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Overview 2004 of NASA-Stirling Convertor CFD Model Development and Regenerator R&D Efforts

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Abstract. This paper reports on accomplishments in 2004 in (1) development of Stirling-convertor CFD models at NASA Glenn and via a NASA grant, (2) a Stirling regenerator-research effort being conducted via a NASA grant (a follow-on effort to an earlier DOE contract), and (3) a regenerator-microfabrication contract for development of a "next-generation Stirling regenerator." Cleveland State University is the lead organization for all three grant/contractual efforts, with the University of Minnesota and Gedeon Associates as subcontractors. Also, the Stirling Technology Company and Sunpower, Inc. are both involved in all three efforts, either as funded or unfunded participants. International Mezzo Technologies of Baton Rouge, Louisiana, is the regenerator fabricator for the regenerator-microfabrication contract. Results of the efforts in these three areas are summarized.

INTRODUCTION

A high-efficiency Stirling Radioisotope Generator (SRG) for use on potential NASA Space Science missions is being developed by the Department of Energy (DOE), Lockheed Martin, Stirling Technology Company (STC), and NASA Glenn Research Center (GRC). Potential missions include providing spacecraft onboard-electric power for deep-space missions or power for unmanned Mars rovers. GRC is also developing advanced technology for Stirling convertors, aimed at improving specific power and efficiency of the convertor and the overall power system. Performance and mass improvement goals have been established for second- and third-generation Stirling radioisotope power systems. Efforts are underway to achieve these goals, both in-house at GRC and via grants and contracts. These efforts include validation of a multi-dimensional (multi-D) Stirling computational-fluid-dynamics (CFD) model, high-temperature materials, advanced controllers, low-vibration techniques, advanced regenerators, and a lightweight convertor (Thieme, 2004; Schreiber, 2004). The objective of this paper is to report on the NASA multi-D code validation effort and NASA regenerator R&D efforts.

MULTI-DIMENSIONAL STIRLING MODEL DEVELOPMENT AND VALIDATION

Mahkamov first reported on development of a multi-D model of a complete Stirling engine (Mahkamov, 2000). He recently reported on using the commercial Fluent code for Stirling engine 3-D modeling (Mahkamov, 2003).

A NASA grant to Cleveland State University (CSU) for development of a multi-D Stirling engine model resulted in delivery of the 2-D CSUmod model to NASA Glenn (GRC) in 2003 (Ibrahim, 2004a). This model was developed using the CFD-ACE commercial code. The grant also included fabrication plus oscillating- and steady-flow visualization and testing of a 90-degree-turn test module at the University of Minnesota (UMN) (Adolfson, 2002, 2003). A new 180-degree-turn test module was designed and fabrication was begun at UMN before the grant ended on July 31, 2004. A new grant to CSU, and subcontractors UMN and Gedeon Associates, was awarded on Sept. 1, 2004 to continue multi-D code validation and support of multi-D code development.

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In the last year, GRC substantially increased its level of in-house effort on CFD modeling of Stirling convertors. The 2-D model of STC's ~55 We Technology Demonstration Convertor (TDC), developed based on the CSUmod model, was further developed (Wilson, 2004a). A Fluent commercial code license was purchased to complement the CFD-ACE commercial code. A 32 processor Microway computer cluster was purchased to enhance the capabilities provided by an earlier 8 processor Dell cluster (Dyson, 2004a; Wilson, 2004a). Dyson has also suggested new approaches for enhancing the speed and accuracy of future Stirling multi-D codes (Dyson, 2004a).

The Stirling engine companies, STC and Sunpower, have both begun to make some use of multi-D Stirling models to support their engine-development efforts (Qiu, 2004; Wood, 2004a).

GRC Stirling-Convertor Model-Development Plans and Progress

Dyson recently drafted a long-range Stirling analysis plan or "roadmap" for GRC's Thermal Energy Conversion Branch (Dyson, 2004b). Some of the elements of this plan are outlined below. Also below, are summaries of plans and progress at GRC in the areas of Sage 1-D modeling and development of commercial multi-D transient models of Stirling convertors.

Stirling-Convertor Multi-D Model-Development Plans

Dyson has suggested that GRC's future multi-D CFD efforts should fall into the following five areas: (1) Help develop upgrades to current commercial transient codes (e.g., improve porous media models, improve conjugate heat transfer convergence). (2) Use available multi-D CFD codes for "engineering services" or engine component modeling, as needed; for example, the CFD-ACE code was used to model the cooling jacket of the laboratory version of STC's TDC engine—since cooler-pressure-vessel-wall temperatures cannot easily be measured (Wilson, 2004b). (3) Develop a new transient code based on high-order accuracy numerical techniques to enhance speed of convergence and accuracy (Dyson, 2002, 2004a). (4) Consider development of 2-D and 3-D steady-periodic Stirling design codes, based on techniques similar to those used in Gedeon Associates' Sage 1-D model (Gedeon, 1999). (4) Develop high-accuracy, fast-convergence 1-D, 2-D and 3-D transient thermodynamic models suitable for integration with GRC's Stirling Dynamic Model or SDM (Regan, 2004; Lewandoski, 2004).

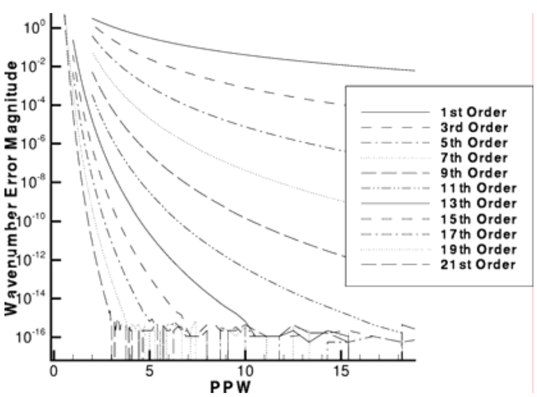

FIGURE 1. Wavelength Error Magnitude as a Function of Grid Points per Wavelength (PPW) for Numerical Techniques of Various Orders of Accuracy.

Dyson noted that most computational Stirling analysis techniques use low-order, finite-volume approaches because high-order accuracy is considered too difficult or expensive (Dyson 2004a). He also noted that new high-order-accuracy techniques overcome these earlier difficulties. To illustrate the benefits of high-order-accuracy techniques, Figure 1 shows wavelength error magnitude as a function of grid points per wave length (PPW) for numerical techniques of various orders of accuracy. The maximum wavenumber, for a geometric length, L, is the maximum number of waves (or the highest harmonic) that can be represented along the length, given a number of grid points, N. The plot shows that the PPW required to reduce the error magnitude to a given level, can be reduced by going to higher-order-accuracy techniques. Prof. Brad Egar of Arkansas State University, awarded an Arkansas State Grant funded by NASA, has proposed to work with GRC to investigate application of high-order-accuracy numerical techniques to Stirling modeling (Egar, 2004).

Sage 1-D Steady-Periodic Code Modeling Plans at GRC

GRC is devoting an increased level of effort to simulating several Stirling engines and a thermoacoustic engine with the Sage 1-D code. A GRC Sage Stirling-engine model exists for STC's TDC engine. Sage models are to be set up for comparison with engine data from STC's ~55 We TDCs 5&6, 7&8, 13&14 and 15&16 and from Sunpower's

~35 We “Buzz” engine (Wood, 2004b). It is also likely that a Sage model will be set up for Sunpower’s new Advanced Stirling Convertor (ASC) engine (Wood, 2004a). Also, the TRW/Northrup Grumman ~100 We Thermoacoustic Stirling Heat Engine will be modeled with Sage (Petach, 2004).

Barry Penswick (Penswick 2004) proposed that GRC develop a new Sage model of the TDC hardware via a step-by-step approach to identify the impact on the Sage solution of adding increasing levels of complexity to the hardware models. The process involves keeping careful records of the overall cycle energy balance and the various losses as each new level of complexity is added to the Sage model. Careful tracking of the losses may identify areas where improvements can be made in the hardware. The process should be carried out for operating conditions corresponding to a well-documented engine test point; thus, model predictions at each stage of increasing complexity can be compared with engine performance test data. Penswick’s suggestion is currently being carried out at GRC (Demko 2004).

Progress and Problems in Development of a Commercial Code Multi-D Stirling Model at GRC

Wilson reported on progress at GRC in further development of a multi-D model of STC’s TDC (Wilson 2004a). He had added calculations of an overall energy balance and, with just a few engine cycles calculated, observed substantial improvement in the energy balance with each additional cycle. Plots of working space temperature, pressure, volume variations, and integrated component heat rates were shown over the first cycle to illustrate the transient nature of the solution. U-velocity vectors and contours from his report are reproduced in Figure 2.

This figure shows the current 2-D representation of the engine’s 3-D cooler and heater geometries. Thus the 3-D cooler and heater’s radial fins and flow passages are replaced by concentric-annular fins and flow passages of approximately equal flow area, hydraulic diameter and overall heat-transfer area. Then, having started with a 2-D axisymmetric representation of the engine, a requirement to use “arbitrary interfaces” to represent sliding-grid interfaces between the displacer and the appendix gap (not visible in Figure 2), forced use of a 3-D pie-slice representation of this equivalent 2-D geometry (since “arbitrary interfaces” were not available in CFD-ACE’s 2-D axisymmetric mode).

The color velocity contours in Figure 2, plus the legend, indicate that the flow in the upper two cooler flow passages is in one direction, while the flow in the lower flow passage is in the opposite direction—with the displacer at it’s mean position (in traveling from the hot to the cold end). If this were the real engine geometry, if steady-periodic convergence had been achieved, and if this non-uniformity in flow persisted over a significant portion of the cycle—the results would indicate a substantial loss in performance. Note that the Sage 1-D code used to design the STC 55 We (TDC) engine assumes uniform axial flow and deviations from such uniformity imply a loss in performance.

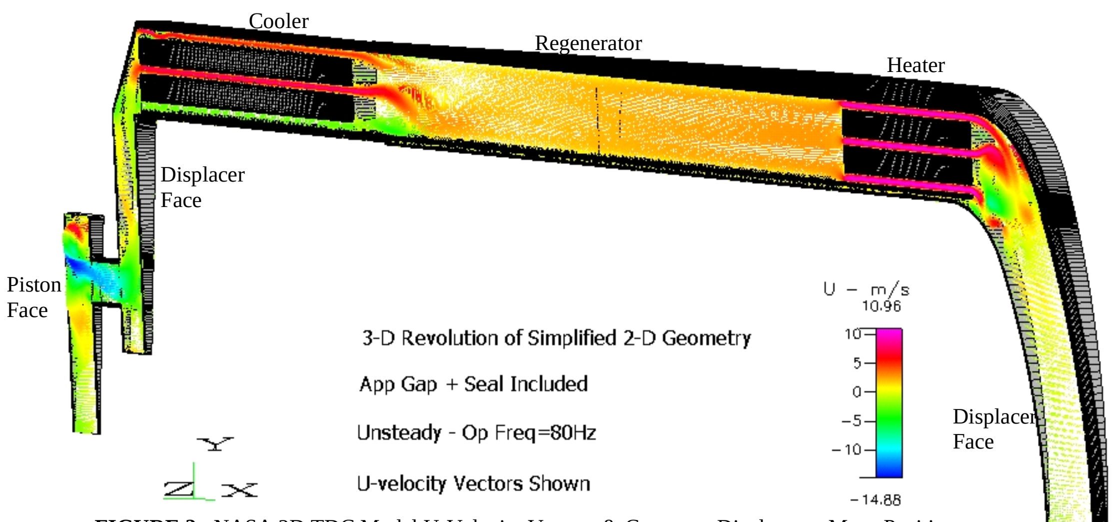

FIGURE 2. NASA 2D TDC Model U-Velocity Vectors & Contours; Displacer at Mean Position

Thus, to maximize the usefulness of a multi-D TDC engine model, it seems essential that the model be converted to the real 3-D engine geometry as soon as possible. Until now, however, the simpler faster-to-converge 2-D geometry has been used to address changes in the engine geometry from the CSUmod design (e.g., including an appendix-gap model, and solving grid-compression problems that resulted with the smaller TDC clearances at displacer top-dead-center and bottom-dead-center positions). Overall and component energy balances have also been incorporated.

It is anticipated that transition to parallel computations on GRC's Dell and Microway clusters will soon enhance the practicality of modeling the real engine (3-D) geometry. However, there are other problems to be addressed in use of commercial codes (CFD-ACE and Fluent in particular) to develop multi-D models of Stirling engines:

(1) The equilibrium-porous-media models in the commercial codes must be replaced by non-equilibrium models, to allow regenerator solid and gas to be modeled with different temperatures. Several non-equilibrium models have been identified and tests at UMN (Niu 2004a, 2004b) are providing values of empirical coefficients (permeability, inertial coefficient, and thermal dispersion) necessary to implement these models.

(2) A number of RANS (Reynolds Averaged Navier Stokes) turbulence models are available in the commercial codes. However, experimental tests in UMN test rigs have suggested that, at a given location in the engine, there is transition from laminar-to-turbulent flow and back over an engine cycle, and that these transitions occur at different times in different locations. In CFD-ACE, one must currently choose laminar flow everywhere in the overall domain being simulated, or a particular RANS model or LES (Large Eddy Simulation); in addition, Fluent has the capability for DES (Detached Eddy Simulation). RANS turbulence model calculations sometimes agree with laminar calculations when appropriate (Tew, 2003), however they cannot be reliably used to predict transitions between laminar and turbulent flow. CSU's modeling of turbulence phenomena in the UMN test rigs, has shown that for one process, one RANS turbulence model (such as k-omega) produces the best agreement with the data. For another process, another RANS turbulence model (such as k-epsilon, or Chien's model) produces the best agreement (Ibrahim, 2003a). Thus accurate modeling of laminar-turbulent transitional flow is a significant problem in multi-D modeling of Stirling engines.

(3) The transient conjugate-heat-transfer problem (large-heat-capacity solids exchanging heat with small-heat-capacity gases), greatly extends the number of cycles and time required for convergence to a steady-periodic cycle. The problem was improved at CSU by solving for wall- and regenerator-solid-temperature distributions using a steady-state solution approach, with piston and displacer held stationary—then allowing the piston and displacer to move; but the cycles required for convergence is still large. If the requirement to converge the solid-wall-temperatures could be eliminated, then flow and temperature distributions in the gas might reach steady-periodic-cycle convergence in perhaps 4 to 6 cycles—based on modeling of MIT test rigs with assumed constant-inside-wall temperatures (Ebiana 2004). In an earlier transient 1-D code developed at GRC, the heat capacity of the pressure vessels walls was not modeled, but that of the regenerator matrix was (Tew, 1978, 1983). Convergence to periodic steady-state was a major problem until one of the authors, Jefferies, found a way to use the regenerator-solid heat transfer over one cycle to extrapolate convergence of the regenerator-solid temperature over the next cycle. Based on a brief summary, a recent cryocooler conference publication (Harvey, 2004), also appears to address a technique for speeding convergence of regenerator-matrix temperature. Some such approach might work in the multi-D codes. However, in CFD-ACE, the same enthalpy relaxation factors are currently applied to the entire solution domain, i.e. to solid and gas. The literature should be searched for approaches to accelerating temperature convergence of conjugate-heat-transfer solids. Such an approach would likely reduce the accuracy of the overall transient solution, but seems desirable in these early stages of trying to use these slow-converging complete-engine, time-marching, CFD models to reach a periodic-steady state.

NASA Grants for Multi-D Stirling Model Validation

A new grant to CSU, and subcontractors UMN and Gedeon Associates, was awarded on Sept. 1, 2004 to continue multi-D model validation and to support further model development. Details of these efforts follow.

Development of New Test Modules for Stirling-Convertor Model Validation

The new CSU multi-D code grant will emphasize validation of Stirling multi-D models. However, CSU will also continue to support GRC in trying to accelerate convergence of these models, and in trying to solve problem areas such as porous-media and laminar-turbulent-transition modeling.

Discussions with engineers at STC and Sunpower led to CSU's focusing on the flow between the heater and expansion space. UMN's new cam-and-follower oscillating-flow generator for the 180-degree-turn test section is shown in Figure 3. A more detailed schematic of the test section is shown in Figure 4. Unlike the earlier 90-degree-turn test section (Adolfson, 2002, 2003), the new test section will accomplish a full 180 degree turning of the flow, as in real hardware, and will include heat transfer. The large size and low frequency (~1 Hz) will allow measurements with high spatial and temporal resolution. Dynamic similarity will be maintained by matching the dimensionless parameters of a pattern Stirling engine. Both flow visualization and detailed measurements of flow velocities and temperatures will be carried out. Heat transfer measurements will be made. Plans are for the heater to initially be a porous section, with later replacement by discrete flow passages and solid walls, so that 3-D flow and temperature fields can be quantified. Velocity and temperature measurements will be made with hot-wire anemometry and thermocouples, respectively. UMN has much experience in making these measurements in an oscillating-flow-regenerator test rig (Niu, 2002, 2003a, 2003b, 2003c). As in earlier UMN test sections, the new one exhausts into and extracts air from the room at 1 bar pressure and 298 K (about 25 C). When heat-transfer measurements are begun, the heat-addition surface temperature will be about 20 C above the flow temperature. Flow vortices and their behavior were an interesting feature of the earlier 90-degree-turn tests (Adolfson, 2002, 2003). It is anticipated that the new test section, which is a much better representation of real Stirling-engine hardware, will provide interesting insights into how expansion-space flow vortices can impact heat transfer in the expansion space and flow-uniformity in the heater.

CSU will test a new Stirling-cooler test section (Figure 6) in the Stirling Laboratory Research Engine (SLRE), shown in Figure 5 (Hoehn, 1982). The alpha-configuration SLRE (two opposed pistons) has feature size and frequency similar to engines of interest (testing has been up to 20 Hz frequency). Temperature, pressure, and pressure-drop measurements will be made for CFD-test-rig model comparison. Hoshino recently used a two-thermocouple technique to make dynamic temperature measurements in the SLRE test facility (Hoshino, 2004). Since the phase angle between the two opposed pistons is adjustable from 0 to 180 degrees, the facility can be used to produce just oscillating-flow through the test section, or a combination of oscillating-flow and pressure level as when operated as a Stirling cooler. SLRE measurements in an earlier test section are reported in (Ibrahim, 2004d).

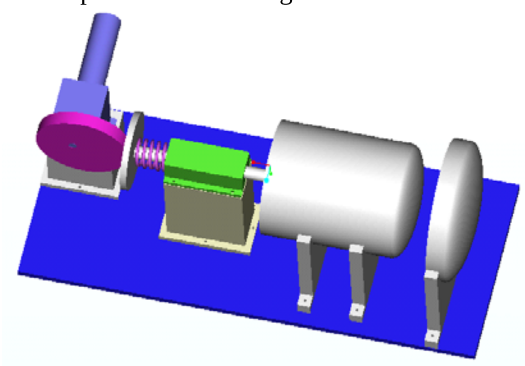

FIGURE 3. New Oscillating-Flow Generator and 180 Degree Test Section.

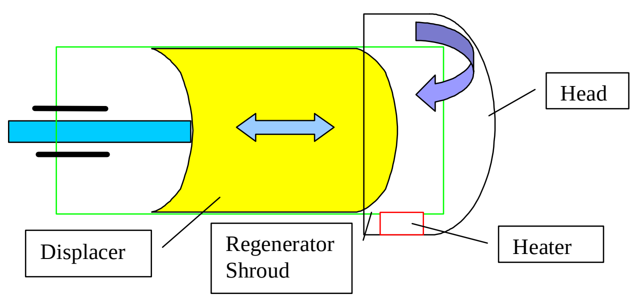

FIGURE 4. Schematic of New 180 Degree Test Section.

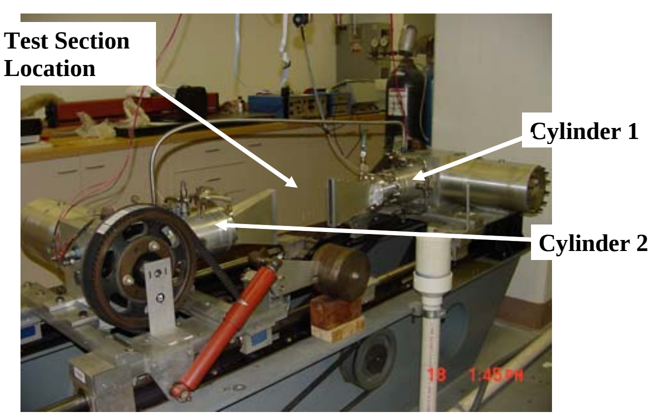

FIGURE 5. SLRE with "Alpha" Arrangement of 2 Cylinders/Pistons, Showing Test Section.

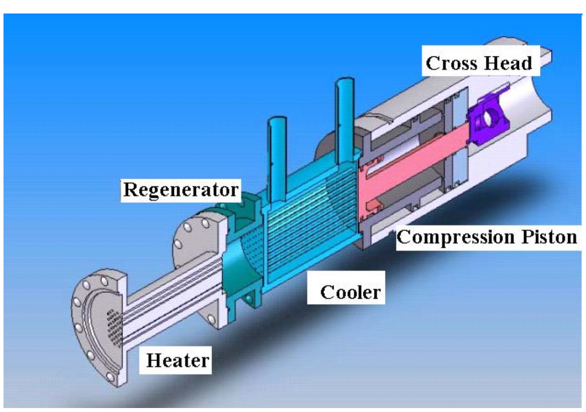

FIGURE 6. New SLRE Stirling Cooler Test Section.

Multi-Dimensional Modeling of Stirling-Process Test Modules

As for earlier UMN test sections, CSU will develop CFD models of the new UMN 180-degree-turn test section, and the CSU SLRE-Stirling-cooler test section. Validation of these CFD models of Stirling-engine-like physical processes, should also help provide confidence in the CSUmod and TDC models of complete Stirling engines. Gedeon Associates' Sage 1-D model will also be used to model the SLRE-Stirling-cooler test section. The Sage 1-D model, which is used in design of STC's and Sunpower's Stirling engines and coolers, provides useful benchmark solutions to assess the progress of multi-D Stirling models.

2nd Law Analysis for Stirling-Process Multi-Dimensional Models

A grant for developing a thermodynamic 2nd law analysis of 2-D CFD models of two Massachusetts Institute of Technology (MIT) test rigs ended Nov. 30, 2004 (Ebiana 2004). The two test rigs were a gas spring, and a modified version of the original gas-spring test rig with an annular heat exchanger mounted on top of the gas spring (Kornhauser, 1989). The work involved careful development of the 2-D models using the CFD-ACE code, including checking for independence of the periodic-steady-state solution to changes in spatial-grid sizes, time-step size, and number of cycles. Solution independence was checked via several approaches including superposition of variable profiles at the same time in sequential cycles, root-mean-square differences in variable values relative to a standard superimposed grid at the same time in sequential cycles, and tracking of the model energy balance from cycle to cycle. The CFD-ACE energy balances, and variable profile plots, were compared with predictions of the Sage code for the two test rigs.

It is interesting to compare some of the CFD-ACE and Sage results: For the gas spring at 10 RPM, 192.4 kPa, and wall temperature of 294 K—Sage calculated a hysteresis loss (equal to power in and heat generated) of 0.434 W and CFD-ACE calculated a hysteresis loss of 0.470 W, or a difference of about 8 %. Whereas, for the gas spring+heat exchanger, Sage calculated a power in/net heat generated of 29.9 W and CFD-ACE calculated 53.2 W, or a difference of about 78 %. Note that Sage is a 1-D code, assumes uniform axial flow, and thus can't directly account for effects of flow separation at changes in flow area. This uniform-flow assumption should be a much better assumption for the gas spring than for the gas spring+heat exchanger, where there is a major change in area from the "gas spring" cylinder to the much smaller flow area of the annular heat exchanger. Thus, one would suspect that agreement is much poorer between the two codes for the gas spring+heat exchanger because of the limitations of Sage in accounting for the effects of changes in area. However, Sage does include approximate equations accounting for pressure drop and heat transfer "end effects," so it's also possible that differences may also be due to CFD-ACE modeling errors (i.e. numerical, geometrical approximations, etc.). Both codes agree reasonably well with the experimental hysteresis loss data for the gas spring. Power in/net heat transfer data was not reported for the gas spring+heat exchanger test rig, unfortunately.

Overall available-energy losses and entropy gains were calculated for the two test rigs, based on interactions of the two systems with the environment (Ebiana, 2004). The remainder of the grant will be devoted to making available energy and entropy calculations throughout the domain, so as to break down the overall available energy loss into those due to heat transfer, viscous friction, and mixing. The sum of these available energy losses should be equal to the overall available energy loss based on interactions of the systems with the environment—except for differences introduced by numerical error. So, differences in these two approaches to calculating overall available-energy loss may provide some indication of the overall numerical error inherent in the CFD calculations. Sage 1-D code performance and available energy losses will provide a benchmark calculation for comparison. A follow-on grant is anticipated which would apply the developed 2nd law analysis procedure to a complete multi-D Stirling engine model.

REGENERATOR RESEARCH AND DEVELOPMENT

Two Stirling-convertor regenerator efforts are being funded by NASA: (1) One is a regenerator grant for regenerator experiments and CFD modeling for learning about various current-technology-regenerator losses, and attempting to identify approaches for their improvement; an important part of the effort has also been determination of empirical coefficients (permeability, inertial coefficient, thermal dispersion) needed for CFD modeling of regenerators.

(2) The second effort is a NASA Research Award Contract for regenerator microfabrication; the goal of this effort is to fabricate a new “defined geometry” (non-random) regenerator, with improved performance, mostly by reducing pressure drop losses, and improved reliability relative to current-technology (wire screen, random fiber).

NASA Regenerator Research Grant and DOE Regenerator Research Contract

The two-year NASA regenerator research grant, begun on Oct. 1, 2003, is a follow-on effort to a previous three-year DOE regenerator research contract (Ibrahim, 2004b). The DOE effort involved measurements of temperatures and heat transfer within a large-scale matrix, and study of the effects of jetting from cooler tubes into the matrix; these measurements were made with a 90% porosity matrix, the same porosity as used in several small Stirling convertors of interest to NASA. Experimental plans for the NASA grant included direct measurements of thermal dispersion in the 90% porosity regenerator, a repeat of previous testing in a new 95% porosity regenerator, investigation of the effect of various heat exchanger tube exit geometries on jetting into the matrix, and heat transfer and pressure drop testing of random-fiber regenerators with porosities as high as ~95% in the NASA oscillating-flow test rig on loan to Sunpower. Direct measurements of thermal dispersion have been recently reported (Niu, 2004a). Measurements for determining permeability and inertial coefficient were previously reported, but revised measurements have recently been made (Niu, 2004b).

The large-scale regenerator measurements have been made at UMN. CSU has been supporting the UMN measurements via CFD models of the UMN test rig, and using the data for model validation. This modeling has involved use of a macroscopic porous media model available in the CFD-ACE code. With appropriate choice of permeability and inertial coefficient, CSU has determined that the CFD-ACE porous media model does a relatively accurate job of modeling fluid flow in the large-scale UMN matrix (Ibrahim, 2003b). However, the CFD-ACE model assumes gas-solid thermal equilibrium. This is not adequate for Stirling-regenerator modeling. CSU identified one thermal-non-equilibrium porous-media model that they feel may be adequate for CFD modeling; they began to try to define some of the empirical coefficients in the model (i.e. to define a “closure” model) via computations with a microscopic model of a wire-screen representative-elementary-volume (Ibrahim, 2004c). Other forms of a thermal-non-equilibrium model were presented at the Porous Media Workshop hosted by GRC in Cleveland in April 2004 (Kaviany, 2004; Ayyaswamy, 2004). Also presented at the workshop was a non-equilibrium porous-media model used by David Gedeon in the Manifest 2-D Regenerator/Manifold Modeling Code (Gedeon, 1989).

NASA Research Award Regenerator Microfabrication Contract

The first year of the regenerator microfabrication contract ended August 31, 2004. Annual presentations for this and nine other competing NRA Award contracts have been made and decisions on continuation of each are pending. Initiation of the 2nd year of effort for successful awardees has been delayed, probably until passage of the FY2005 NASA budget. Successful 2nd year contractors may also receive awards for a 3rd year of effort.

Encouraging progress was made during the 1st year of the regenerator microfabrication effort. Several approximations of a parallel-plate regenerator were chosen as potential candidates for a new microfabrication concept. Many potential manufacturers were surveyed (Sun, 2004). David Gedeon developed a revision of an existing regenerator figure of merit (by including thermal dispersion) and projected that the power and efficiency of a particular new Sunpower engine could be improved by 6-9% by using a new microfabricated regenerator (Gedeon, 2003, 2004); these comparisons were based on one design optimized for a random-fiber regenerator and designs optimized for a new microfabricated regenerator. Terry Simon and Yi Niu developed an argument supporting the validity of dynamic similitude in regenerators, to support testing of large-scale regenerators, as requested by NASA. After interviewing many potential manufacturers and concepts, requests for proposals were sent to only two manufacturers. Based on the submitted proposals, about 8 months into the first year, International Mezzo Technologies of Baton Rouge, LA was chosen to be the fabricator.

The chosen manufacturing process, based on Mezzo’s expertise, is a combination of LIGA (lithography, electroplating and molding) and EDM (electric discharge machining). After Mezzo was chosen, a variation of an “involute” approximation of a parallel-plate regenerator was chosen for development. A solid model of the concept is shown in Figure 7. The current plan is to stack these disks with successive disks “flipped” in order to alternate the involute direction. This should help reduce axial conduction and allow for redistribution of flow between disks. Mezzo succeeded, in the short time available, to use LIGA to fabricate the EDM tool shown in Figure 8. The contractual effort also includes fabrication and testing of a Large-Scale-Mock-Up (LSMU) of the regenerator at UMN. There they will be able to test “flipped” and “unflipped” stacks of disks. In the third year of the effort, stacks of these disks are to be tested first in the Sunpower oscillating-flow test rig, and later in an actual Stirling engine.

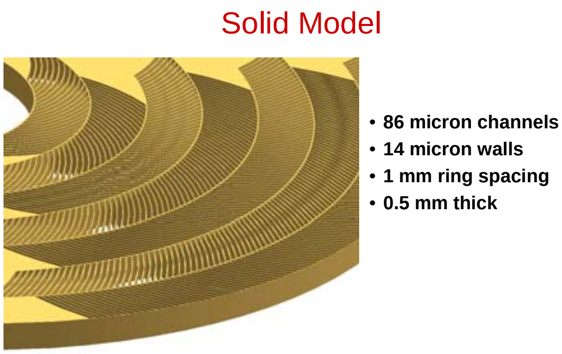

FIGURE 7. Chosen Involute Concept.

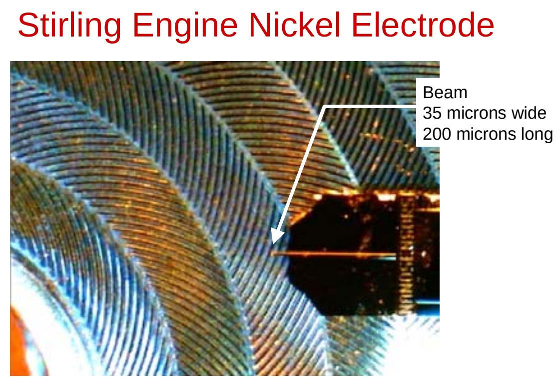

FIGURE 8. Mezzo EDM Tool, fabricated via LIGA.

CONCLUDING REMARKS

The results of several advanced Stirling technology efforts have been summarized. The goals are improvements in Stirling convertor performance via (1) development and validation of multi-dimensional Stirling CFD models, (2) experimental and computational research to investigate regenerator fluid-flow and heat-transfer phenomena and define empirical coefficients for CFD modeling, and (3) development of a new improved regenerator via microfabrication. Progress and problems associated with continued development of two-dimensional Stirling engine models and the experiments being conducted to validate the models are reported. With Cleveland State University’s delivery of the CSUmod-Stirling-engine model to NASA and addition of more manpower to the NASA in-house Stirling analysis effort, NASA has increased its level of effort in Stirling computational analysis. However, it is anticipated that NASA will continue to need grant and contractual support in the areas of validation testing and further development of CFD techniques to improve the time efficiency and accuracy of multi-D Stirling modeling.

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

This paper reports on accomplishments in 2004 in (1) development of Stirling-convertor CFD models at NASA Glenn and via a NASA grant, (2) a Stirling regenerator-research effort being conducted via a NASA grant (a follow-on effort to an earlier DOE contract), and (3) a regenerator-microfabrication contract for development of a "next-generation Stirling regenerator." Cleveland State University is the lead organization for all three grant/contractual efforts, with the University of Minnesota and Gedeon Associates as subcontractors. Also, the Stirling Technology Company and Sunpower, Inc. are both involved in all three efforts, either as funded or unfunded participants. International Mezzo Technologies of Baton Rouge, Louisiana is the regenerator fabricator for the regenerator-microfabrication contract. Results of the efforts in these three areas are summarized.

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