TECH BEAT

Dr. Neil Canter / Contributing Editor

Gas-expanded lubricants

A liquid carbon dioxide enables end-users to adapt these materials to different real-world operating conditions.

KEY CONCEPTS

- Gas-expanded liquids are mixtures of a gas such as carbon dioxide and a solvent under elevated pressures.
- One major benefit for potentially using gas-expanded liquids in lubricants is the ability of the end-user to adjust the properties of the mixture to meet changes in operating conditions.
- Initial work with 15% carbon dioxide in polyalkylene glycols in a modeling study has shown a reduction of 20% in power loss in a journal bearing.

Gas-expanded liquids have been widely studied in the chemical sector for a variety of applications since the 1990s. According to Andres Clarens, assistant professor of civil and environmental engineering at the University of Virginia in Charlottesville, Va., "These liquids are often a mixture of a gas such as carbon dioxide and a solvent under elevated pressures. By controlling the pressure and the temperature of the mixture, it is possible to carefully specify the properties of the fluid, which has important implications in a lot of applications where tunability is desired."

These mixtures make for easy separation of carbon dioxide from a solvent. Clarens indicates that one other benefit is that these mixtures reduce the total amount of solvent required for a specific operation. He says, "Adding carbon dioxide reduces the amount of solvent required for a specific application, and this lowers the cost and reduces the environmental footprint."

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But Clarens indicates that these mixtures have only taken off in the pharmaceuticals sector and other high-value applications such as nanoparticle formations and in the recycling of homogeneous catalysts. Part of the reason is that high-pressure equipment is needed that can withstand pressure of a few megapascals.

Lubrication is an area that may be receptive to this approach. In a previous TLT article, a new metalworking fluids technique known as Advanced Minimum Quantity Lubrication (AMQL) was described.[1] Solid carbon dioxide particles are combined with a metalworking fluid and then this mixture is treated with a propellant such as carbon dioxide gas. The mixture is delivered at speeds greater than 200 meters per second to combine lubricity with very efficient cooling.

Clarens has initiated a project to extrapolate the gas-expanded liquid concept to lubricants. He says, "One of the reasons for my interest is that I conducted research in graduate school on the use of supercritical carbon dioxide in metalworking fluids."

Initial work shows that gas-expanded lubricants demonstrate great promise as shown below.

JOURNAL BEARING MODELING STUDY

Clarens envisions that introduction of liquid carbon dioxide into a lubricant will provide the end-user with the ability to adjust the mixture's properties to meet changes in operating conditions. He adds, "Most conventional lubricants are de-

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veloped to meet specific applications, but their properties cannot be altered if changes occur in the operation unless the lubricant is removed. Use of liquid carbon dioxide will enable the end-user to change physical properties such as viscosity to adapt the lubricant to different real-world operating conditions.”

An initial system evaluated by Clarens involves the use of carbon dioxide in polyalkylene glycols (PAGs). He says, “We picked this lubricant because of past work done using PAG-based lubricants in refrigeration applications. Slight changes in the carbon dioxide content can lead to huge changes in the viscosity of the gas-expanded lubricant.”

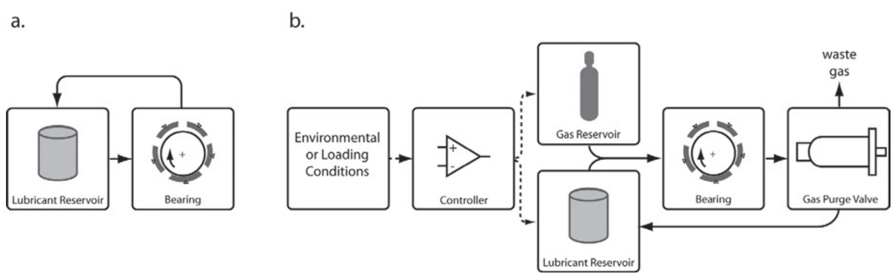

Figure 1 | **The contrast between using a conventional lubricant in a bearing system (a.) and a gas-expanded lubrication system (b.) is shown. A gas reservoir and a purge valve are used to adjust the gas concentration in the lubricant.** *(Courtesy of the University of Virginia)*

A gas-expanded lubricant has the appearance of a homogeneous liquid with the carbon dioxide dissolved in the mixture. Carbon dioxide exhibits a viscosity slightly lower than water. This means that addition of even 1% to 2% carbon dioxide can rapidly reduce the viscosity of the mixture. One of the main advantages of using liquid carbon dioxide under slight pressure is that, if the viscosity of the lubricant must be increased, the pressure can be reduced and the carbon dioxide will separate out as a gas, restoring the properties of the original base lubricant.

Clarens found this effect with PAGs of varying viscosities. The value of using carbon dioxide is especially apparent if the viscosity of a specific lubricant needs to be reduced by adding a higher level of the liquid.

A better understanding of the impact that carbon dioxide has on the performance of a PAG lubricant was obtained through a modeling study on a journal bearing operation. This modeling approach was conducted on an ISO 32 PAG fluid that is treated with 5% and 15% carbon dioxide. The results are compared to a petroleum oil-based ISO 32 fluid and to the untreated PAG lubricant.

The key parameter measured is power loss. Addition of 15% carbon dioxide into the PAG lubricant led to the largest reduction in power loss for bearings operated between 3,000 and 14,000 rpm. Overall, Clarens reports that the modeling study indicates that a 20% reduction in power loss is achievable using gas-expanded lubricants.

The differences between using a conventional lubricant and a gas-expanded lubricant are shown in Figure 1 for the bearing system. Additional elements needed for using a gas-expanded lubricant are a gas reservoir and a purge valve, which is used to adjust gas concentration in the lubricant. Gas can be added or purged depending upon the demands placed on the lubricant by the bearing system.

Clarens finds that other synthetic basestocks such as polyalphaolefins and polyol esters can be used to prepare gas-expanded lubricants with carbon dioxide. But petroleum oil has proven to be more of a challenge. He says, “Petroleum oil is a mixture containing high and low molecular weight molecules. Carbon dioxide is not compatible with all of these components, and some separation is seen.

Clarens believes that a lubricant needs to be as aliphatic and as homogeneous as possible to be compatible with carbon dioxide. Additives used in lubricant formulations will also have to be evaluated.

With the entrainment of a gas in the lubricant, foam might be anticipated to be a concern. Clarens comments, “We do not believe foam will be a problem, as we have sheared gas-expanded lubricants in studies we have done at high rates. But accelerated oxidation of the lubricant could be an issue.”

Future work will involve the preparation of a rotor-test bed in which fluid film bearings are floated in the gas-expanded lubricant to go beyond the results of the modeling study and do some actual testing.

Information on the initial work done by Clarens can be found in an upcoming presentation that has been submitted for publication.[2] Clarens can also be contacted at **aclarens@virginia.edu**.

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Switchable adhesion: Ability to walk on walls

Researchers develop a device that can create reversible adhesion using electronic control.

KEY CONCEPTS

- A switchable, electronically controlled capillary adhesion device has been developed that mimics the muscular action of a leaf beetle.
- Liquid bridgelets are formed by using an electric field to pump water droplets through an orifice in the SECAD to contact a solid substrate.
- On reversal of the electric field, the bridgelets break contact with the substrate while the liquid is pumped back through the orifice.

Surface adhesion is a necessary element in lubrication as there is need for a specific component, whether a fluid or grease, to adsorb onto a surface in order to minimize friction and wear. One goal of researchers has been to develop a reversible adhesive that can adhere to a surface for a finite time frame and then release. This process would be followed by establishing the adhesion on a different surface at a later time.

Inspiration for reversible adhesion comes from our imagination and from Mother Nature. Many of us know about the comic book hero, Spiderman, who can literally walk on walls and climb up buildings.

Animals have been found that produce adhesives, which develop high levels of adhesion with surfaces. In a previous TLT article, an adhesive gel developed by the slug, *Arion subfuscus* is described.[1] This slug secretes an adhesive, which is a combination of carbohydrates and proteins that exhibits a shear strength of 100 kilopascals. The adhesive is also highly effective in water.

In seeking to develop a switchable adhesive device, Paul Steen, professor of chemical and biomolecular engineering at Cornell University in Ithaca, N.Y., took inspiration from a leaf beetle native to the state of Florida studied by his Cornell colleague, Tom Eisner. Steen says, "The beetle develops adhesive forces that can resist loads that exceed 100 times its body weight. But the beetle also has the unique ability to switch off this bond, move in a relatively quick fashion (less than one second) and adhere at another spot on the leaf."

The key to the beetle's switchable adhesion behavior is that it can make contact with the leaf surface through the use of approximately 10^5 feet. Steen says, "The beetle has the ability to use the force generated by surface tension of liquid situated between its feet and the leaf. This force is amplified by the large number of contacts between the beetle and the leaf."

The surface tension generated is analogous to the force produced when a liquid droplet holds two glass slides together. Steen realizes that preparing a switchable adhesive device, which utilizes muscular action to mimic the beetle, is quite challenging.

But development of a device that can create reversible adhesion using electronic control is doable. Such an approach has now been realized.

SECAD

Steen and his research group have developed a device that combines the surface tension force exhibited by the beetle with electronic control that enables the adhesion to be reversible. This device is known as the switchable electronically controlled capillary adhesion device or SECAD and contains two plates that sandwich a middle layer.

The surface tension is established by the droplet between the SECAD and the substrate. One contact by itself does not produce much adhesion, but Steen has built a SECAD made from silicon that contains a top plate with nearly 5,000 holes

‘We built the SECAD so that the droplets do not overlap, and the size of the pores in the glass frit middle layer is an order of magnitude smaller than the holes to resist back flow and thereby to minimize liquid rearrangement and coalescence.’

each with a diameter of 150 microns. The SECAD has a bottom plate below the holes that contains a water reservoir. In-between the plates a porous, glass frit middle layer acts as an electroosmotic (EO) pump.

The SECAD is approximately 1 millimeter thick and can be made from common materials such as glass, silicon, plastic and epoxy. It contains no moving solid parts.

Steen says, “We combined the utilization of surface tension force with electronic flow through the use of an EO pump to develop the SECAD. The pump moves water droplets at sizes down to 10 microns up through an orifice to contact a solid substrate, thereby forming liquid bridgelets. Pumping is done by the electric field. On reversal of the electric field, the bridgelets break contact with the substrates as liquid is pumped back through the orifice array, eliminating the adhesive effect.”

Figure 2 | **Substrates can be reversibly attached to the SECAD, as shown with the placement of 73 paper clips weighing just over 32 grams in just over seven minutes. Adhesion is maintained until a release voltage is applied.** *(Courtesy of Cornell University)*

Experiments were conducted to show the ability of the SECAD to attach to substrates and also to place substrates on the SECAD. An example shown in Figure 2 is the placement of 73 paper clips weighing just over 32 grams on the SECAD for just over seven minutes. Adhesion is maintained until a release voltage is applied.

One of the challenges faced by the researchers is making sure that the individual water droplets do not coalesce. Steen says, “This system would like to minimize free energy by making water droplets coalesce. We built the SECAD so that the droplets do not overlap, and the size of the pores in the glass frit middle layer is an order of magnitude smaller than the holes to resist back flow and thereby to minimize liquid rearrangement and coalescence.”

Two elements were designed into the SECAD to reduce the possibility of coalescence. Steen says, “We fabricated the geometry so that a lip is present around the hole to retard adjacent drops from combining. The second step is the laying down of a superhydrophobic, non-wetting coating to waterproof the environment outside of the contact line.”

Steen believes that coalescence will eventually occur, but it will take many days for the water droplets to combine. Evaporation can also be an issue in using water. The leaf beetle has overcome this issue by utilizing a long-chain hydrocarbon as the liquid instead of water.

Using smaller holes also makes for faster switching of the SECAD from the attached to the detached states. Steen says, “In the paper clip example (*see Figure 2*), switching between the states was achieved in a fraction of a second.”

A nine-volt battery can be used to generate the electric field necessary for the attach and detach steps. Steen estimates that this battery can power approximately one million, half-second cycles.

Future work will be devoted to improving the adhesive force that can be generated by the SECAD. Steen indicates that the magnitude of the adhesion can be increased through the reduction of the droplet size, as this parameter is inversely proportional to pressure. He says, “Our objective is to develop adhesion that is comparable to atmospheric pressure. We believe that hole sizes less than 0.1 micron should enable us to develop pressures greater than 1 atmosphere, which could lead to the development of switchable adhesives with strengths comparable to epoxies.”

Steen envisions that the SECAD could be used as a controllable friction device when two surfaces are moving next to each other. Additional information can be found in a recent publication[2] or by contacting Steen at **phs7@cornell.edu**.

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Neil Canter heads his own consulting company, Chemical Solutions, in Willow Grove, Pa. Ideas for Tech Beat items can be submitted to him at **neilcanter@comcast.net.**