The Latest Buzz on Gas Separation

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Researchers have found a way to separate gas mixtures using acoustic waves.

Greg Swift and his colleagues at Los Alamos National Laboratory (LANL, Los Alamos, NM) are separating gas mixtures with a device that generates some serious sound waves, but the neighbors aren't complaining (Figure 1). In fact, "you can't really hear it over the other noises in the lab," says Swift, because most of the sound is inside the device.

In 1998, postdoc Phil Spoor was working on heat engines powered by sound waves. His supervisor, Swift, has been working on this concept since he joined the LANL staff in 1981 (see box, "Sounds Like a Refrigerator") (*1*). Spoor had coupled two of these thermoacoustic engines to see if the phases of the sound waves in the two engines would synchronize, or "mode lock". He had been using pure helium as an acoustic conductor, but in an attempt to change the mass ratio of gas to structural elements, he mixed in some xenon, a much heavier gas. The results met his predictions, except for a "small anomaly" on the order of about 1%. Swift wrote this off as experimental uncertainty, but Spoor kept digging. He discovered that the sound waves were actually separating the two gases.

Separating Gases with Sound

Here's how it works. Two reservoirs, both containing the same two-gas mixture, are connected by a metal tube. Oscillating pistons produce waves, or density fluctuations, in the gas mixture in the tube (*2*). The resulting sound wave is a "pure tone" (it has only one frequency), and the wavelength is much larger than the diameter of the tube. The sound wave produces a periodic fluctuation of the gas pressure within the tube and sinusoidal motion of the gas along the length of the tube (Figure 2). Swift explains that the sound wave leads the two gases through a "four-step dance". During the first step, a pressure maximum, thermal diffusion drives the heavier gas toward the tube wall, where it adheres to the viscous boundary layer of gases at the surface of the tube. At the same time, the lighter gas diffuses away from the wall. During the next quarter-cycle (the second step), as the pressure decreases, the gas mixture moves toward the first reservoir. In the center of the tube, the gas that is enriched in the lighter component moves faster than the gas in the viscous boundary layer, which is enriched with the heavier component. This behavior is reversed during the second half of the cycle, when the heavier gas migrates out of the boundary layer as the pressure reaches a minimum (the third step). The gas that is enriched in the heavier component is carried toward the second reservoir as the pressure begins to increase again (the fourth step). Over several wave cycles, each reservoir becomes increasingly enriched in one component of the mixture.

FIGURE 1: Drew Geller adjusts a speaker on a thermoacoustic separator for neon isotopes. Three of six speakers are shown, connected by the gas-separating tube.

PHOTO: JOHN FLOWER, LANL

In real-life terms, this translates into an off-the-shelf 200-Hz frequency generator connected to an amplifier and two or more speakers of the type you would buy from the neighborhood electronics store (Figure 1). The speakers push and pull on pistons (small, rigid metal plates that move the bellows to which they are attached), which vibrate to produce pressure fluctuations in the gas. The separation tube is approximately 1 m long and a few mm in diam.

Spoor observed the gas separation effect in his 1998 device because of the large mass difference between helium and xenon. Swift and postdoc Drew Geller switched to mixtures of helium and argon for subsequent studies because argon is cheaper and has a more accurately known thermal diffusion coefficient than xenon. After a 50–50 mixture of helium and argon had been in their apparatus for only a few min, they observed a difference of about 1% between the mole fractions of helium and argon in the two reservoirs. Recently, they achieved a 9% separation under optimum conditions (*3*). The highest flux recorded reached 6.2×10^{-8} mol/s (about 100 mm^3/min of each gas flowing to each reservoir), consuming a calculated 10 mW of acoustic power.

Now that the basic physical principles are understood (*4*), they can be applied to other gas mixtures with more subtle differences in properties. Swift's group envisions scaling up their apparatus, using technology that has already been developed for large thermoacoustic engines and refrigerators, to a possible 100-W device using a 10-cm-diam tube and achieving separation fluxes on the order of 1 mole/h.

A Buzz Ready To Boom

Compared to the large-scale distillation processes used in the petroleum industry, thermoacoustic separation is too inefficient to be economical. However, it could be competitive in niche markets (e.g., medical imaging or radiation therapy) where distillation is inefficient, or when gases must be separated shortly before each use. Thermoacoustic separation provides the greatest advantage in applications where simple, reliable equipment takes precedence over energy efficiency.

At present, Geller is pursuing this method to separate tritium from other hydrogen isotopes to support the nuclear

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weapons research program at LANL. The distillation process currently used leaves a significant amount of tritium behind in the distillation apparatus, and thermoacoustic separation may offer some advantages here. Another recently built prototype for separating ^{20}Ne and ^{22}Ne (shown in Figure 1) is operating at close to theoretical predictions. The manufacturers of helium–neon lasers might take an interest in this application, because they use various mixtures of neon isotopes to fine-tune laser gain and coherence length.

Thermoacoustic separation might also be used for isotopes of gases such as oxygen, carbon, or nitrogen that are used in medical imaging, tumor detection, and radiation therapy. There are only a few isotope separation facilities in the United States, and the equipment is massive and expensive. Last year, LANL reactivated its mothballed ICON (isotopes of carbon, nitrogen, and oxygen) separation facility and leased it to Spectra Gases (Branchburg, NJ). The demand from the nuclear medicine and biomedical research communities had exceeded supplies to the extent that the National Institutes of Health had begun deferring or canceling research projects that required these isotopes (*5*). The ICON facility uses a cryogenic distillation apparatus that occupies "a 500-foot hole in the ground," says Swift. Thermoacoustic devices are potentially cheaper and simpler to use, bringing up the possibility of a much more plentiful supply of pure isotopes, with generating facilities close to the laboratories where they are to be used. This in turn would provide a boon to newer applications, such as the use of isotopically labeled growth media for use in biomolecular NMR research (*www.isotec.com/isogro.pdf*).

Some problems, such as second-order acoustic streaming that tends to remix the gases, still need to be fully understood and addressed. Parallel arrays of ducts may be necessary for large-scale separations. "We haven't made any big breakthroughs in the last several months, but the neon separator has been getting better and better as Drew [Geller] works the bugs out of it," says Swift. "It's behaving like it ought to now, and it's our first demonstration of a setup that can be extended to arbitrarily high purities." Business may not be booming quite yet, but the development work appears to be humming along. The high reliability, absence of moving parts, and low capital cost of acoustic separation devices may one day make them viable competitors in the small-scale gas separations market.

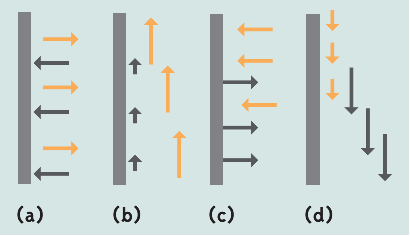

FIGURE 2: Low-frequency acoustic waves drive gases in opposite directions along the length of a tube connecting two gas reservoirs. The four-step process is shown schematically for a region near the inner wall of the tube. At the pressure maximum (a), the heavier gas (dark arrows) diffuses toward the viscous boundary layer near the tube wall. As the pressure decreases (b), the acoustic wave preferentially sweeps the lighter gas (light arrows) toward the first reservoir. The heavier gas is released from the tube walls at the pressure minimum (c), and is swept along the tube toward the second reservoir as the pressure increases again (d).

Sounds Like a Refrigerator

The Los Alamos National Laboratory (LANL) thermoacoustic separation project grew out of an existing effort to develop a heat-driven cryogenic refrigerator with no moving parts. Greg Swift and then-postdoc Scott Backhaus were working on a thermoacoustic refrigerator in collaboration with Cryenco, Inc. (Denver). (Backhaus joined the LANL staff this year.) They intended to develop on-site refrigeration as an economical means of liquefying natural gas (*6*).

The refrigerator, in turn, was an adaptation of the thermoacoustic Stirling heat engine, a resonating chamber in which helium converts heat energy into acoustic power (*7, 8*). The helium absorbs heat from an external source in the high-pressure phase of the cycle, then deposits it into a heat sink during the low-pressure phase. The fluctuating pressure and density create an acoustic wave, which is reinforced by subsequent cycles. To convert the heat engine to a refrigerator, the process is reversed, and the energy source is the sound wave itself. The sound creates regions of high and low pressure in the gas. "Packets" of heat surf on the sound wave, using periods of high and low gas pressure to travel between heat exchangers.

Praxair (Danbury, CT) announced this year that it has received an Advanced Technology Program grant from the U.S. Department of Commerce to design, build, and test the first megawatt thermoacoustic Stirling heat engine, in collaboration with the LANL group (Praxair news release, June 12, 2002). They intend to develop this technology for use in refrigeration units to liquefy natural gas fuel for heavy fleet vehicles. About two years ago, Phil Spoor joined CFIC, Inc. (*www.cficinc.com*, Troy, NY), a small entrepreneurial company that makes thermoacoustic devices. Last year, CFIC formed a strategic alliance with Praxair to broaden the market for its cryogenic and gas compression technologies.

Existing thermoacoustic devices have been used to cool the electronics in radar systems aboard a U.S. Navy destroyer and to liquefy natural gas at a rate of 140 gallons per day (*7*). CFIC also envisions home cogeneration units, where thermoacoustic energy is used to produce both electricity and heat.

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