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Friction Factor Characterization for High-Porosity Random Fiber Regenerators

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August 2001

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FRICTION FACTOR CHARACTERIZATION FOR HIGH-POROSITY RANDOM FIBER REGENERATORS

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Summary

NASA Glenn Research Center, the Department of Energy (DOE), and Stirling Technology Company (STC) of Kennewick, WA are developing a Stirling convertor for a high-efficiency Stirling Radioisotope Power System to provide spacecraft on-board electric power for NASA deep space missions. Stirling is also now being considered for unmanned Mars rovers, especially for missions of long duration. STC is developing the 55-We Technology Demonstration Convertor (TDC) under contract to DOE. NASA Glenn is conducting an in-house technology project to assist in developing the convertor for readiness for space qualification and mission implementation. NASA Glenn is also evaluating key technology issues through the use of NASA Phase II Small Business Innovation Research (SBIR) contracts with STC and providing technical consulting for the DOE effort under an Interagency Agreement.

As part of the Interagency Agreement, NASA Glenn performed a review of the TDC design. The HFAST computer code was used to compare projected convertor performance to that predicted by the GLIMPS code used by STC to design the convertor. These comparisons showed a large difference in the regenerator pressure drop losses due to significantly different regenerator friction factors used by the two codes. Neither code's friction factor correlations appeared to be based on regenerator test data at the regenerator porosities that were being considered for the design (90-96%). Therefore, NASA Glenn recommended that steady-flow pressure drop tests be conducted to better determine the friction factor for these high-porosity regenerators.

STC fabricated a flow test fixture and three random fiber regenerator test samples, one each at approximately 80%, 88%, and 96% porosities. The flow tests were then completed by the NASA Glenn Flow Calibration Laboratory, and the data reduced to Reynolds number and friction factor. The results showed that the 80% and 88% porosity samples had similar characteristics while the 96% porosity sample had significantly higher friction factors for given Reynolds numbers compared to the samples with lower porosities. Comparisons were also made between the test data and existing correlations. STC used this data to derive a modified regenerator friction factor correlation for use in GLIMPS for porosities greater than 88%. Using this new correlation, the final optimized regenerator design porosity was reduced from 96% to 90%.

It is important to note that no adjustments were made to the heat transfer correlation used in GLIMPS for the higher regenerator porosities. Heat transfer test data would be very worthwhile to obtain but are difficult to measure. It was felt that the straightforward steady-flow pressure drop tests would give at least some idea of the similarity of high-porosity regenerators to those for which both friction factor and heat transfer data exist. In the future, an existing NASA Glenn regenerator test rig may be used to perform heat transfer testing on high-porosity random fiber regenerator samples.

Introduction

NASA Glenn Research Center, the Department of Energy (DOE), and Stirling Technology Company (STC) of Kennewick, WA are developing a Stirling convertor for an advanced radioisotope power system to provide spacecraft on-board electric power for NASA deep space missions. Stirling is being evaluated as an alternative to replace RTG's (Radioisotope Thermoelectric Generators) with a high-efficiency power source and has been identified for potential use on the Europa Orbiter and Solar Probe missions. Stirling is also now being considered for unmanned Mars rovers, especially for missions of long duration. The efficiency of the Stirling system, in excess of 20%, will reduce the required amount of isotope by a factor of at least 3 compared to RTG's. This significantly reduces radioisotope cost, radiological inventory, and system cost and provides efficient use of scarce radioisotope resources.

STC has designed, fabricated, and completed first testing of the 55-We Technology Demonstration Convertor (TDC) under contract to DOE [1,2]. TDC's are now being tested singly and in dynamically-balanced opposed pairs by STC. The design power of 55 We and an efficiency of about 25% have been demonstrated for TDC operating conditions of 650°C hot-end temperature and 120°C cold-end temperature. The TDC's have been mapped over a range of temperatures and strokes. NASA Glenn is providing technical consulting for this effort under an Interagency Agreement with DOE.

NASA Glenn is conducting an in-house technology project to assist in developing the convertor for readiness for space qualification and mission implementation [3]. As part of this effort, the TDC has been characterized for electromagnetic interference/electromagnetic compatibility (EMI/EMC) and also successfully passed launch environment random vibration testing at qualification levels while operating at full stroke and full power. An independent performance verification and mapping of multiple TDC's is now being done. Heater head life assessment and NdFeB magnet aging characterization tasks are underway. Substitute organic materials for the linear alternator for use in a high radiation environment have been identified and have been incorporated by STC in TDC's recently built for GRC. Electromagnetic and thermal FEA for the linear alternator are also being conducted.

As part of the overall radioisotope Stirling development, NASA Glenn is evaluating key technology issues through the use of two NASA Phase II SBIR contracts with STC [4]. Under the first SBIR, STC demonstrated a synchronous connection of two thermodynamically independent Stirling convertors. Synchronization was achieved over a wide operating range, and a 40 to 50 fold reduction in vibrations compared to an unbalanced convertor was shown. System operation was also demonstrated with the synchronized convertors feeding a battery charger load. This connection method is now being used to connect the TDC's. The second SBIR contract is for the development of an Adaptive Vibration Reduction System (AVRS) that will further reduce vibration levels under normal operating conditions and will add the ability to adapt to any changing convertor conditions over the course of a mission.

As part of the Interagency Agreement, NASA Glenn performed a review of the TDC design. As part of this review, the HFAST computer code was used by NASA Glenn to analyze the TDC performance. HFAST was developed by Mechanical Technology, Inc. (MTI), in part, during the NASA effort to develop Stirling for space power for the SP-100 program. NASA Glenn has unrestricted rights to use and distribute HFAST. Comparisons were made to the STC GLIMPS computer code predictions for the TDC. GLIMPS was the primary code used by STC for design purposes. NASA Glenn also owns a license to use the GLIMPS code and has completed previous comparisons between HFAST and GLIMPS. NASA Glenn's past experience in using the two codes has not revealed any clear superiority of one code over the other. Although there are differences between them, both have been found to give reasonable overall results.

Overall comparisons of the GLIMPS and HFAST projections for the TDC showed that the two codes predicted similar performance with an adjustment for friction factor in the regenerator to make the two codes use similar regenerator friction factors. Without this adjustment, HFAST predicted much lower performance than did GLIMPS due to higher pressure drop losses through the regenerator.

The friction factor correlations used in each code were evaluated to understand these differences in pressure drop losses. This then led to a recommendation to complete steady-flow pressure drop tests to better determine the friction factor for the high-porosity regenerator that is used in the TDC design. NASA Glenn performed these tests in the NASA Glenn Flow Calibration Laboratory. This report describes the evaluation of the GLIMPS and HFAST friction factor correlations, the steady-flow testing and data reduction procedures, and the test results and comparisons to existing correlations.

Comparison of the HFAST and GLIMPS Friction Factor Correlations

STC was considering porosities of about 90-96% for the TDC random fiber regenerator design. Both GLIMPS and HFAST include a porosity dependence in their friction factor correlations. However, as shown by figures 1 and 2, HFAST has a much higher sensitivity to porosity than does GLIMPS, especially for screen regenerators. The agreement between the two codes is better for 94% random fiber regenerators as shown in figure 3, but the codes still vary by about 40%. The friction factor correlations for both codes agree well at 78% porosity for both types of regenerators.

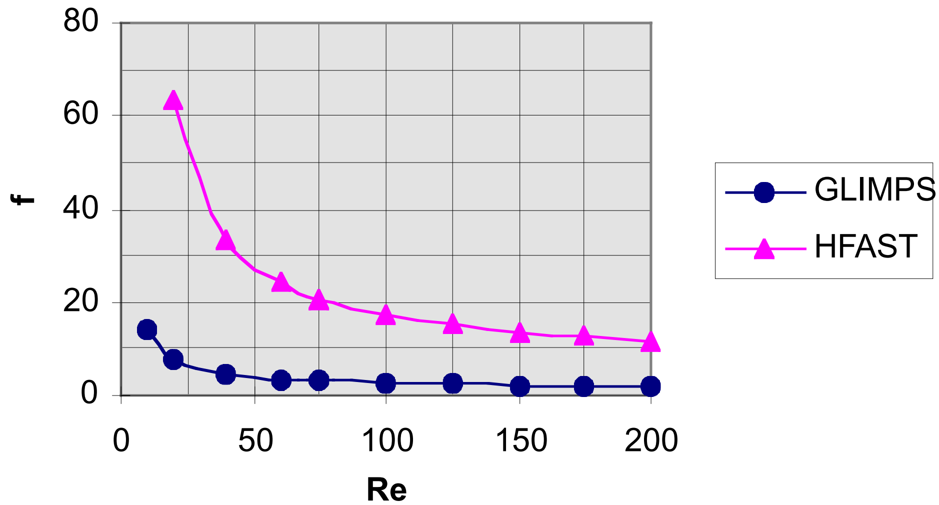

Figure 1 - GLIMPS and HFAST Friction Factor (f) vs. Reynolds Number (Re) for 94% Porosity Screen Regenerators.

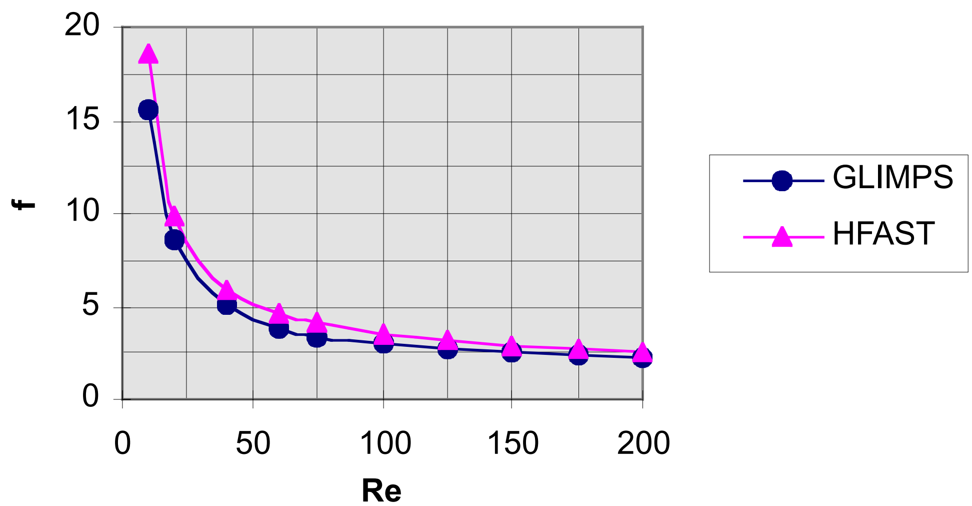

Figure 2 - GLIMPS and HFAST Friction Factor (f) vs. Reynolds Number (Re) for 78% Porosity Screen Regenerators.

Gedeon, in his final report on regenerator pressure drop and heat transfer testing in oscillating flow done at Ohio University [5], concluded that he could not determine any porosity dependence for the range of screens and felts (random fiber) that were tested in that project. These tests covered porosities of 62-78% for screens and 69-84% for felts. The HFAST manual states that its screen regenerator friction factor is based on Kays and London data and appears to be the same as used in an earlier version of GLIMPS. Kays and London show that their test data were taken for a range of porosities of 60-83% for screens [6]. GLIMPS (version 4.0) uses relationships for screens and random fibers that are based, in part, on earlier testing at Ohio University [7]. Pressure drop tests for steady and oscillating flow were also completed by

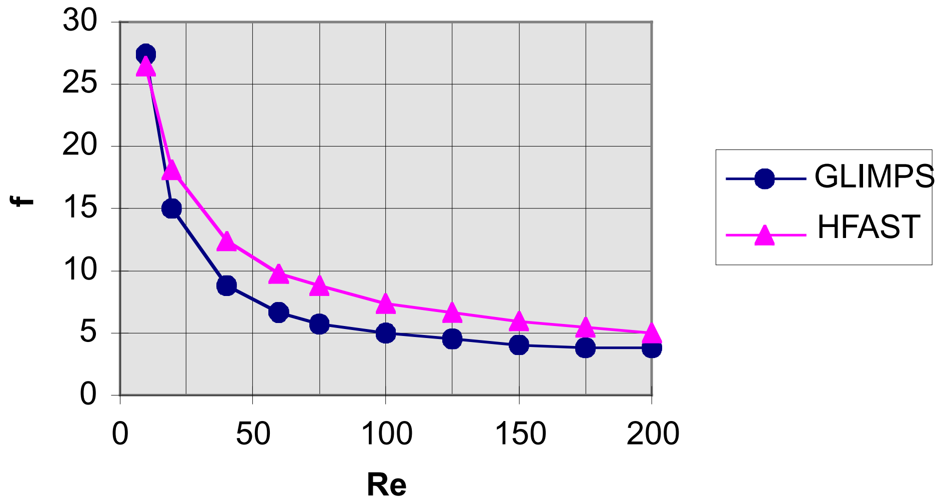

Figure 3 - GLIMPS and HFAST Friction Factor (f) vs. Reynolds Number (Re) for 94% Porosity Random Fiber Regenerators.

Sunpower, Inc. with the same rigs that were later moved to Ohio University [8]. These tests included regenerator porosities of 61-68% for screens and 80-84% for random fibers.

So it appears that neither code's friction factor correlations are based on regenerator test data at the regenerator porosities that were being considered for the design (90-96%). Due to this concern, NASA Glenn recommended that STC consider running a steady-flow pressure drop test on a high-porosity regenerator sample to get good empirical data on the friction factor for these regenerators. Gedeon indicated that steady-flow testing should be adequate for determining friction factors for typical regenerators [7]. Heat transfer test data would also be very important but are much more difficult to obtain. It was felt that the straightforward pressure drop tests would give at least some idea of the similarity of high-porosity regenerators to those for which both friction factor and heat transfer data exist.

Steady-Flow Pressure Drop Tests

STC agreed with the recommendation to conduct steady-flow pressure drop tests to determine the friction factor for a high-porosity regenerator sample. It was determined that the Flow Calibration Laboratory at NASA Glenn could do these tests in a quick, economical, and accurate manner.

STC selected and fabricated three random fiber regenerator test samples, one each at approximately 80%, 88%, and 96% porosities. The 80% porosity sample was chosen to give a comparison to the correlations used in GLIMPS and HFAST at a porosity level where empirical test data exist. The wire diameter used in all samples was 0.0009 in (22 microns). Each test sample consisted of two disks that were stacked in the sample holder. STC provided the length, diameter, and porosity of each disk. The values of diameter and porosity for the two disks in each sample were averaged and the lengths of the two disks were added to arrive at the following sample characteristics:

Sample	Ave. diameter, cm (in)	Ave. porosity	Length, cm (in)
80%, disks 1,2	2.22 (0.875)	0.797	2.57 (1.011)
88%, disks 3,4	2.22 (0.873)	0.878	2.53 (0.995)
96%, disks 5,6	2.21 (0.872)	0.957	2.42 (0.952)

STC also designed a test fixture, with inputs from NASA Glenn, and then fabricated this fixture to hold the samples for testing. The test fixture and the three test samples are shown in figure 4. The pressure taps can be seen on each half of the test fixture. A coarse wire screen was used on each half of the test fixture to help straighten the flow on each end of the regenerator sample. Photomicrographs of sections of each of the three test samples are shown in figure 5.

Consideration was given for flow testing with helium, nitrogen, or air. The TDC uses helium at about 2.41 MPa (350 psia) absolute mean pressure; the maximum flow rate in the regenerator predicted by GLIMPS was about 3.6 g/sec (0.008 lbm/sec). Based on discussions with the NASA Glenn Flow Calibration Laboratory and STC, it was decided that testing with air at about 0.69 MPa (100 psia) absolute inlet pressure provided the best combination of meeting the desired flow rates and producing the data in a timely, economical manner. STC provided their desired flow rates for testing. These were chosen to both cover the range of Reynolds numbers as appropriate for the TDC and to include higher flow rates that may be applicable to future convertor designs.

Figure 4 - Regenerator test samples and flow test fixture.

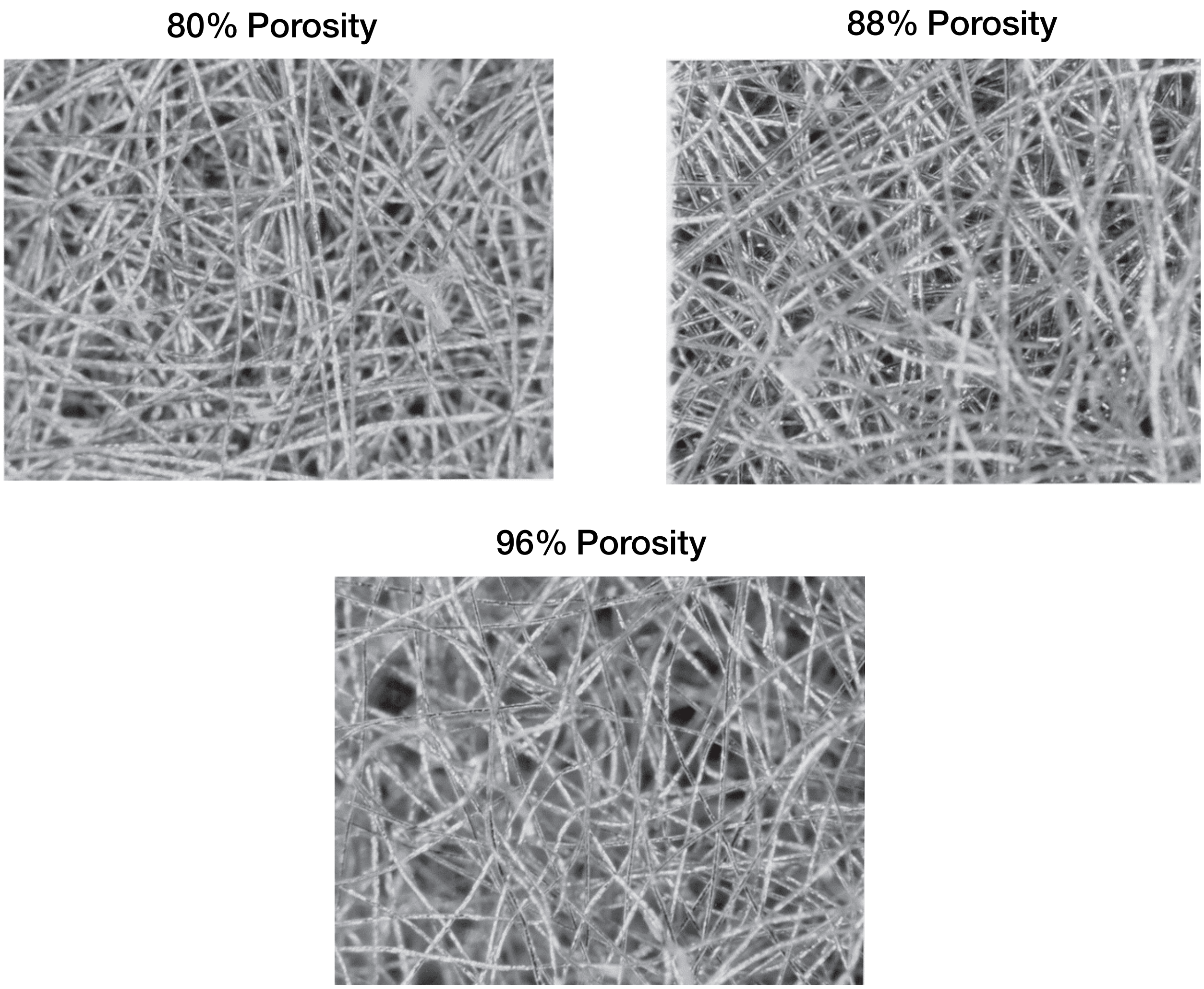

Figure 5 - Random Fiber Regenerator Samples at 50x Magnification.

The flow tests were then completed by the NASA Glenn Flow Calibration Laboratory. The test data are included in Appendix A. A test was also run with no sample to determine the effect of the coarse screens that were used as flow straighteners. There was no measurable pressure drop for this test until the flow rate reached 5.4 g/sec (0.012 lbm/sec). At the highest flow rate, 11.8 g/sec (0.026 lbm/sec), the pressure drop was only 0.17 kPa (0.025 psid). It was felt that this pressure drop was negligible, and it was ignored in the data reduction.

Figure 6 shows the measured steady-flow pressure drop as a function of mass flow rate for each of the three samples. Testing was done with air at 0.69 MPa (100 psia) absolute inlet pressure for all samples. Flow conditions were chosen to include the range of Reynolds numbers that were expected to occur in the actual convertor. Tests were also run in each of the two different flow directions for the 96% porosity sample. These results are shown in figure 7 and can be seen to be essentially identical. Flow directions 5-6 and 6-5 refer to the regenerator disk numbers 5 and 6, which were the two 96% porosity disks that were used in this sample.

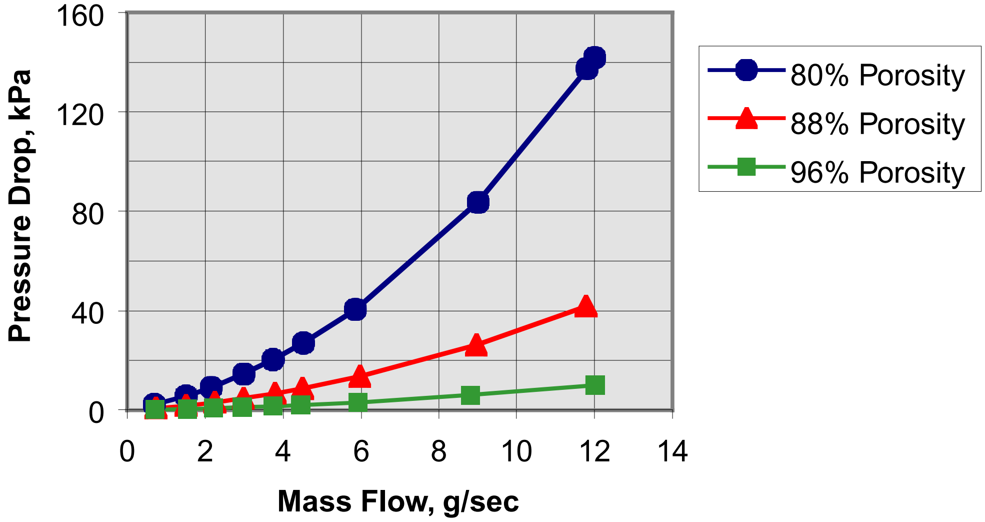

Figure 6 - Pressure Drop vs. Mass Flow for Random Fiber Regenerator Samples.

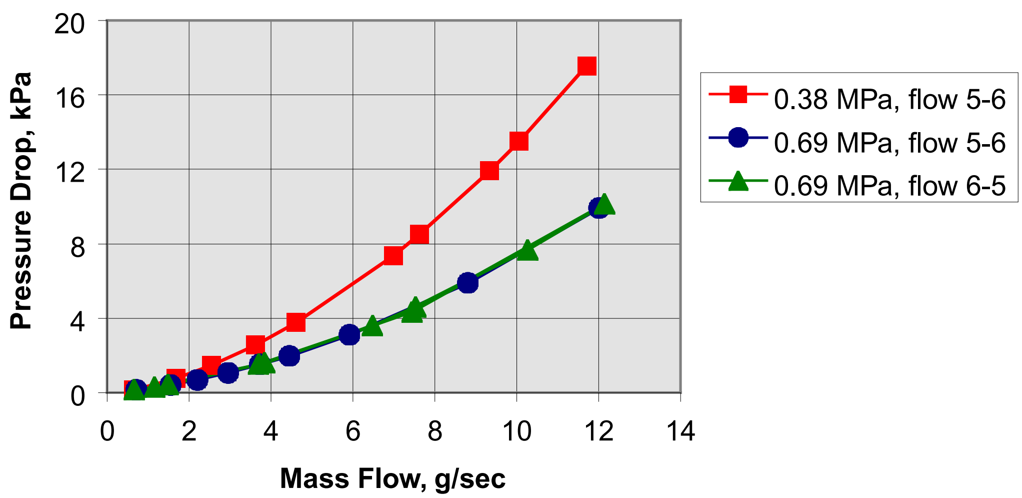

Figure 7 - Pressure Drop vs. Mass Flow for 96% Porosity Random Fiber Regenerator Sample for Different Inlet Pressures and Different Flow Directions.

A test was also run at 0.38 MPa (55 psia) absolute inlet pressure for the 96% porosity sample to check the effect of ΔP/P, and these pressure drop results are compared to those for the 0.69 MPa (100 psia) absolute inlet pressure in figure 7. An expansion factor correction based on the ΔP/P [9], calculated using inlet pressure, was made on one of these sets of data to correct it back to the data at the other pressure level. The thought was to then use this type of correction on any data points that had high ratios of ΔP/P. However, it was found that similar results were obtained by using the average of the inlet and outlet pressures when calculating the density of the fluid so this method was used for all data and assumed to be satisfactory for any data points that had a high ratio of ΔP/P. In general, it was preferred to maintain the ΔP/P below 0.1. Appendix A shows that most of the test data had a ΔP/P of less than 0.06.

The measured flow data were provided to STC. STC and NASA Glenn first independently reduced this data to friction factor versus Reynolds number and then resolved any significant differences. The Reynolds numbers and friction factors as calculated by NASA Glenn are included in Appendix A. These values were obtained from the test data by using the following equations:

$$Re = mdot * D_h / (\mu * A_{sample} * p)$$

$$D_h = p * d_w / (1-p)$$

where:

Re – Reynolds number
mdot – mass flow rate, lbm/sec
D_h – regenerator sample hydraulic diameter, ft
μ - fluid absolute viscosity, lbm/ft-sec
A_{sample} – total cross-sectional area of the regenerator sample, ft^2
p - regenerator sample porosity
d_w – regenerator sample wire diameter, ft

$$f = \Delta P * D_h * (A_{sample} * p)^2 * \rho * 2g_c * 144 / (L * mdot^2)$$

where:

f – friction factor
ΔP – pressure drop, psi
D_h – regenerator sample hydraulic diameter, ft (as defined in previous equation)
A_{sample} – total cross-sectional area of the regenerator sample, ft^2
p - regenerator sample porosity
ρ - fluid density, lbm/ft^3
g_c – gravitational conversion factor = 32.2 lbm-ft/(lbf-sec^2)
L – regenerator sample length, ft
mdot – mass flow rate, lbm/sec

Friction factor versus Reynolds number (based on NASA Glenn's data reduction) is shown for each of the samples in figure 8. The curves for the 80% and 88% porosity samples are very similar while the friction factor is significantly higher for the 96% porosity sample. Figure 9 shows the friction factor versus Reynolds number results for the two different pressure levels run for the 96% porosity sample. They are identical for most of the Reynolds number range with significant variations at the lower Reynolds numbers. These variations appear to be caused

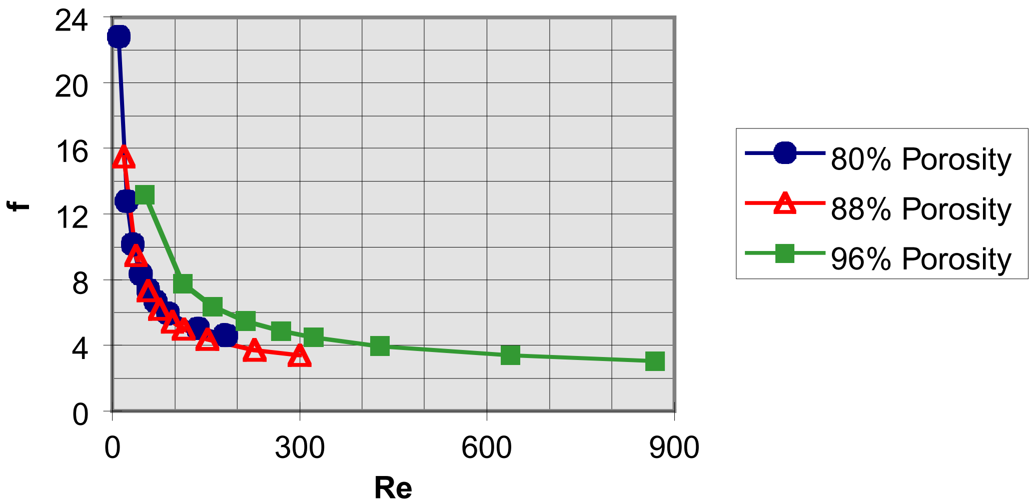

Figure 8 - Friction Factor (f) vs. Reynolds Number (Re) for Random Fiber Regenerator Samples.

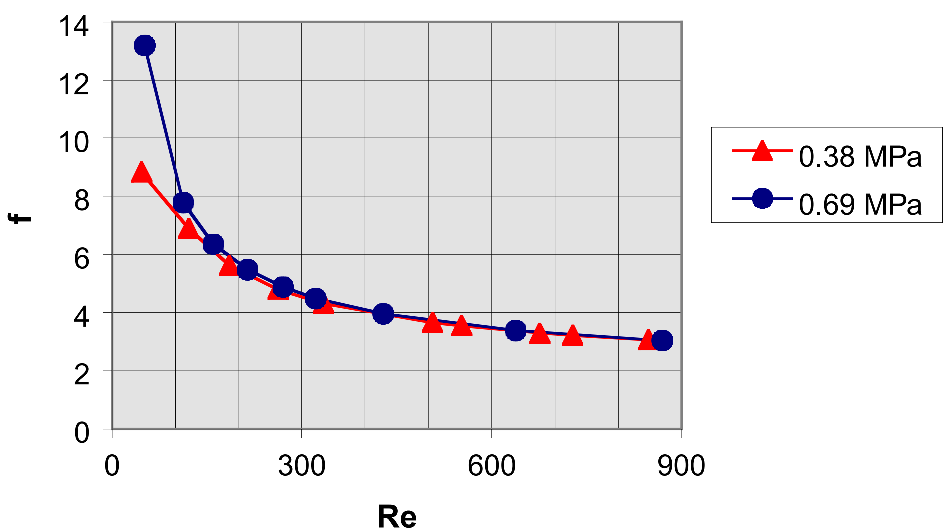

Figure 9 - Friction Factor (f) vs. Reynolds Number (Re) for 96% Porosity Random Fiber Regenerator Sample for Different Inlet Pressures.

by errors in the measurement of pressure drop as the values of the pressure drop are very low for these data points.

Estimated errors for all data are shown in figure 10. Errors were calculated based on the following [10]:

$$w_R = [((\partial R/\partial x_1)w_1)^2 + ((\partial R/\partial x_2)w_2)^2 + \ldots + ((\partial R/\partial x_n)w_n)^2]^{1/2}$$

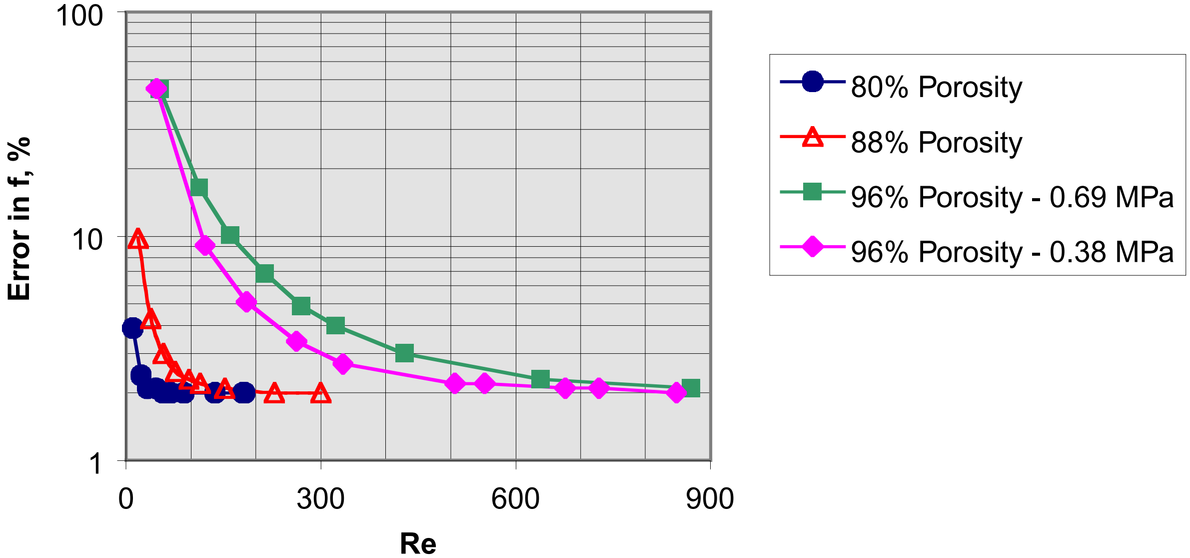

Figure 10 - Percent Error in the Friction Factor (f) vs. Reynolds Number (Re) for Random Fiber Regenerator Flow Tests (the error in Reynolds number is 1.0% of reading for all points).

where:

w_R – uncertainty of the calculation, units of the calculation
$\partial R/\partial x_1, \partial R/\partial x_2, \ldots, \partial R/\partial x_n$ – partial derivatives of the calculation with respect to each independent variable in the calculation
$w_1, w_2, \ldots, w_n$ – uncertainties of the independent variables, units of the independent variables

The measurement error for the mass flow rate was 1% of reading for all data points. The error in Reynolds number was taken as 1% of reading based on just this error in the mass flow rate. Uncertainties in the pressure drop, mass flow rate, inlet pressure, and temperature were included in the calculation of uncertainty for the friction factor. Figure 10 shows the error in the friction factor as a function of Reynolds number for each of the three samples; curves are shown for each pressure level for the 96% porosity data. Most of the errors in friction factor are less than 10%. Significantly higher errors occur for the low Reynolds number points for the 96% porosity curves. These larger errors appear to explain the difference in friction factor for the two different pressure levels at these low Reynolds numbers for the 96% porosity sample.

The friction factor curves for the three samples are compared with three correlations in figures 11-13. The three correlations shown are those for GLIMPS, HFAST, and the latest correlation based on test data taken at Ohio University [5]. All three correlations agree well with the test data for the 80% porosity sample (figure 11). Figure 12 shows that the GLIMPS correlation and the correlation based on test data taken at Ohio University agree well with the test data for the 88% porosity sample while the HFAST correlation yields a higher friction factor. Finally, figure 13 shows the same comparison for the 96% porosity sample. Now, HFAST compares the best with the test data (data shown is for the 0.69 MPa (100 psia) absolute inlet pressure only) at the

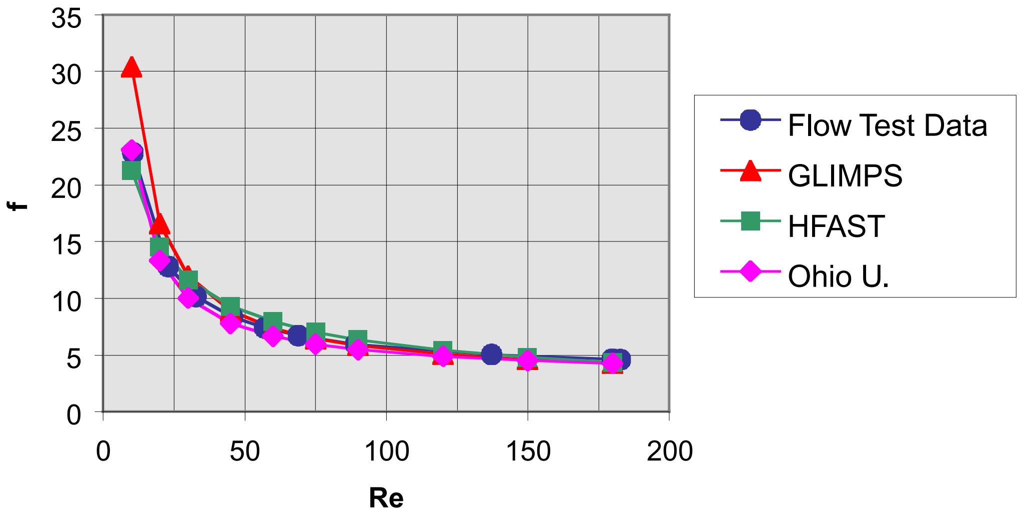

Figure 11 - Friction Factor (f) vs. Reynolds Number (Re) for 80% Porosity Random Fiber Regenerator - Comparison of Test Data with Correlations.

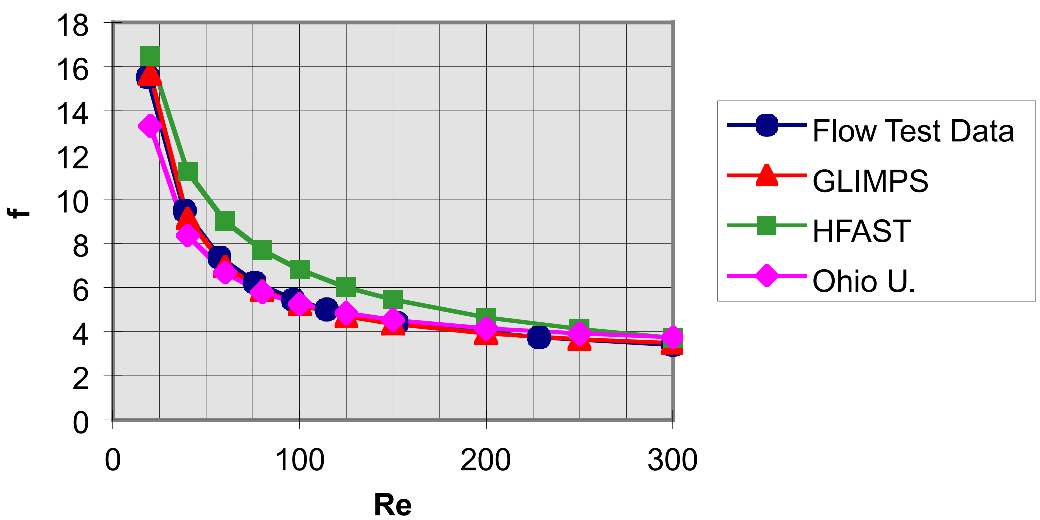

Figure 12 - Friction Factor (f) vs. Reynolds Number (Re) for 88% Porosity Random Fiber Regenerator - Comparison of Test Data with Correlations.

lower Reynolds numbers, 0-300, which was the expected range for the TDC design with a 96% porosity regenerator.

Following analyses of these results, STC decided to use the GLIMPS correlation for all regenerator porosities up to 88%. They then derived a curve based on the GLIMPS friction factor for 88% porosity and the 96% porosity test data (average of the curves for 0.38 MPa (55 psia) and 0.69 MPa (100 psia) absolute inlet pressures) that extrapolates between these for porosities from 88-96%. Figure 14 shows the GLIMPS friction factor curve for 88% porosity and the two test data curves for the 96% porosity sample over the Reynolds number range of 0-350.

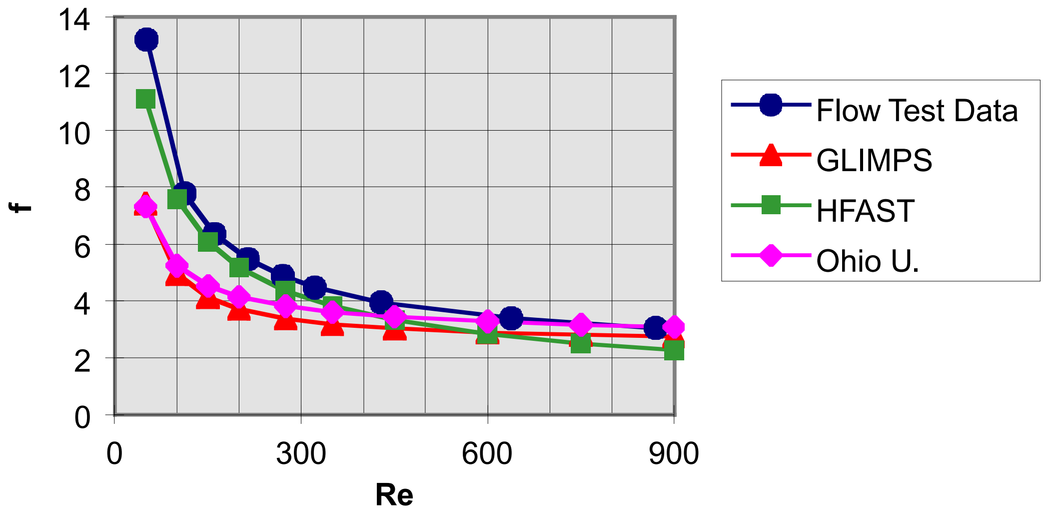

Figure 13 - Friction Factor (f) vs. Reynolds Number (Re) for 96% Porosity Random Fiber Regenerator - Comparison of Test Data with Correlations.

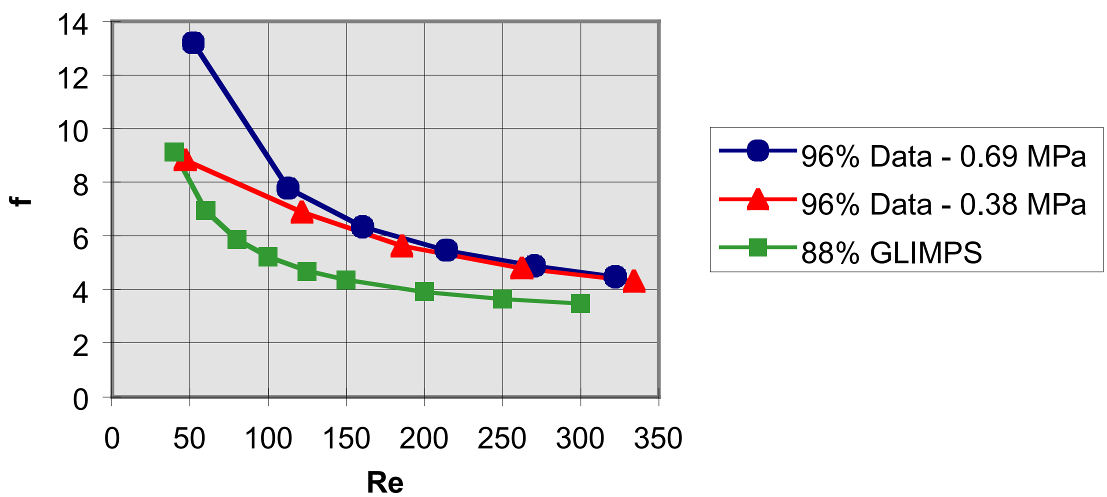

Figure 14 - Input Curves for STC Correlation for Friction Factor for Random Fiber Regenerator Porosities Between 88% and 96%.

Based on these overall results and recognizing that heat transfer data does not exist for the higher porosities, STC decided to limit the design regenerator porosity to a value no greater than 90%. STC GLIMPS results with the new friction factor input for 88-96% porosities showed that the final design optimized around 90% porosity (with no constraint on the porosity), and this is the regenerator porosity that was then used for the TDC. It should be kept in mind that no adjustments were made to the heat transfer correlation used in GLIMPS for the higher porosities. In the future, an existing NASA Glenn regenerator test rig may be used to perform heat transfer testing on high-porosity random fiber regenerator samples.

Conclusions

Prior to the testing discussed in this report, the random fiber regenerator for the DOE/STC TDC design was optimizing at porosities of about 96%. Comparisons of the GLIMPS and HFAST computer codes showed large differences in the regenerator friction factor correlations for these porosities although the correlations compared well for porosities around 80%. It was felt that the large differences for the higher porosities were due to the correlations being extrapolated too far from existing regenerator test data on which the correlations were based. The highest-porosity regenerator flow test data from which the GLIMPS and HFAST correlations were derived appear to be for porosities of around 84%. Thus, it was recommended to perform flow tests on high-porosity random fiber regenerators to better determine the friction factor.

Steady-flow tests were run for 80%, 88%, and 96% porosity random fiber regenerator samples, and the data were reduced to Reynolds number and friction factor. The results showed that the 80% and 88% porosity samples had similar characteristics while the 96% porosity sample had significantly higher friction factors for given Reynolds numbers compared to the lower porosities. STC used this data to derive a modified regenerator friction factor correlation for use in GLIMPS for porosities greater than 88%. Using this new correlation, the final regenerator design optimized at a porosity of 90%.

It is important to note that no adjustments were made to the heat transfer correlation used in GLIMPS for the higher regenerator porosities. Heat transfer test data would be very worthwhile to obtain but are difficult to measure. It was felt that the straightforward pressure drop tests would give at least some idea of the similarity of high-porosity regenerators to those for which both friction factor and heat transfer data exist. In the future, an existing NASA Glenn regenerator test rig may be used to perform heat transfer testing on high-porosity random fiber regenerator samples.

References

1. White, M.A.; Qiu, S.; and Augenblick, J.E.: Preliminary Test Results from a Free-Piston Stirling Engine Technology Demonstration Program to Support Advanced Radioisotope Space Power Applications, Proceedings of the Space Technology and Applications International Forum, 2000.

2. White, M.; Qiu, S.; Augenblick, J.; Peterson, A.; and Faultersack, F.: Positive Results from a Free-Piston Stirling Engine Technology Demonstration Program for Advanced Radioisotope Space Power Systems; Proceedings of the 35th Intersociety Energy Conversion Engineering Conference, paper no. AIAA–2000–3023, 2000.

3. Thieme, L.G. and Schreiber, J.G.: NASA GRC Technology Development Project for a Stirling Radioisotope Power System, Proceedings of the 35th Intersociety Energy Conversion Engineering Conference, paper no. AIAA–2000–2840, NASA/TM—2000-210246, 2000.

4. Thieme, L.G.; Qiu, S.; and White, M.A.: Technology Development for a Stirling Radioisotope Power System, Proceedings of the Space Technology and Applications International Forum - 2000, NASA/TM—2000-209791, 2000.

5. Gedeon, D. and Wood, J.G.: Oscillating-Flow Regenerator Test Rig: Hardware and Theory With Derived Correlations for Screens and Felts, NASA CR–198442, 1996.

6. Kays, W.M. and London, A.L.: Compact Heat Exchangers, 2nd Edition, McGraw-Hill, Inc., 1964.

7. Gedeon, D. and Wood, J.G.: Oscillating-Flow Regenerator Test Rig: Woven Screen and Metal Felt Results, Ohio University Center for Stirling Technology Research, status report for NASA grant NAG3–1269, 1992.

8. Koester, G.; Howell, S.; Wood, G.; Miller, E.; and Gedeon, D.: Oscillating Flow Loss Test Results in Stirling Engine Heat Exchangers, NASA CR–182288, 1990.

9. Flow of Fluids Through Valves, Fittings, and Pipe; Engineering Division of the Crane Co., Chicago; Technical Paper No. 410, 1957.

10. Holman, J.P.: Experimental Methods for Engineers, 2nd Edition, McGraw-Hill, Inc., 1971.

Appendix A – Steady-Flow Test Data and Reduced Data

Sample: 80% Porosity - Disks 1,2
Flow Direction: 1-2 Date: 3/3/98

Inlet Pressure psia	Inlet Pressure kPa	Flow Rate lbm/sec	Flow Rate g/sec	Pressure Drop psid	Pressure Drop kPa	Delta P/P	Temp. degrees F	Temp. degrees C	Re	f (Darcy)
99.93	689.0	0.00152	0.689	0.30	2.1	0.003	75.3	24.1	10.5	22.8
100.22	691.0	0.00332	1.51	0.81	5.6	0.008	75.5	24.2	22.9	12.8
99.97	689.3	0.00474	2.15	1.32	9.1	0.013	75.5	24.2	32.8	10.2
100.14	690.5	0.00660	2.99	2.11	14.5	0.021	75.5	24.2	45.6	8.4
100.11	690.2	0.00825	3.74	2.92	20.2	0.029	75.4	24.1	57.0	7.4
100.02	689.6	0.00997	4.52	3.90	26.9	0.039	75.1	23.9	68.9	6.7
100.02	689.6	0.0129	5.86	5.86	40.4	0.059	74.9	23.8	89.2	6.0
100.00	689.5	0.0199	9.00	12.12	83.5	0.121	75.2	24.0	137	5.0
100.09	690.1	0.0260	11.8	19.94	137.4	0.199	75.5	24.2	180	4.62
100.01	689.5	0.0264	12.0	20.56	141.8	0.206	75.5	24.2	183	4.60

Sample: 88% Porosity - Disks 3,4
Flow Direction: 3-4 Date: 3/3/98

Inlet Pressure psia	Inlet Pressure kPa	Flow Rate lbm/sec	Flow Rate g/sec	Pressure Drop psid	Pressure Drop kPa	Delta P/P	Temp. degrees F	Temp. degrees C	Re	f (Darcy)
100.33	691.7	0.00162	0.735	0.10	0.7	0.001	74.9	23.8	18.7	15.5
100.11	690.2	0.00331	1.50	0.27	1.8	0.003	74.7	23.7	38.2	9.5
100.40	692.3	0.00494	2.24	0.46	3.2	0.005	74.7	23.7	57.1	7.3
100.46	692.6	0.00658	2.98	0.69	4.7	0.007	74.9	23.8	76.0	6.2
100.15	690.5	0.00837	3.80	0.98	6.7	0.010	75.0	23.9	96.7	5.4
99.96	689.2	0.00991	4.50	1.26	8.7	0.013	75.2	24.0	114	5.0
100.00	689.5	0.0132	5.97	1.96	13.5	0.020	75.3	24.1	152	4.38
100.05	689.8	0.0198	8.96	3.79	26.1	0.038	75.4	24.1	228	3.72
99.97	689.3	0.0260	11.8	6.05	41.7	0.060	75.6	24.2	300	3.39

Sample: 96% Porosity - Disks 5,6
Flow Direction: 5-6 Date: 3/3/98

Inlet Pressure psia	Inlet Pressure kPa	Flow Rate lbm/sec	Flow Rate g/sec	Pressure Drop psid	Pressure Drop kPa	Delta P/P	Temp. degrees F	Temp. degrees C	Re	f (Darcy)
100.35	691.9	0.00158	0.717	0.02	0.2	0.0002	76.0	24.4	51.9	13
100.58	693.5	0.00343	1.56	0.06	0.4	0.001	76.1	24.5	113	7.8
100.36	691.9	0.00488	2.21	0.10	0.7	0.001	76.4	24.7	160	6.4
100.59	693.5	0.00652	2.96	0.16	1.1	0.002	76.6	24.8	214	5.5
100.31	691.6	0.00823	3.73	0.22	1.5	0.002	76.6	24.8	270	4.9
100.42	692.4	0.00981	4.45	0.29	2.0	0.003	76.6	24.8	322	4.5
100.10	690.1	0.0131	5.92	0.45	3.1	0.005	76.6	24.8	429	4.0
100.49	692.9	0.0194	8.81	0.86	5.9	0.009	76.6	24.8	638	3.38
100.00	689.5	0.0265	12.0	1.44	9.9	0.014	76.6	24.8	870	3.04
55.01	379.3	0.00143	0.649	0.02	0.2	0.0004	75.4	24.1	47.0	9
56.52	389.7	0.00370	1.68	0.11	0.8	0.002	74.9	23.8	122	6.9
56.13	387.0	0.00565	2.56	0.22	1.5	0.004	74.8	23.8	186	5.6
55.48	382.5	0.00799	3.62	0.37	2.6	0.007	74.7	23.7	262	4.8
55.01	379.3	0.0102	4.61	0.55	3.8	0.010	74.6	23.7	334	4.3
55.23	380.8	0.0154	7.00	1.07	7.4	0.019	74.6	23.7	507	3.66
54.98	379.1	0.0168	7.63	1.24	8.5	0.022	74.6	23.7	552	3.54
55.02	379.3	0.0206	9.33	1.73	11.9	0.031	74.7	23.7	676	3.30
55.06	379.6	0.0222	10.1	1.96	13.5	0.036	74.9	23.8	728	3.21
54.91	378.6	0.0258	11.7	2.55	17.5	0.046	75.2	24.0	848	3.06

Sample: 96% Porosity - Disks 5,6
Flow Direction: 6-5 Date: 3/3/98

Inlet Pressure psia	Inlet Pressure kPa	Flow Rate lbm/sec	Flow Rate g/sec	Pressure Drop psid	Pressure Drop kPa	Delta P/P	Temp. degrees F	Temp. degrees C
100.14	690.5	0.00146	0.662	0.02	0.2	0.0002	75.8	24.3
100.16	690.6	0.00329	1.49	0.06	0.4	0.001	75.7	24.3
100.19	690.7	0.00816	3.70	0.22	1.5	0.002	75.8	24.3
101.04	696.7	0.0143	6.48	0.52	3.6	0.005	75.9	24.4
100.31	691.6	0.0166	7.53	0.67	4.6	0.007	75.9	24.4
100.02	689.6	0.0226	10.3	1.11	7.7	0.011	76.0	24.4
100.06	689.8	0.0268	12.1	1.47	10.1	0.015	76.0	24.4
104.52	720.6	0.0164	7.44	0.63	4.3	0.006	76.1	24.5
101.47	699.6	0.00848	3.85	0.23	1.6	0.002	76.1	24.5
100.07	690.0	0.00256	1.16	0.05	0.3	0.0004	76.2	24.6

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13. ABSTRACT ***(Maximum 200 words)***

NASA Glenn Research Center, the Department of Energy (DOE), and Stirling Technology Company (STC) of Kennewick, Washington are developing a Stirling convertor for a high-efficiency Stirling Radioisotope Power System to provide electric power for NASA Space Science missions. STC is developing the 55-We Technology Demonstration Convertor (TDC) under contract to DOE. Steady-flow tests were completed to determine the friction factor for the high-porosity regenerators that are used in the TDC. STC fabricated a flow test fixture and three random fiber regenerator test samples, one each at approximately 80, 88, and 96 percent porosities. The flow tests were then completed by the NASA Glenn Flow Calibration Laboratory, and the data reduced to Reynolds number and friction factor. The results showed that the 80 and 88 percent porosity samples had similar characteristics while the 96 percent porosity sample had significantly higher friction factors for given Reynolds numbers compared to the samples with lower porosities. Comparisons were also made between the test data and existing correlations. STC used this data to derive a modified regenerator friction factor correlation for use in the Stirling design code GLIMPS for porosities greater than 88 percent. Using this new correlation, the final optimized regenerator design porosity was reduced from 96 to 90 percent.

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