ICAES INNOVATION: FOAM-BASED HEAT EXCHANGE

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The Heat-Exchange Problem

Compressed-air energy storage (CAES), which entails pressure changes from 1 atmosphere up to more than 200 atmospheres and back, offers great promise for integrating renewable energy and stabilizing modern electric grids. However, CAES can produce extremes of air temperature that demand costly special handling and additional energy, because gas being compressed heats up, while expanding gas cools down. In addition, stored hot gas loses heat to its environment, reducing round-trip storage efficiency, unless it is thoroughly insulated to prevent such loss, which raises the cost of storage. The key barrier to realizing the potential of CAES is the need to limit these temperature extremes.

The most effective way to limit these extremes is by using an isothermal (constant-temperature) gas compression and expansion process. Isothermal compression is thermodynamically ideal—that is, requires the least possible work—and by definition avoids temperature extremes. An isothermal expansion process is also ideal, recovering the most possible work from the compressed air. However, isothermal compression or expansion requires continuous heat exchange between the gas and some other substance to remove heat as the gas is compressed, or to add heat as it is expanded.

Although perfectly isothermal compression or expansion is not practical, a gas can be expanded or compressed near-isothermally if heat exchange occurs quickly enough relative to density change. Faster heat exchange is also better because it enables an isothermal compressor/expander system of a given size to process more gas in a given time.

SustainX has developed an isothermal CAES process that achieves near isothermal compression and expansion, thereby enabling effective large-scale storage of electrical energy. See Fig. 1 for a summary of SustainX's approach to isothermal gas processing compared to standard (adiabatic) processing.

Approaches

The rate of heat exchange between a gas and a liquid is proportional to the area of contact between the two phases: the greater the contact area, the faster the heat flow. Achieving rapid heat exchange between a gas and a liquid therefore means, in practice, maintaining a large contact area (relative to mass) between the two.

There are three basic approaches to increasing two-phase contact area while a gas is being expanded or compressed: bubbling, spraying, and foaming (see Fig. 2). Bubbling is impractical, as it would require devoting too much system volume to liquid and so

Adiabatic air-only	SustainX air-liquid mix
Compression ratio	
4:1 per stage	12:1 per stage
Number of stages for 1 to 200 atm compression	
5 stages	2 stages
Inlet-to-outlet temperature difference for a stage	
~150 C	~20 C
Work of compression compared to ideal isothermal	
~1.50	~1.05

***Fig. 1**. Comparison of air-only, adiabatic (varying-temperature) air compression to SustainX's two-phase, approximately isothermal (constant-temperature) compression process.*

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Liquid Spray	Aqueous Foam	Air Bubbles
Typical useful mixture (parts air to parts water by volume)		
> 20:1	1.5:1 to 50:1	<1.5:1
Stability for port injection		
Poor	excellent	Good
Energy for generation		
moderate	low	Low
Liquid surface area		
sphere	shell	Sphere

Fig. 2. *Comparison of three methods for creating large contact area between a liquid and a gas: spraying, foaming, and bubbling.*

reduce system energy density. Spraying works well for direct liquid injection into a compression/ expansion chamber at low air pressures with low water-to-air volume ratios. Foaming allows port injection (i.e., generation of foam outside a compression/expansion cylinder, followed by injection into the cylinder through a port); requires less energy than spraying for a given gas-liquid contact area; and works well at all air pressures over a large range of water-to-air volume ratios. SustainX has performed extensive simulation and test stand research on both spraying and foaming.

Limitations of Sprayed Droplets

Spraying entails forcing a liquid through an orifice or atomizer to produce a large number of droplets. The droplets then pass through a volume of gas (e.g., as projectiles or drizzle). The gas and the liquid, if at different temperatures, approach thermal equilibrium by exchanging heat while they are in contact.

SustainX's first demonstrations of isothermal compression and expansion used spraying at all air pressures. However, sprays have certain drawbacks, especially at elevated air pressures. Surface tension tends to make spray formation energetically expensive, and although in theory any energy added to the two-phase (liquid-gas) mixture may be recoverable, in practice most energy expended on droplet formation is lost. Also, droplets can dwell only temporarily in a volume of non-turbulent gas: when they strike a sidewall or rain to the bottom of the chamber, two-phase surface area decreases and heat exchange slows.

Foam Advantages

Foams, by comparison, have several advantages. First, aqueous foams can be generated reliably and with less energy compared to droplets. Second, it is possible to engineer foams that are long-lived relative to heat-exchange cycle time (e.g., less than a second), yet short-lived relative to storage time (e.g. minutes to hours). Third, two-phase contact area for a given liquid mass can be made larger for a foam at low energy cost, whereas for spraying, contact area can in general only be increased by decreasing droplet size and increasing droplet number, which is energetically expensive. Fourth, a spray cannot be readily carried in a flow of gas and so must be injected directly into the gas as it is expanded or compressed in a cylinder. Foam, which can retain its integrity while flowing, can be generated outside a cylinder and admitted during a filling stroke – a procedure SustainX terms "port

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injection." With port injection, foam generation and conditioning mechanisms can be separated from the cylinder, easing design constraints.

SustainX has taken foam heat-exchange from theory into extensive practice, first in experiments and now in a megawatt-scale compressor/expander. Fig. 3 below shows how isothermal expansion is closely approximated in an actual cylinder.

In summary, foams are easy to generate, give large two-phase contact area relative to liquid mass and therefore facilitate rapid heat exchange, can be as stable or short-lived as desired, and can be generated and conditioned in separate mechanisms and then injected into cylinders for compression or expansion. In addition, foam allows more efficient heat exchange with less energy overhead than spray.

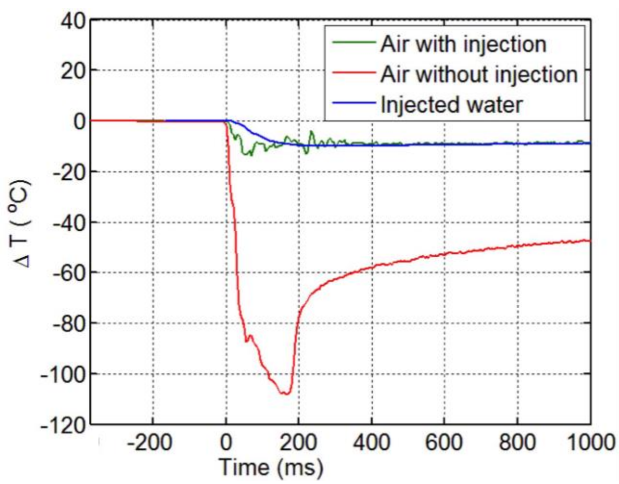

***Fig. 3**. Comparison of non-isothermal air expansion to isothermal air expansion with foam. Air temperature is shown without heat exchange (red) and with foam (green): quarter-second piston stroke (0–250 ms), pressure change from ~200 atmospheres to ~20 atmospheres. Liquid temperature (blue) decreases slightly as heat is transferred to air: liquid and air quickly achieve thermal equilibrium (approach same temperature). Without foam, maximum temperature drop is 108 K; with foam, only 12 K.*

Foam Engineering

Foam-generation mechanisms tend to be bulkier than spray-generation mechanisms (which may consist simply of compact nozzles). Also, sprays allow spontaneous separation of gas and liquid as the droplets rain out, whereas to separate foam one must either wait until the foam breaks down of its own accord or subject it to a breakdown process (e.g., whisking). Finally, the transfer of foams into cylinders is limited under some conditions by shear forces generated during passage through valves and the like.

With port injection, foam-generator bulk is not a problem. Nor is liquid-gas separation, since foams need be long-lived only relative to a piston stroke, and breakdown processes are neither complex nor energy-intensive. Through careful design, including patented large-area valves, SustainX manages shear and foam breakdown issues in a robust, efficient way.

Other areas of SustainX innovation in foam generation include the use of large-orifice nozzles (reducing energy usage and maintenance requirements) and robust multi-layer screens that generate foam of the right texture and expansion ratio over a large operating range, assuring foam integrity at pressure and during flow.

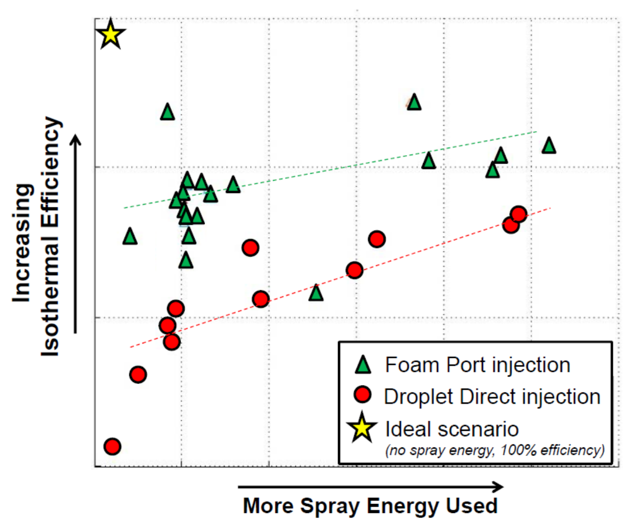

***Fig. 4.** Data on spray and foam heat transfer from air expansions at the same power levels in a SustainX heat-transfer test stand. Foam generated before expansion ("foam port injection"—green triangles) achieves substantially higher efficiency at lower spray-energy (work) input levels than direct spray injection of droplets (red circles).*

Foam in SustainX Technology

Water's properties make it a highly suitable heat-exchange liquid: it is nontoxic and low-cost, has extraordinarily high heat capacity (joules of heat needed to heat or cool a kilogram by one kelvin), and is almost incompressible, i.e., can coexist with a gas that is undergoing pressure changes without itself changing in volume. Additives are widely available

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that can promote foaming and provide additional benefits, such as controlling corrosion, bacterial growth, and other aspects of a water-based heat-exchange liquid.

SustainX has therefore opted for *aqueous foam-based heat exchange* in its isothermal compressed-air system (ICAES™) technology. Our extensive test setups have given us a uniquely thorough, data-driven grasp of foam mechanics in compressed-air energy storage. Several patents protect SustainX's leading position in the application of water-based heat transfer for integral heat exchange in isothermal compressed-air energy storage systems.

SustainX's patented two-phase heat-transfer processes enable near-isothermal gas expansion and compression between 1 atmosphere and 200 atmospheres with only two stages and at scales and speeds appropriate for large-engine reciprocating machinery. Rapid heat exchange between liquid and air has allowed development of a megawatt-scale compressor/expander with >95% isothermal efficiency over a large operating range and at large-engine stroke speed, keeping the temperature change of the liquid-air mixture to under 50ºC across the full operating range of the system.

With the advantages conferred by its core isothermal technology, the SustainX ICAES has the potential to revolutionize utility-scale bulk energy storage.

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