DOE/CE/15440--T1

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DE91 005741

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U.S. Department of Energy
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QUARTERLY TECHNICAL REPORT

Contract Quarter Ending: 04 December 1990

27 December 1990

Identification Number: 90CE15440
Program/Project Title: Microtube Strip Heat Exchanger

Doty Scientific, Inc.
600 Clemson Rd.
Columbia, SC 29223

F. David Doty, Principal Investigator

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Introduction

General-When Doty Scientific began exploring the theoretical limits of compact gas-to-gas heat exchangers about eight years ago, we could not find any other research programs outside of cryogenics with interest in the subject. By the time we first applied for the DOE ERIP support two-and-a-half years ago, some interest was beginning to emerge in related technology in the NASP program for cooling the leading edges of supersonic aircraft. During the past year, the groundswell of concern about global warming and energy independence has caused many researchers to again "warm-up" to studies of alternative energy cycles, enhanced conservation, and ultra-clean energy conversion. We remain extremely optimistic about the prospects of our Microtube-Strip Heat Exchanger to contribute significantly to (a) the closed Brayton cycles being pursued at MIT, NASA, and elsewhere; (b) reverse Brayton cycle cryocoolers, currently being investigated by NASA for space missions, being applied to MRI superconducting magnets; and (c) high-efficiency cryogenic gas separation schemes for CO₂ removal from exhaust stacks. The goal of this current study is much less ambitious than the above statement might imply. Our goal is to show the potential for substantial progress in high-effectiveness, low-cost, gas-to-gas heat exchangers for diverse applications at temperatures from below 100 K to above 1000 K.

To date, the highest effectiveness we have measured is about 98%, and we have measured relative pressure drops below 0.1% with a specific conductance of about 45 W/kgK. During the next quarter, we expect to measure effectiveness above 99% and specific conductance near 300 W/kgK.

While the grant was in-process, Doty Scientific, Inc. (DSI) proceeded with heat exchanger development at its own expense. During the pre-award period DSI built a 3-module heat exchanger bank using 103-tube microtube strip (MTS) modules. It was tested both in-house and by the Mechanical Engineering Department at Clemson University. In addition, we proceeded to procure tooling for a 408-tube MTS heat exchanger module and obtained parts to build 10 heat exchanger banks using this module. To add to our analytical capabilities, we have acquired computational fluid dynamics (CFD) software. Since receiving the grant we have been able to proceed at an accelerated pace, preparing a project schedule, designing and building assembly equipment, and entering into a subcontract with the University of South Carolina to test the 10 module bank.

Publications, Presentations and Software-Three professional presentations were made during the past year (Doty, 1990a; Doty, 1990b; Jones, 1990) at the Symposia of Space Nuclear Power Systems (SSNPS) and the Intersociety Energy Conversion Engineering Conference (IECEC). Corresponding papers appeared in the proceedings of IECEC, and a paper is expected in a publication by SSNPS. Copies of the IECEC papers are appended to this report. Our patent application on the method of assembling tube arrays was issued as U.S. patent #4,896,410. A copy of this patent is attached. We recently received notification that our submission to Heat Transfer Engineering has been accepted for publication. A copy of this paper will be appended to a subsequent report. A patent application was submitted on a microtube radiator concept several months before the DOE funding began. A copy of this application (or perhaps the issued patent) will be appended to a later report.

During the past year we have made substantial progress on MTS exchanger analysis software. Both a BASIC and a PASCAL version of this program have been completed to provide quick, accurate calculation of all important features of the heat exchanger: Reynolds numbers, Prandtl numbers, flow velocities, pressure drops, temperature differences, exchange power, axial conduction losses, insulation losses, pumping power losses, effectiveness, specific conductance, mass, and steady-state stresses. The program also calculates all thermodynamic properties of arbitrary gas mixtures at the desired operating conditions. The CFD work now in progress will allow us to improve the treatment of flow maldistribution.

Pre-award Work

Three-Module Bank Testing- In order to understand the performance of the MTS heat exchanger modules operating in parallel more fully, and to develop techniques for building heat exchanger banks, DSI designed a 3-module heat exchanger bank based on the 103-tube MTS module and built two prototypes. One prototype was built to operate at low shell-side pressure and did not have a pressure vessel. The other was installed in a pressure vessel to permit higher shell-side pressures.

Figure 1
3-Module MTS Heat Exchanger Bank Cutaway Drawing

Figure 1 shows a cutaway drawing of the 3-module prototype bank, without pressure vessel. This prototype has baffles between each module and between the top and bottom modules and the heat exchanger shell to divide the shell-side flow and channel it around the outsides of the microtubes. Although the baffles appear open at the ends, they are spot welded to the baffle tubes to impede flow down the baffles. A connecting sheet extends the length of the baffles and from the top of the top baffle to the bottom of the bottom baffle. The baffles and connecting sheets form the channels for the

shell-side flow. The connecting sheets and the top and bottom baffles also establish the boundaries for the volume designed for exchanging heat between the two fluids. The baffles are made of 0.13 mm. thick stainless steel and the connecting sheets are made of 0.20 mm thick stainless steel. These thicknesses provide adequate strength for the shell-side flow channels while keeping shell side conduction losses low. The end clips have tabs bent inwards and outwards at one end of each clip to locate and secure the heat exchanger modules and have holes to locate and secure the baffles and connecting sheets. The long, single tabs on the end clips prevent shell-side flow between the connecting sheets and the shell.

The tube-side manifold connects to each module header via a tube. The headers are TIG welded to the header-to-manifold tubes and are laser welded to the tube-strips. TIG welds join the tube-side manifolds to the tube-side manifold nipples and manifold end caps. Silver solder secures and seals the header-to-manifold tubes to the tube-side manifolds. TIG welds join the shell-side nipples to the shell end cap and seal the outer shell member joints.

On the bank without a pressure vessel, we used silver solder to seal the tube-side manifold nipple to the shell ends. On the bank installed in a pressure vessel, we did not seal the tube-side manifold nipple to shell end joint. This allowed the pressure between the outside of the heat exchanger shell and shell-side pressure to equilibrate, minimizing the pressure gradient across the shell wall. Figure 2 shows the three modules in a partially assembled shell.

Figure 2
Partially Assembled 3-Module MTS Heat Exchanger Bank

After assembling the bank and checking it for external leaks, we tested the heat exchanger to compare its actual performance with the predicted performance. Figure 3 shows a schematic diagram of the heat exchanger bank test setup. It should be noted that the very low power requirements and minuscule temperature differences involved in testing a small, high-effectiveness exchanger require extreme care in insulation and thermometry. These details are discussed in the experimental section of the testing by Clemson

University and will be appended to a later report. Table 1 summarizes the test data and compares it with theoretical predictions from our computer model. These data show good correlation between the model and actual data. The table shows that as the exchange power increases, the error between the actual and predicted exchange powers decreases, indicating that the model could be made more accurate by including heat loss estimates through the shell insulation and manifold connections. The increase in error between the actual and predicted effectiveness as effectiveness increases indicates that the actual heat exchanger has greater flow maldistribution than assumed in the model. Flow maldistribution always reduces effectiveness, but at very high effectiveness, it introduces much greater relative error between predicted and actual T_g .

Tube-side and shell-side pressure drop showed similar agreement with the above analysis.

Figure 3
3-Module MTS Heat Exchanger Bank Test Setup

After completing our in-house testing, we sent the heat exchanger bank to Clemson University Mechanical Engineering Department for independent testing. They reached the same conclusions that shell-side flow inhomogeneities reduced the actual effectiveness compared to the theoretical effectiveness. Dr.'s Gaddis, Beasley and Zumbrunnen of Clemson University discussed enhancing heat

exchanger performance by improving shell-side flow distribution. As a result of these discussions we devised a part which maintains uniform shell-side tube spacing, and enhances uniform flow distribution. This report will describe this device in greater detail in a subsequent section. As of this writing, we have not yet received the final report of the test work performed at Clemson; therefore, we have not included any of their test data nor quoted recommendations from their test work.

Fluid	Mass Flow Rate (g/s)	Shell-side		Tube-side		Exchange			Effectiveness	
		Temp. In (°C)	Temp. Out (°C)	Temp. In (°C)	Temp. Out (°C)	Power (W)	Error		Model	Test
						Model	Test	(%)		
N ₂	0.20	56.9	28.1	25.8	52.8	6.6	6.0	9.6	91.0	86.7
N ₂	0.29	68.1	29.2	26.0	63.3	12.8	11.8	8.5	91.3	88.5
N ₂	0.38	72.5	29.7	25.9	67.5	18.4	17.1	7.8	90.8	89.2
N ₂	0.48	72.2	27.3	22.9	66.5	24.5	22.6	8.5	90.0	88.4
N ₂	0.56	73.3	27.3	22.7	67.2	28.8	27.1	6.4	89.2	87.9
He	0.07	70.0	30.0	27.4	66.0	16.4	15.7	4.4	95.7	92.7
He	0.11	82.9	29.8	27.5	78.9	30.1	29.4	2.4	96.1	92.7
He	0.14	88.0	29.9	27.6	84.0	43.4	42.6	2.0	96.1	93.3

Table 1. Comparison of MTS heat exchanger mini-bank model with test data

Project Schedule

After receiving the grant, DSI established a project schedule to accomplish all of the assigned tasks within the allotted time. Figure 4 shows the project schedule established at the beginning of the grant period. This schedule covers all of the tasks and works toward a completion date of 8 September 1991, approximately six months ahead of schedule. However, we have made more rapid progress than anticipated in some areas, and slower progress than anticipated in other areas. This will warrant revising the schedule during the next quarter to reflect these changes.

Status of Tasks

Task 1. Analyze distribution of flow within individual modules and within the manifolds of a ten-module heat exchanger bank; analyze thermal stresses in the bank, with particular attention to transients.

During this quarter we have been using the Phoenix 1.53 CFD software to model heat exchanger shell-side flow. However, this modeling effort has taken more time than anticipated. Although we made good progress in the last three weeks of the quarter, we had not been able to achieve a properly converged solution. We anticipate obtaining a converged CFD solution during the next quarter. We will then use this tool to model heat exchanger flow for a number of flow conditions, including asymmetric location of the modules between the baffles, and non-uniform tube spacing.

Notes	1990							1991								
	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
HEAT EXCHANGER ANALYSIS																
MTS Flow Analysis.																
Steady--state Stress Analysis.																
Transient Thermal Stress Analysis.																
MTS Bank Design.																
MTS MODULE ASSEMBLY FIXTURE DESIGN																
Potting Die Design.																
Tube--strip Press Design.																
Centorr Oven Modification Design.																
Header Weld Fixture Design.																
Module Leak Test Fixture Design.																
High--speed μ--Tube Insertion Fixture Design.																
MTS BANK ASSEMBLY FIXTURE DESIGN																
End Clip Bending Fixture Design.																
Center Clip Bending Fixture Design.																
Baffle Bending Fixture Design.																
Bank Leak Test Fixture Design.																
PURCHASED PARTS AND TOOLING																
Obtain Production Quality Tubestrips.																
Obtain Production Quality μ--Tubes.																
Spacer Form Fabrication at Vaughn Precision.																
Tubestrip Fixture Fabrication Fabrication at Vaughn Precision.																
DSI PRODUCED TOOLING																
Fabricate μ--Tube Potting Die.																
Modifications to Centorr Oven.																
Fabricate Header to Tubestrip Weld Fixture.																
Fabricate Module Leak Test Fixture.																
Fabricate High--speed μ--Tube Insertion Fixture.																
CONSTRUCT BANK ASSEMBLY FIXTURES																
Fabricate End Clip Bending Fixture.																
Fabricate Center Clip Bending Fixture.																
Fabricate Baffle Bending Fixture.																
Fabricate Bank Leak Test Fixture.																
ASSEMBLE MTS MODULES																
Assemble First 20 MTS Modules.																
Assemble Second 20 MTS Modules.																
Assemble MTS Modules Using High--speed μ--Tube Insertion Fixture.																
HEAT EXCHANGER BANK ASSEMBLY																
Assemble First Heat Exchanger Bank. Assemble Second Heat Exchanger Bank.																
Assemble Eight Heat Exchanger Banks.																
HEAT EXCHANGER BANK TESTS

Figure 4

During this quarter we concentrated most of our analytical energies on the CFD modeling effort. Consequently, we have not done any stress analysis beyond that done in our pre-proposal work. We will analyze the heat exchangers thermal stresses during the next quarter.

Task 2: Design a heat exchanger bank consisting of ten (10) modules with approximately four hundred (400) microtubes per module. In parallel with this, design module assembly fixtures, potting dies, tubestrip pressing fixtures, header dies and welding fixtures.

Our pre-award work included designing a 10-module bank with 408 tubes per module similar to the 3-module bank described above. Based on test experiences from the 3-module bank, we made revisions to the shell-side design of the 10-module bank. The primary change was the addition of shell-side spacers.

In order to ensure uniform tube spacing we will place spacers at uniform intervals along the tubes. Each spacer locates all eight rows of tubes relative to each other without totally obstructing shell side flow. With 0.56-mm diameter holes on 0.8-mm centers in a triangular pitch, this presented a particularly interesting challenge. We examined two options, shown in Figures 5 and 6. The design shown in Figure 5 uses six rounded points of contact to locate the tubes and allows gas to flow through around the spacers in the open areas between the spacer and the tubes. The design shown in Figure 6 uses contact between the tubes and the straight sides of the triangular openings to locate the tubes and allows the gas to flow through that portion of the triangular opening not occupied by the tube. Both designs adequately maintain hole location and redistribute shell-side flow at each spacer location. The spacers should also act as flow mixers to help homogenize shell-side temperature at each location.

Although the former design has approximately 1 percent greater flow opening than the latter design, the former design has significantly greater tooling and die maintenance costs for blanked sheet metal parts. Therefore, we chose the latter design on the basis of manufacturability and lower costs. Although we plan on obtaining fineblanking tooling for the spacer, we procured parts for the first 408-tube module using photoetching technology. Figure 7 shows a closeup of the spacer. Figure 8 shows a closeup of the triangular holes. These spacers also feature holes to locate the spacers while inserting the microtubes using automated assembly techniques. After inserting all of the microtubes through the spacer holes, the tabs with the locating holes can be detached from the spacers and discarded.

The 3-module prototype bank and tests also showed us that we could reduce the metal thickness for the baffles, connecting sheets and the shell. We reduced the baffle sheet metal thickness from 0.13 mm to .08 mm, the connecting sheet thickness from 0.20 mm to 0.08 mm and the shell wall thickness from 0.5 mm to 0.25 mm. These changes will reduce the thermal mass and time constant of the heat exchanger bank, improving its thermal response.

Figure 5
Six-pointed Microtube
Spacer Option

Figure 6
Triangular Opening Microtube
Spacer Option

Figure 7
2X Enlargement of Microtube Spacer

Figure 8
4X Enlargement of Microtube Spacer Triangular Openings

The pre-award analyses and test work showed that adding the shell-side tube spacer and decreasing the thickness of some sheet metal parts were the major design modification required to improve heat exchanger performance.

As part of the pre-award work we also designed fixtures to bend the end clips, center clip and baffle sheet metal parts.

On the basis of the 10-module bank design, we have designed the potting dies, tubestrip pressing fixtures, tubestrip to microtube diffusion welding fixture for an in-house vacuum oven, tubestrip to header welding fixture, and leak test fixtures for the individual modules and the 10-module subassembly.

Task 3: Obtain production-quality fineblanking tubestrip die and AISI 304 tubestrips.

As part of the pre-award work we ordered the tubestrip die from Southern Fineblanking (SFB) Division of Michigan Precision Industries. The close spacing of the holes posed some significant problems for SFB. Die strength limitations prevented them from blanking all of the holes simultaneously as they did with the 103-hole tubestrip. Using a company proprietary progressive punching process developed for this application, they were able to achieve hole spacing very close to that required for the tubestrips. Unfortunately, the part length increased as the dies punched out the closely spaced holes. Working with SFB we helped them modify the tooling to use a high precision linear positioner to index the material through the dies and compensate for "part growth". As of the end of the quarter, SFB and DSI were still fine tuning the process and we did not yet have acceptable tubestrips. However, success was demonstrated in the last few days. Details will be presented in the next report.

During the next quarter, SFB should be able to produce enough acceptable tubestrips to more than satisfy the requirements of the project.

Task 4: Obtain production quality microtubing.

As part of the pre-award work DSI obtained an adequate supply of AISI 304 microtubes from K-Tube in San Diego, California, to satisfy the requirements of the project.

We have completed this task and subsequent reports will not discuss it further.

Task 5: Construct revised MTS heat exchanger assembly fixtures, potting dies, tubestrip pressing fixtures, header dies, and welding fixtures to permit prototype MTS module sub-assembly and welding.

By the end of the quarter we had constructed the module potting die, tubestrip to microtube diffusion welding fixture for in-house vacuum oven, tubestrip to header welding fixture, and leak test fixture for the individual modules. We had also received the shell-side tube spacers.

During the next quarter, we will complete the tube spacer forms to locate the microtubes in the potting die during fusible alloy injection and the fixtures to press the tubestrips on to the microtubes. Completing these pieces of the tooling will permit us to begin producing diffusion welded 408-tube MTS modules, welding the headers to the tubestrips, and leak testing the individual modules.

Task 6: Construct dies and fixtures for prototype heat exchanger banks and manifolds.

As part of the pre-award work we ordered and received laser-cut sheet metal pieces for the heat exchanger bank center clips, end clips, and baffles.

By the end of this quarter, we had completed the leak test fixture for the 10-module subassembly. We have begun work on the bending fixtures for the baffles, and we will soon begin work on the bending fixtures for the end and center clips.

During the next quarter we will finish all of the fixtures necessary to build the prototype 10-module banks.

Task 7: Using prototype tooling, construct 100 MTS modules.

During the next quarter we will finish all of the module assembly fixtures and receive production quality tubestrips. Completing these two tasks will enable us to begin assembly of the MTS modules.

Task 8: Using the prototype tooling, assemble the modules into 8-10 prototype MTS heat exchanger banks.

During the next quarter we will begin assembly of the 408-tube MTS modules and finish the heat exchanger bank assembly fixtures. Completing Task 6 and and starting Task 7 will enable us to begin assembling heat exchanger banks.

Task 9: Test the prototype MTS heat exchanger banks to verify fluid flow distribution and heat transfer analysis.

During the next quarter, we will begin in-house testing of the heat exchanger banks. However, we will have to modify our test setup and procedure. Figure 9 shows a schematic drawing of a test setup. The ten-module bank will require an order-of-magnitude more heat input and 2 to 10 times the flow of the 3-module bank. The 3-module bank tests taxed the output of our current gas regulators. Therefore, one ten module bank test will use a closed loop with a microturbogenerator and a two-stage microcompressor. The test is intended to show suitability for cryocooler applications and will be discussed in more detail in a subsequent report.

Figure 9
Ten-Module Bank Test Setup

Task 10: Verify MTS heat exchanger test through independent testing.

During this quarter we negotiated a subcontract with the University of South Carolina (USC) Mechanical Engineering Department to test the heat exchanger bank. Our experiences in dealing with Clemson University, a three hour drive each direction, motivated us to arrange for the test work closer to our work site. This will facilitate interaction and allow us to provide the necessary material and technical support for the USC researchers to complete the testing in a timely manner.

USC will begin the analytical work to support their test effort in January of 1991, begin to assemble and setup the experiment in February 1991, begin calibrating instruments in March 1991, begin testing in June 1991 and complete their report in September 1991.

Related Work - Independent R&D

During the past month, two abstracts were submitted for presentations on our progress in compact heat exchangers and microturbines at next year's IECEC. An abstract was submitted for a presentation on our reverse Brayton cycle work at next year's Cryogenic Engineering Conference. Copies of these abstracts are appended to this report. Copies of the papers will be appended to a later report. We anticipate collaboration with Clemson in the closed Brayton cycle cryocooler project.

A patent application on a novel radial-inflow microturbine suitable for reverse Brayton cycle cryocoolers was recently submitted in collaboration with David Gordon Wilson of MIT. A copy of this application (or perhaps the issued patent) will be appended to a later report. We are also supporting collaborative microturbine research at Simon Fraser University in Burnaby, British Columbia.

We have begun working on a proposal for continued funding of the required manufacturing development effort through the Advanced Technology Program, which supports the development of precompetitive generic technology, at the National Institutes of Standards and Technology (NIST). We were honored to be visited recently by Ray Kammer, deputy director of NIST, and Philip Nanzetta, NIST MTC Program Director, both of whom expressed praise for our technical and business progress in a number of areas. Some of our findings on the broad range of applications for ultra-compact, high-effectiveness heat exchangers will be included in the proposal to NIST. These findings will be appended to a later report.

We recently presented our business plans for the development of an automated manufacturing process suitable for low-cost MTS exchangers at a Venture Capital Conference. Doty Scientific's profitability and the continued strong growth in our NMR product lines have caused several venture capital firms to take interest in our energy product developments as described in our business plan. Serious interest is being expressed by two venture capital firms, and meetings will be arranged early in January. A copy of the current business plan will be provided upon request.

Doty Scientific will soon require a larger facility to accommodate our growing NMR and RF products as well as our R&D in compact heat exchangers. We are considering relocating to a more favorable location rather than expanding at our present location. An update on this business decision will be reported later.

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