Manufacturing

Two Heat-Transfer Improvements for Gas Liquefiers
Medical oxygen liquefiers could operate more efficiently.

Lyndon B. Johnson Space Center, Houston, Texas

Two improvements in heat-transfer design have been investigated with a view toward increasing the efficiency of refrigerators used to liquefy gases. The improvements could contribute to the development of relatively inexpensive, portable oxygen liquefiers for medical use.

A description of the heat-transfer problem in a pulse-tube refrigerator is prerequisite to a meaningful description of the first improvement. In a pulse-tube refrigerator — in particular, one of in-line configuration — heat must be rejected from two locations: an aftercooler (where most of the heat is rejected) and a warm heat exchanger (where a small fraction of the total input power must be rejected as heat). Rejection of heat from the warm heat exchanger can be problematic because this heat exchanger is usually inside a vacuum vessel.

When an acoustic-inertance tube is used to provide a phase shift needed in the pulse-tube cooling cycle, another problem arises: Inasmuch as the acoustic power in the acoustic-inertance tube is dissipated over the entire length of the tube, the gas in the tube must be warmer than the warm heat exchanger in order to reject heat at the warm heat exchanger. This is disadvantageous because the increase in viscosity

with temperature causes an undesired increase in dissipation of acoustic energy and an undesired decrease in the achievable phase shift. Consequently, the overall performance of the pulse-tube refrigerator decreases with increasing temperature in the acoustic-inertance tube.

In the first improvement, the acoustic-inertance tube is made to serve as the warm heat exchanger and to operate in an approximately isothermal condition at a lower temperature, thereby increasing the achievable phase shift and the overall performance of the refrigerator. This is accomplished by placing the acoustic-inertance tube inside another tube and pumping a cooling fluid (e.g., water) in the annular space between the tubes. Another benefit of this improvement is added flexibility of design to locate the warm heat-rejection components outside the vacuum vessel.

The second improvement is the development of a compact radial-flow condenser characterized by a very high heat-transfer coefficient and a small pressure drop. The solid heat-transfer medium in this condenser is a core of aluminum foam with a mean pore diameter of ≈100 μm and a very high surface-area/volume ratio. At its radially innermost surface, the

aluminum foam core is in contact with a cold head.

The vapor (e.g., oxygen) that one seeks to condense enters the condenser through a feed tube, then flows into an annular inlet plenum that surrounds the foam. The vapor then flows radially inward through the foam, toward the cold head, condensing along the way as it encounters colder foam. At the inner radius, the condenser, the subcooled liquid enters axial holes that lead out of the condenser.

The narrowness of the pores and the high surface-area/volume ratio of the foam give rise to an extremely high volumetric heat transfer coefficient (of the order of $10^6 \text{W/m}^3\text{K}$); as a result, the condenser volume needed to obtain a given degree of cooling is very small. Another advantage of the high heat-transfer coefficient is that little subcooling is needed to condense the vapor and, therefore, the amount of cooling power is less than would otherwise be needed.

This work was done by Jerry L. Martin of Mesoscopic Devices, LLC for **Johnson Space Center**. *For further information, contact the Johnson Technology Transfer Office at (281) 483-3809.*
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Controlling Force and Depth in Friction Stir Welding
The proportionality between penetration force and penetration depth is exploited.

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Feedback control of the penetration force applied to a pin tool in friction stir welding has been found to be a robust and reliable means for controlling the depth of penetration of the tool. This discovery has made it possible to simplify depth control and to weld with greater repeatability, even on workpieces with long weld joints.

Prior to this discovery, depths of penetration in friction stir welding were controlled by hard-tooled roller assemblies or by depth actuators controlled by feedback from such external sensors as linear variable-differential transformers or

laser-based devices. These means of control are limited:
• A hard-tooled roller assembly confines a pin tool to a preset depth that cannot be changed easily during the welding process.
• A measurement by an external sensor is only an indirect indicative of the depth of penetration, and computations to correlate such a measurement with a depth of penetration are vulnerable to error.

The present force-feedback approach exploits the proportionality between the

depth and the force of penetration. Unlike a depth measurement taken by an external sensor, a force measurement can be direct because it can be taken by a sensor coupled directly to the pin tool. The reading can be processed through a modern electronic servo control system to control an actuator to keep the applied penetration force at the desired level. In comparison with the older depth-control methods described above, this method offers greater sensitivity to plasticizing of the workpiece metal and is less sensitive to process noise, resulting in a more consistent process.
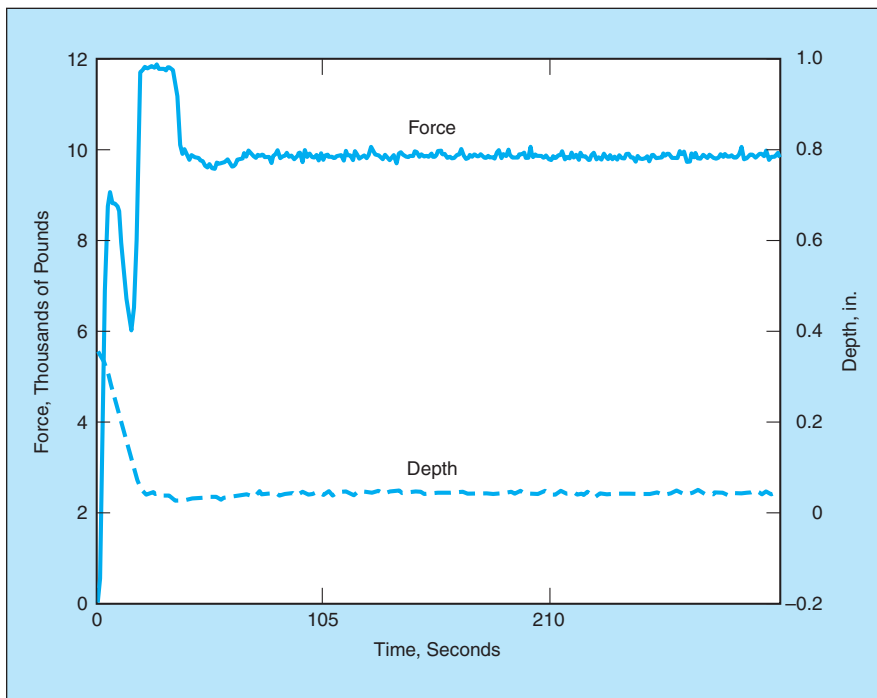
The **Force of Penetration Was Maintained** within a narrow range, thereby causing the depth of penetration to remain within a narrow range.

In an experiment, a tapered panel was friction stir welded while controlling the force of penetration according to this method. The figure is a plot of measurements taken during the experiment, showing that force was controlled with a variation of 200 lb (890 N), resulting in control of the depth of penetration with a variation of 0.004 in. (0.1 mm).

This work was done by Glynn Adams, Zachary Loftus, Nathan McCormac, and Richard Venable of Lockheed Martin Corp. for **Marshall Space Flight Center**.

Title to this invention has been waived under the provisions of the National Aeronautics and Space Act {42 U.S.C. 2457(f)}, to Lockheed Martin Corp. Inquiries concerning licenses for its commercial development should be addressed to:

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