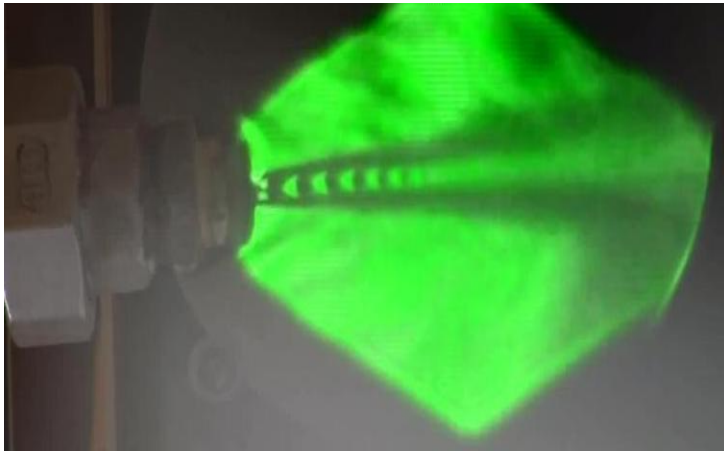
3. 110v electrical outlet

4. Holding tank for processed CO2 product

5. Commercial air compressor or stack gas compressor

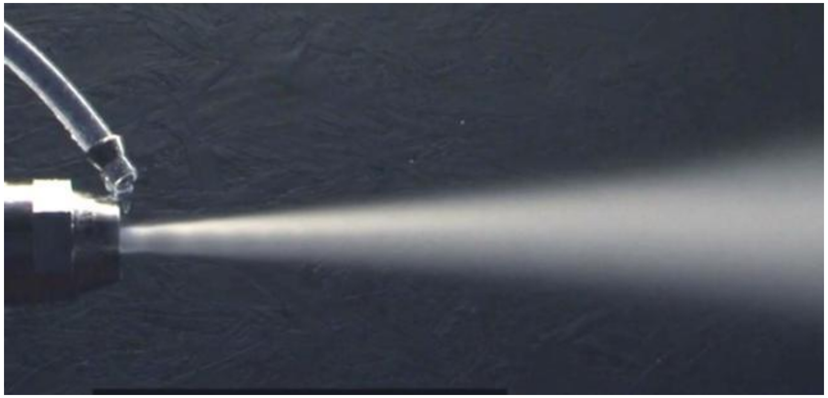
What is Shockwave Technology?

Efficient chemical mixer and contactor for mass/energy transfer using compressed fluid (air, steam, or stack gas)

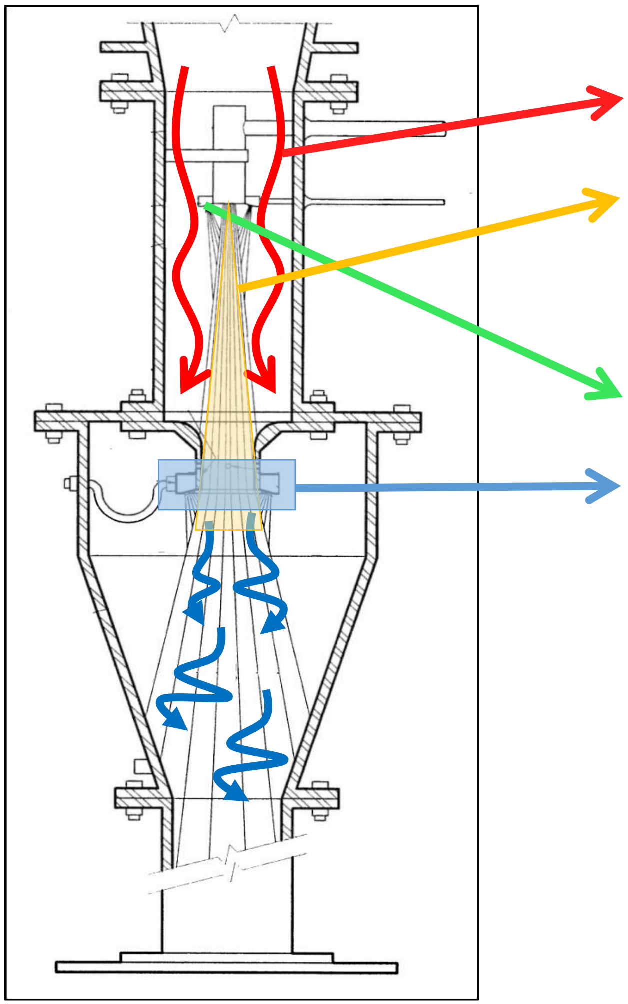


Benefits:

- High speed liquid vaporizer
- Collision energy transfer
- Robust mixer in forced reaction zone
- Controllable gas expansion



How is Shockwave Used?



- Stack gas flows through pipe
- Shockwave turns into high speed air blender and collides and mixes entire stack gas flow
- Inject chemicals into shock mixer
- Chemicals are vaporized and forced to mix with entire stack gas using shockwave inside confined shocktube (primary mixer)
- Gas expands in designed mixing pattern in production tanks (secondary mixer)

Well-Published Technology

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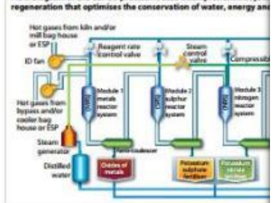
EMISSIONS REDUCTION TECHNOLOGY

How shockwaves can cut energy penalty

An update on the now patented CEFCO multi-pollutant control and carbon cap promises considerable energy efficiency through its use of power plant "spent" st designed reactors to promote pollutant capture processes. A pilot scale system is i Mfg Co facility in Wichita Falls, Texas.

Robert Tang, *CEFCO Global, Dallas, Texas, USA (robert.tang@cefcoglobal.com, www*
Anupam Sanyal, *International Environmental & Energy Consultants, Lakeland, Flori*

Flow diagram of the CEFCO process. It uses a comprehensive syste regeneration that optimises the conservation of water, energy an



Using shockwaves

The CEFCO process in brief

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Chemical Activation through Super Energy Transfer Collisions

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Supporting Information

ABSTRACT: Can a molecule be efficiently activated with a large amount of energy in a single collision with a fast atom? If so, this type of collision will greatly affect molecular reactivity and equilibrium in systems where abundant hot atoms exist. Conventional expectation of molecular energy transfer (ET) is that the probability decreases exponentially with the amount of energy transferred, hence the probability of what we label "super energy transfer" is negligible. We show, however, that in collisions between an atom and a molecule for which chemical reactions may occur, such as those between a translationally hot H atom and an ambient acetylene (HCCH) or sulfur dioxide, ET of chemically significant amounts of energy commences with surprisingly high efficiency through chemical complex formation. Time-resolved infrared emission observations are supported by quasi-classical trajectory calculations on a global *ab initio* potential energy surface. Results show that ~10% of collisions between H atoms moving with ~60 kcal/mol energy and HCCH result in transfer of up to 70% of this energy to activate internal degrees of freedom.

Collisions serve to thermalize molecules and generate vibrationally excited activated species. Polanyi emphasized the role of molecular activation in reactivity[1] and many studies have demonstrated enhancement of a reaction channel for one or more quanta of vibrational excitation in specific modes.[2,3] Recent studies have begun to elucidate the role of short-lived quantum mechanical resonances in enhancing collisional excitation.[4,5] As well, energetic collisions well above the minimum energy path for reaction are revealing new mechanisms even for $H + D_2$.[6,7] Here we delineate an important role for chemical complex-forming collisions in generating highly vibrationally activated molecules.

In collisional deactivation of highly internally excited molecules, the "strong collision" assumption,[8−10] experimentally verified for numerous systems (e.g., NO_2,[11] CS_2,[12] SO_2[13]), has been applied in unimolecular reaction theories where one collision can deactivate an excited molecule from a dissociative state to a non-reactive state. The reverse, i.e., collisions in which large amounts of energy are transferred from ambient colliders to molecules, is also a critically important phenomenon that still needs to be characterized. Here we introduce a generally applicable mechanism by which a molecule can become activated with a large amount of internal excitation with *high efficiency* in a collision with a translationally hot atom through "super energy transfer" (SET) collisions.

Atoms with high translational energy, or so-called "hyperthermal" atoms, are abundant in high temperature environments like combustion chambers or photolytic systems such as the atmosphere. The outcome of collisions between a hyperthermal atom like hydrogen and an ambient molecule is fundamentally important and affects the equilibrium and molecular reactivity in those systems. We demonstrate that these types of collisions can, in contrast to the widely accepted exponential energy gap law, result in large translation-to-vibration (T-V) energy transfer (ET). These SET collisions produce species with high internal energy which substantially affects their reactivity,[14] and can also act as a translational energy sink and lower the temperature of the system.

Here we present the first experimental and theoretical examination of this highly efficient mechanism for energizing molecular species with chemically significant amounts of energy that occurs through the formation of a reaction complex. For a collision encounter between a hyperthermal atom and a molecule, if a collision complex lives long enough during the collision encounter to allow redistribution of the available energy, the vibrational degrees of freedom of the molecule after the dissociation of the complex may host a large quantity of internal energy that cannot be achieved through traditional hard-sphere collisions. Most importantly, as distinct from the well-known "long tail" ET probability, we show that SET collisions, making use of this reaction complex mechanism, occur with a surprisingly large probability, (i.e., 10% of collisions).

This reactive complex collision mechanism is generally applicable to all atom-molecule collision systems in which chemical bonding can occur during the encounter. A few prior studies suggest the possibility of unconventional T-V ET mechanisms.[15−19] Wight and Leone first pointed out the importance of transient HNO and HCO species in their T-V ET studies of hot H atoms with NO or CO.[17] While an impulsive-force based model with exponential probability function could qualitatively fit their resulting CO vibrational energy distribution, it could not predict the NO distribution. Further studies on the H + CO system also suggest the role of

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CEFCO's lower energy penalty CO2 capture system

CO2 hydrate as a possibility for CO2 storage

Why is shockwave “ultra low-cost”?

CAPEX:

- Shocktube systems are simple and compact
- Common materials with no pressure buildup or heat input
- Modular configuration with add-on components
- Skid is the size of a pickup truck

Shockwave system is so easy and convenient, it captures CO_2 and produces product with no special equipment!

OPEX:

- 100psi compressed air or stack gas at 3.5#/min for shock nozzle
- Shockwave needs to be 10% of the mass of the stack gas to react the entire stack gas
- 110v liquid chemical pump
- Each shocktube uses $5/hr of total electricity
- No internal moving parts, minimal caking, little downtime

What carbon products does the system make?

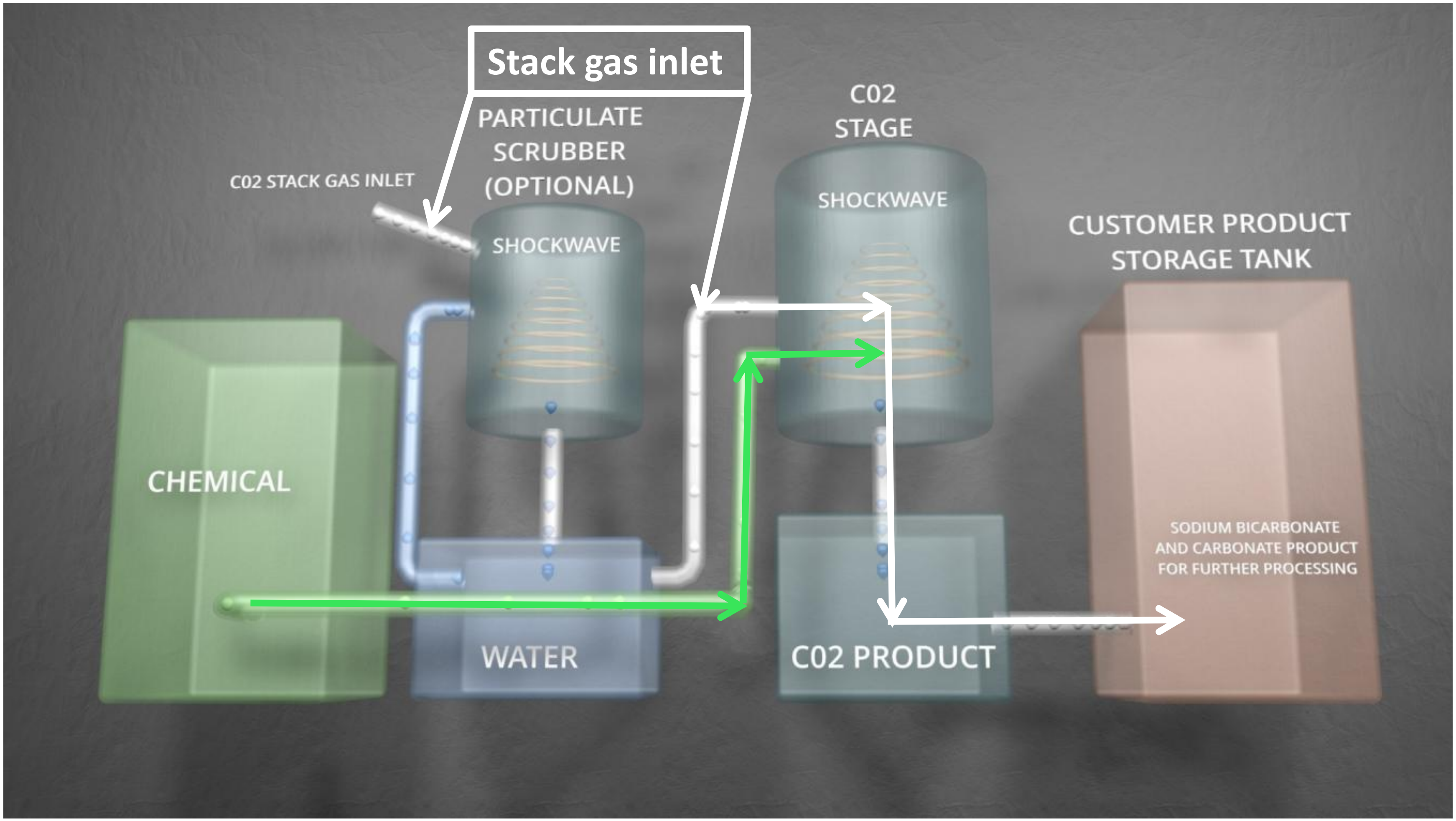
If using sodium hydroxide, then sodium carbonate and/or bicarbonate is produced

If using sodium carbonate, then sodium bicarbonate is produced

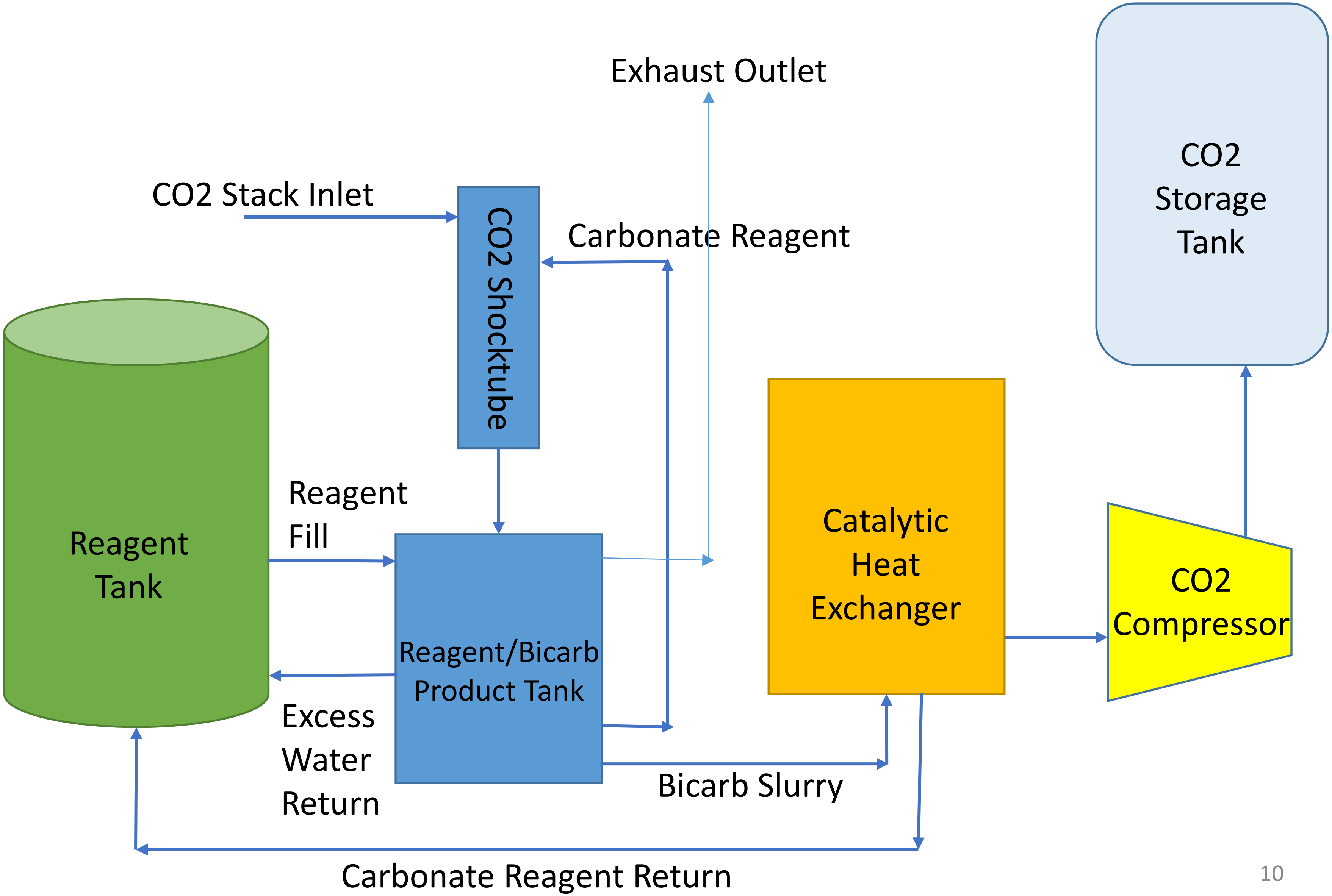
If using other chemicals (i.e. K, Mg, Ca, amine, etc.), then K_2CO_3, $KHCO_3$, $MgCO_3$, $Mg(HCO_3)_2$, etc. is produced under correct conditions

If heating bicarbonate, then 99.9% CO_2 is produced for process application

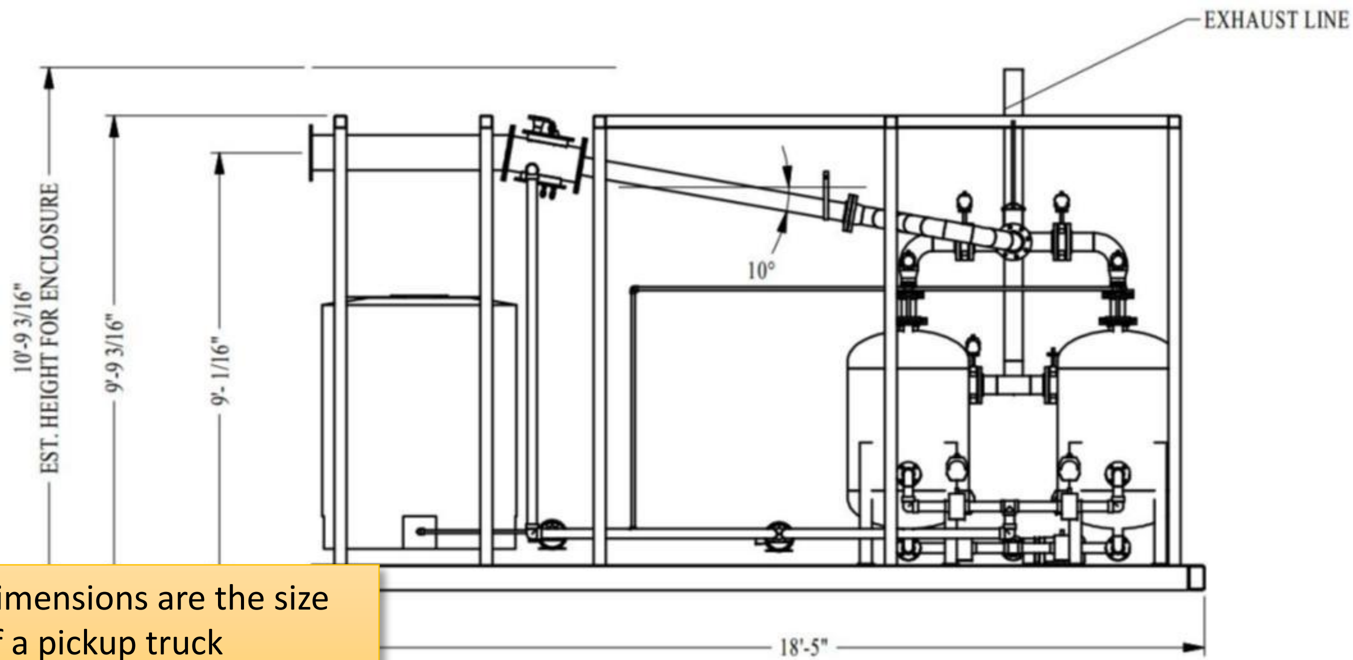
Process Flow for Bicarb



Process Flow for Sustainable CO2



Base Model System



Dimensions are the size of a pickup truck

- 1x proprietary CO2 processing shocktube
- 2x custom alternating production tanks
- 450 gallon onboard reagent holding tank
- Pumps, meters, gauges, and gas analyzers
- External connections for “plug ‘n play”
- Self cleaning cycle
- Climate controlled enclosure
- Programmed logic controls, basic automation, online data monitoring

Add-on Configurations

Available Now

- Second onboard CO_2 shocktube – doubles output volume
- Particulate scrubber – removes 99.9% PM material

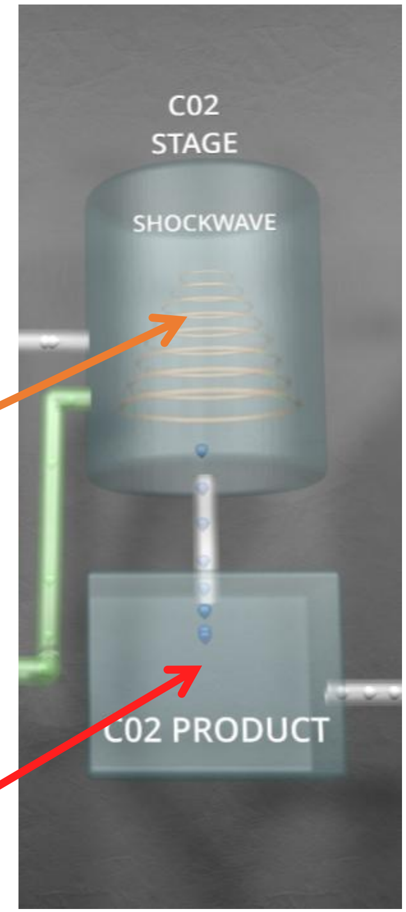
In Development

- Stack gas compressor – radically increases efficiency instead of using compressed air
- CO_2 release heat exchanger – produces pure CO_2 from bicarbonate for process applications
- CO_2 release catalyst – accelerates desorption of CO_2 from bicarbonate, halving the heat requirement to produce concentrated CO_2
- CO_2 compressor – liquefies CO_2 for process applications

Bicarbonate cyclone and rotary dryer


CO_2 compressor

Stack Gas Compressor Upgrade



Tertiary Mixer - Stack gas atomizes chemicals in two-fluid reagent nozzle, forcing contact and reaction

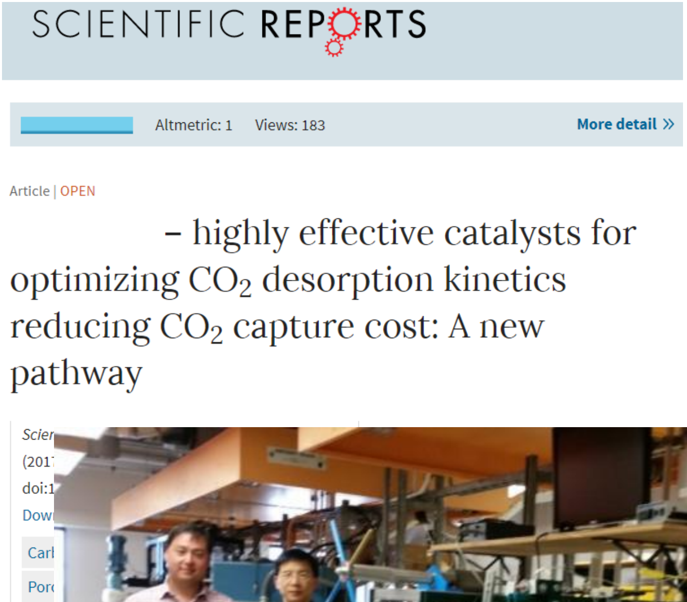
Primary Mixer - Stack gas becomes the compressed shockwave fluid, eliminating CO2 dilution using compressed air

Secondary Mixer - More reaction, contact and retention time in controlled gas diffusion

3 forced reaction points and 2 mixers for 1 energy input = very high efficiency

Catalyst Upgrade

- Working with a highly recognized research team with a proven catalyst that accelerates desorption of CO2
- Catalyst is highly stable and has infinite reusability
- Can improve the release of CO2 from bicarbonate up to 2,500% at only 150°F with no moisture buildup
  - With a heat exchanger, this catalyst produces concentrated CO2 from bicarbonate at negligible cost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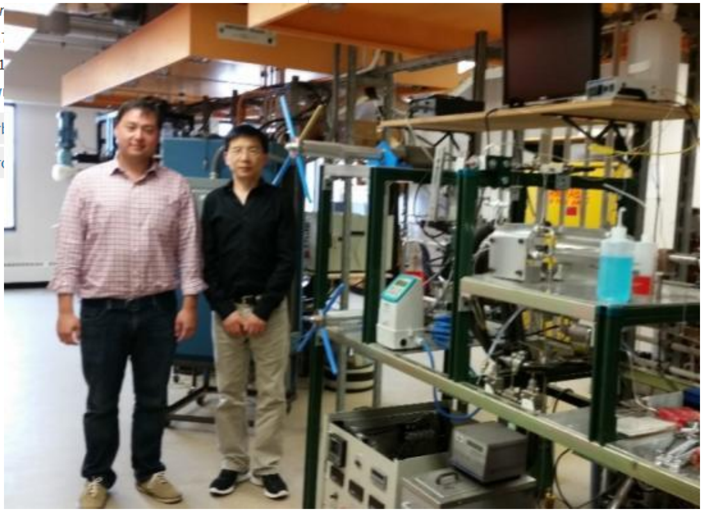
– highly effective catalysts for optimizing CO_2 desorption kinetics reducing CO_2 capture cost: A new pathway



Brian Tang standing next to catalyst inventor at his research lab

Potassium Reagent Substitution

- Using potassium carbonate will drastically improve CO_2 capture efficiency, enabling stricter CO_2 scrubbing applications
  - Better solubility
  - Better absorption and reaction rates
  - Higher heat tolerance

- Able to capture and produce more and cheaper CO_2 at scale, especially when paired with catalyst
- Ideal applications include the production of CO_2 from pre-combustion H_2 and natural gas scrubbing

Economics and Efficiency Using Sodium

Each shocktube produces 3 to 5 tons/day (or more) of product depending on:

- Flow rate and (assisted) pressure of stack gas
- Chemical concentration of reagent liquid
- Richness of CO_2 in stack gas stream

- Targeting 70% CO_2 capture efficiency
- Projected bicarbonate production cost ≈$24 - $40/ton
- Projected 99.9% CO_2 production using catalyst and heat exchanger ≈$48-80/ton
- Each shocktube only requires $5/hr of electricity

Potential to increase production to 5 – 10 tons/day ($12-24/ton) of bicarbonate with mechanical improvements and add-ons. CO_2 production would then be $24-48/ton.

Proposed Cost Structure to Customers

Base model

- $150,000 upfront payment
- 3 year lease at $3,000/month
- 5 year lease at $2,500/month

Add-ons

- Second CO_2 shocktube with tanks for $50,000 + $1,500/month
- PM scrubber for $35,000 + $1,000/month

Optional Maintenance

- $2,000/month maintenance plan for 24/7 call support and 1 service visit per month

Over 20 customers have already said, "YES, they will buy if we can supply CO_2." In fact, no customer has ever said "NO," even if our cost to produce CO_2 is similar or slightly higher than their current purchase price.

Price and terms are flexible for the right customer and partner to help develop our system to maximize bicarbonate/CO_2 production.

Scalability

Shockwave technology on 35MW coal-fired boiler in China

1MWe system in Dallas, TX

Highly Motivated CO2 Customers

Food (making, preservation, preparation) ≈$500M in U.S.

Refrigerated Transportation
>$20B in U.S.

Greenhouse Agriculture
<$20M in U.S.

Industrial Refrigeration
<$10M in U.S.

Enhanced Oil Recovery >$40B in U.S.

CO2 Blast Cleaning
<$10M in U.S.

Technology Summary

- We are NOT the highest performance, high cost system capturing CO2 from large-scale sources trying to meet emission regulations

- We ARE the lowest cost, good performance, most affordable and practical system in compact, portable footprint for commercial and industrial customers

- We CAN improve performance and product yield through add-ons, using multiple systems, and further development

- If you use CO2 and want to recycle your CO2 to save money, you should want to try us out.

Ideal Customer *and* Partner Characteristics

Initial Customer

- Has appetite for adopting new technology
- Wants and monetizes carbonate or bicarbonate product
- Has insight and expertise in producing and processing bicarbonate

Partner

- Understands bicarbonate as an intermediate to produce CO2
- Can help develop efficient bicarbonate refining and CO2 release processes
- Sees the vision and potential market for a low-cost portable CO2 production system

Contact Info

Live system demo available starting summer 2017. For more info, please call or email.

SHOCKWAVECO2

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