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Introduction

The first year of our effort in the development of ultra-compact heat exchangers has seen a marked maturing of the project. During the past year, we have come to comprehend even more fully the enormous significance that a low-cost, ultra-compact heat exchanger could have on industry, but we have also developed a more realistic appreciation for the complexity of the various steps involved in the manufacture of our microtube exchanger. It has often been said that the degree of optimism in a project is inversely proportional to the maturity of the project. We now have a more accurate understanding of the practical limits to miniaturization.

Detailed discussions of the theory, some experiments, and our progress in manufacturing may be found in the two papers appended to this report. The reader unfamiliar with our prior work should read these papers first.

The most important experiment in the past year was one that failed. We found it impossible to achieve the effectiveness we had expected as we reduced the spacing aspect ratio β (microtube center-to-center spacing divided by microtube outside diameter) from 2 to 1.4. Subsequent analysis suggested that we could expect manufacturing stochastic effects to generate maldistribution at least proportional to $\beta/(\beta-1)^3$, which gives a factor of 11 for the above reduction in β . This was roughly in agreement with our experiments, where we saw minimum flow maldistribution of about 2% for $\beta=2$ and over 20% for $\beta=1.4$.

We must keep in mind that the major motivation for the project is not high effectiveness ϵ but rather high specific conductance (SC) - heat transfer per mass per temperature difference, W/kgK. As long as flow maldistribution, relative pressure drops, and axial conduction losses are small compared to $1-\epsilon$, specific conductance alone determines the mass of a laminar-flow exchanger for any given application. Furthermore, under such conditions, exchanger mass and cost are inversely proportional to $1-\epsilon$. Hence, system optimizations for mobile power (especially recuperated Brayton cycles) usually recommend exchanger effectiveness near 85% for aircraft gas turbines (for shaft power) and 90% for land- or sea-based gas turbines. For stationary power plant applications, recuperator effectiveness of 98% could be optimum. Obtaining this level of effectiveness with several percent flow maldistribution in the exchanger modules will require the use of several exchangers in series with flow mixing stations between the units. Total exchanger mass would then still be determined by specific conductance.

It now appears that the practical limit to normalized specific conductance (helium-to-helium at 350 K) with our microtube design is about 400 W/kgK, which is a factor of six higher than the best aerospace-grade high-temperature recuperators (to our knowledge) and a factor of 20 higher than typical compact exchangers currently available. The minimum practical microtube outside diameter appears to be about 0.62 mm.

The sharp increase in flow maldistribution as β decreases negates the specific conductance advantage of small β . We now expect optimum β always

to be greater than 1.8 - and greater than 2.3 for applications with low shell-side pressure. This makes it possible to achieve extremely uniform tube spacing by including several spacer sheets without adding excessive shell-side flow constriction. The increased tube spacing also simplifies two major manufacturing problems - the tubestrip fineblanking and array encapsulation (required for support while pressing the tubestrips onto the tubes). We expect to demonstrate 1% flow maldistribution and SC of 200 W/kgK in the near future when sufficient funding is available for further work.

Major applications for compact heat exchangers were identified in recuperated gas turbines for applications ranging from automobiles to ships and planes. The modular approach we have taken appears to offer advantages over the alternatives - including the rotating ceramic honeycomb regenerators. The advantages and drawbacks are discussed in some detail in proposals that were submitted during the past four months to (1) the Army for Recuperated Aircraft Gas Turbines, (2) NASA for Nuclear Thermal Propulsion of Trans-Atmospheric Vehicles, and (3) NIST ATP for diverse applications in cryogenics and transportation.

Finally, we have acquired a much more accurate understanding of the requirements for economically successful manufacturing of the microtube exchanger. Our attempts to utilize available staff (for example, with expertise in fluid dynamics) outside their areas of expertise (for example, in automated machine design) served only to remind us that a much higher level of funding will be required for full development by a team of experts with strengths in a number of different areas.

The DOE funds were nearly depleted by the beginning of the last quarter, and the recession greatly reduced the availability of internal (DSI) funds to continue the MTS project. As a result, staff reductions were necessary and the project is now largely on hold. However, we hope to be able to make some progress on the manufacturing automation using limited internal funding during the next quarter. For that reason, we have decided to postpone the Final Report for one more quarter.

In the long run, the current funding situation will probably be viewed in a positive light. We expect our core business to experience a strong upturn during the next two quarters and provide additional funding to continue the MTS exchanger project. We are also optimistic about obtaining additional funding from other government and private sources. When such further funding becomes available, we will hire individuals with appropriate expertise for the next important phase of the development - demonstration of economically viable manufacturing.

Manufacturing Processes

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The appended papers summarize the main features of the manufacturing process being developed. Below, we highlight some of the main results of our progress during the past year.

** removed and cycled separately -*

Diffusion-Welded Tube-to-Tubestrip Joints. The high level of success we achieved initially with 0.64-mm tubes on 1.3-mm spacings was not replicated when we dropped to 0.57-mm tubes on 0.8-mm centers. We attribute the unacceptable leak rates of the latter experiments to (1) out-of-roundness in the holes from tubestrip distortion and (2) highly variable interference from improper tube finishing. The fineblanking subcontractor had expected roundness problems, since minimum web thickness between holes was only 0.23 mm and the tubestrip thickness was 0.4 mm. More experiments are required to determine the minimum ratio of web to strip thickness, but a ratio greater than 1.4 has been shown to be satisfactory, and values approaching 1.1 may work.

Perhaps the major contributor to the failures in recent diffusion-welding experiments was inadequate control over tube length and the electrochemical chamfering of the tube ends. Minor changes in the mold and pressing fixturing will allow us to relax the tube length and chamfer tolerances. At the same time, minor changes in tube finishing processes can achieve higher precision. Hence, this problem appears easy to solve.

One possible method of addressing many difficult manufacturing problems simultaneously would be to substitute laser welding for diffusion welding. This obviates the need for the interference fit and its requirements of superprecision fineblanking and fusible alloy encapsulation. However, it would require superprecision machine vision to compensate for thermal expansion during the welding process, and laser welding is a much slower process that would add at least \$100 to the welding cost of a 1000-tube module in high volume production. For this reason, our major emphasis is still on diffusion welding, but we will continue to study the possibility of laser welding.

Fineblanking limitations. To prevent die rupture in the high-density pattern (408 0.57-mm diameter holes on 0.8-mm centers) it was necessary to resort to a multiple-hit approach. Five strokes punched sixteen groups of five holes for a total of 80 holes per stroke. The pattern was such that no nearest-neighbors were punched in the same stroke. When the pattern was repeated five times, it completed 400 closely spaced holes with four holes missing at each end. A final hit with a separate punch was required to punch these eight holes.

Although the multiple-hit technique was not able to achieve the hole location accuracy that had been expected (partially because of part growth and partially because of die play), its positioning accuracy of ± 0.03 mm appears to be adequate from the perspective of tube alignment. However, the hole distortion problem is worsened, making it impossible to obtain leak-tight diffusion welds - at least with small β .

Whether or not the multiple-hit technique would work with β greater than 2 is still in doubt for another important reason. Even with the most precise blanking, small breakout burrs are produced on the back side of the hole. With the multiple-hit technique, these burrs get pressed back into the hole on a subsequent hit. Electrochemical deburring is extremely difficult to control sufficiently to maintain hole size tolerances because of the

unavoidable variability in the burrs that results from the variable number of hits experienced by the different burrs. Mechanical deburring using multiple, high-speed micro-spindles may be a satisfactory alternative. The substantial die cost savings afforded by the multiple-hit technique suggests that further development will be supported at some point in the future using multiple-spindle mechanical deburring of tubestrips with β greater than 2.

The fineblanking subcontractor, SFB, does not believe single-hit dies can be built for β less than 2 with hole sizes in the 0.62 to 0.68-mm range. The greater the number of rows of holes, the thinner the tubestrip material (or the lower its shear strength) must be to avoid die rupture. Experiments with five rows of 0.64-mm holes on 1.3-mm centers were successful for Haynes alloy 230 (shear strength 600 MPa, R_B hardness 93) 0.4-mm thick. Punch pins failed - but the die survived - during experiments on 0.56-mm-thick Haynes C-22 (shear strength 550 MPa, R_B hardness 90). The die and the pins were made from either tool alloy M-2 or M-42. Several tool steels (especially T-15) offer higher strength and hardness but at increased grinding difficulty.

When additional funding becomes available, the next work will be with a 1000-hole, single-hit die, suitable for production. We will begin by punching a large number of tubestrips from soft, 0.35-mm-thick SS304 before risking the dies on heavier and harder materials. The most promising option for the harder materials is a sequential-shearing technique that uses a complete set of holes with pins of various lengths so that they penetrate the material at different times during the stroke. It appears that this technique will be limited only by the strength of the pins and will permit punching strips of thickness comparable to the minimum web dimension or hole diameter, whichever is smaller.

Tube Array Encapsulation. Pressing the tubestrips onto the tubes in interference fit sufficient for effective diffusion welding has only been possible consistently when the tubes were completely encapsulated (except near the ends) in a fusible alloy to prevent tube flexing. Reducing the tube spacing from 0.66 mm in the initial modules to 0.23 mm in the latter work greatly complicated this process. The vacuum injection technique still produced satisfactory encapsulation, but the molten alloy had to be much cleaner to allow free flow between the tubes.

Major problems arose during removal of the potting material following the pressing operation. Melting under boiling water with ultrasonic vibration removed less than 80% of the material. Acid etching was not effective in removing this material without mechanical assistance in the form of manual scraping. Substantial amounts of potting alloy, and apparently insoluble oxides and hydroxides of the potting constituents from reactions with the acid etch bath, remained trapped between the tubes. Careful cleaning of the molten alloy by filtering through ceramic frits prior to vacuum injection did not solve this problem. Coating the tubes with a release agent (WD-40 spray oil) helped to some extent, but it appears that the source of the problem is fundamentally related to the surface tension of the alloy and the tube spacing dimensions. The alloy removal problem is relatively easy with tube spacings of 0.66 mm, but it is a show-stopper at 0.23 mm. Hence, we began investigating alternatives.

Several tubestrip pressing experiments with 100-tube modules of 0.64-mm tubes on 1.3-mm centers gave promising results without alloy encapsulation. Seven spacer forms spaced apart along the tube length prevented flexing during pressing when tube finishing and hole chamfering were optimum. We are not presently optimistic about achieving consistent diffusion welds without the use of the potting metal because of the much tighter tolerance requirements with the dry method, but some further work will be supported in an effort to eliminate the complex potting and cleaning process. One approach being studied is laser welding in place of diffusion welding, as discussed previously under diffusion welding.

Experimental 4000-Tube Exchanger Banks

Two banks of 10 modules were assembled and preliminary tests were run before funding limitations terminated the experiments. The excessive tube-to-tubestrip leaks made it very difficult to quantify the performance, but it appeared that flow maldistribution was approximately 20% and the leakage was approximately 10% on both units tested. We were not able to establish conditions of sufficiently high flow rate to make the flow maldistribution small compared to the ineffectiveness. Hence, our calculations of specific conductance were of little value. The maldistribution problem was attributed to excessive bypass flow caused by bowing of the side panels at the pressures required (about 0.2 MPa) to achieve high flow with the excessive restriction from the tube spacers with low β . This motivated us to perform the following analysis.

The ratio of by-pass flow rate G_1 to total shell-side flow rate G in a module can be estimated as follows. Assume negligible tube-side flow maldistribution, negligible pressure losses, and negligible longitudinal conduction losses. Define flow maldistribution χ as $1-E$, where E is the maximum effectiveness that can be obtained.

The pressure drop δp for laminar flow between parallel plates with spacing h , length L , viscosity μ , and velocity v is

$$\delta p = 12\mu Lv/h^2. \quad (1)$$

$$v = h^2\delta p/12\mu L, \quad (2)$$

and

$$G_1 \approx 2(n_r+n_c)sh\rho v \approx 2(n_r+n_c)sh^3\rho\delta p/12\mu L, \quad (3)$$

where n_r and n_c are the number of rows and number of columns per module respectively and s is the tube center-to-center spacing. The shell-side pressure drop δp can be shown to be of the following form (with considerable uncertainty in the coefficient):

$$\delta p \approx 24\mu LG/[n\pi\rho(\beta-1)^3(\alpha d)^4] \quad (4)$$

where n is the total number of tubes, d is the tube ID, αd is the OD, and center-to-center spacing is $\alpha\beta d$.

Then

$$x_1 = G_1/G \approx 4(n_r + n_c)\beta h^3/[n\pi(\beta-1)^3(\alpha d)^3] \quad (5)$$

If h is a manufacturing constant, the bypass-flow contribution to maldistribution is very sensitive to $\beta-1$. The effect of $\beta/(\beta-1)^3$ gives a factor of 11 reduction in x_1 in the proposed open Brayton recuperators (where β is 2) compared to the current cryogenic recuperator where β is 1.4. The 12% increase in d means another 40% reduction in sensitivity to a constant manufacturing tolerance. If we assume spacing tolerances to be proportional to length (a best case scenario), the diameter effect disappears, but the $\beta/(\beta-1)^3$ factor remains.

We expect similar analysis of the effects of non-uniform tube spacing would yield similar conclusions for the core (as distinguished from bypass) effects on maldistribution.

Subsequent modules will have $\beta=2$. This will allow the use of tube spacer strips with adequately sized shell-side flow-by holes between each tube. The tubes may be held precisely in position without causing excessive shell-side pressure losses, and satisfactory conditions may be established for leak-tight diffusion welds as demonstrated previously. We expect the new modules to achieve 1% flow maldistribution and zero leakage.

Conclusions

- * We have demonstrated feasibility of higher specific conductance by a factor of five than any other work in high-temperature gas-to-gas exchangers.
- * These laminar-flow, microtube exchangers exhibit extremely low pressure drop compared to alternative compact designs under similar conditions because of their much shorter flow length and larger total flow area for lower flow velocities.
- * The design appears to be amenable to mass production techniques, but considerable process development remains.
- * The reduction in materials usage and the improved heat exchanger performance promise to be of enormous significance in advanced engine designs and in cryogenics.

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Recently Submitted Proposals

- U.S. Army, SBIR A91-191. Solicitation for compact, light-weight heat exchangers for aircraft gas turbine engines.
Proposal Title: Micro-Tube Recuperators for Aircraft Brayton Cycle Engines.
- NASA, SBIR 11.12. Solicitation for advanced space propulsion concepts.
Proposal Title: Ultra-Compact Exchangers for Closed-Loop Nuclear Thermal Propulsion.
- NIST ATP 91-01. Concepts likely to have broad industrial significance.
Proposal Title: Low-Cost Manufacture of High-Performance Universal Heat Exchangers.

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