Using Composite Materials in a Cryogenic Pump

Shaft speed is increased and conductive leakage of heat is reduced.

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Several modifications have been made to the design and operation of an extended-shaft cryogenic pump to increase the efficiency of pumping. In general, the efficiency of pumping a cryogenic fluid is limited by thermal losses (the thermal energy that the pump adds to the fluid). The sources of the thermal losses are pump inefficiency and leakage (conduction) of heat through the pump structure. Most cryogenic pumping systems are required to operate at maximum efficiency because the thermal energy added to the fluids by the pumps is removed by expensive downstream refrigeration equipment. It would be beneficial to reduce thermal losses to the point where the downstream refrigeration equipment would not be necessary.

A typical cryogenic pump includes a drive shaft and two main concentric static components (an outer pressure containment tube and an intermediate static support tube) made from stainless steel. In order to reduce the leakage of heat, the shaft is made longer than would otherwise be needed. The efficiency of the pump could be increased most easily by increasing the speed of rotation of the shaft, but the speed must be kept below the lowest of the rotordynamic critical speeds. (In essence, the rotordynamic critical speeds are resonance frequencies at which the interaction of rotational dynamics and elasticity of the shaft and the rest of the rotor can cause the rotor to vibrate uncontrollably, possibly damaging the pump.)

The modifications include replacement of the stainless-steel drive shaft and the concentric static stainless-steel components with components made of a glass/epoxy composite. The leakage of heat is thus reduced because the thermal conductivity of the composite is an order of magnitude below that of stainless steel. Taking advantage of the margin afforded by the decrease in thermal conductivity, the drive shaft could be shortened to increase its effective stiffness, thereby increasing the rotordynamic critical speeds, thereby further making it possible to operate the pump at a higher speed to increase pumping efficiency.

During the modification effort, an analysis revealed that substitution of the shorter glass/epoxy shaft for the longer stainless-steel shaft was not, by itself, sufficient to satisfy the rotordynamic requirements at the desired increased speed. Hence, it became necessary to increase the stiffness of the composite shaft. This stiffening was accomplished by means of a carbon-fiber-composite overwrap along most of the length of the shaft. Because the thermal conductivity of the carbon-fiber composite exceeds that of the glass-epoxy composite, it was necessary to choose the thickness of the overwrap as a compromise between adequate stiffening and a need to minimize leakage of heat along the shaft. It was found to be possible to choose a compromise thickness [0.020 in. (≈0.5 mm)] to satisfy the heat-leakage requirement while stiffening the shaft by a factor >10 and thereby satisfying the rotordynamic requirements.

Concomitantly with the modifications described thus far, it was necessary to provide for joining the composite-material components with metallic components required by different aspects of the pump design. The metal/composite joints are required to withstand differential thermal contraction and expansion between ambient and cryogenic temperatures and to withstand torque and piping loads while maintaining a vacuum seal throughout the ambient-to-cryogenic temperature range. The joints are also required to have reasonable dimensional tolerances, to be easy to assemble in a repeatable process, and otherwise generally to be manufacturable at a level of effort and cost equivalent to that of the prior stainless-steel design.

An adhesive material formulated specially to bond the composite and metal components was chosen as a means to satisfy these requirements. The particular adhesive material has a history of excellent performance in cryogenic applications. The joints were designed to put all the loading in shear and reduce stress concentrations. The joint design was optimized with respect to bond thickness, preparation of surfaces to be bonded, and the viscosity of the adhesive itself. A finite-element analysis predicted that the joints would satisfy the load-bearing requirements. Some mechanical tests verified that the joints could withstand the most severe loads imposed. (The loads were chosen, in part, to simulate the temperatures to be encountered in operation.) Other mechanical tests (tensile tests) demonstrated a factor of safety of 6 with respect to anticipated loads. Results of helium testing lent credence to the expectation that joints will not leak during operation.

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