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National Aeronautics and Space Administration
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Work performed for
U.S. DEPARTMENT OF ENERGY
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ABSTRACT

An assessment of Stirling engine thermodynamic modeling and design codes shows a general deficiency; this deficiency is due to poor understanding of the fluid flow and heat transfer phenomena that occur in the oscillating flow and pressure level environment within the engines. Requirements for improving modeling and design are discussed. Stirling engine thermodynamic loss mechanisms are listed. Several experimental and computational research efforts now underway to characterize various loss mechanisms are reviewed. The need for additional experimental rigs and rig upgrades is discussed. Recent developments and current efforts in Stirling engine thermodynamic modeling are also reviewed.

NASA LEWIS BEGAN MANAGING the Stirling engine program for the Department of Energy (DOE) about 12 years ago; at that time, there were no satisfactory Stirling engine computer models generally available and no engine data available for validating such models. Therefore work began promptly on development of a model at NASA Lewis to help guide the engine test program and to aid in managing the work of contractors.

Early in the Stirling program, the General Motors GPU-3 engine was tested at NASA Lewis and the NASA Lewis Stirling performance model was calibrated against the data (1,2)*. A United Stirling (USAB) P-40 engine and the Philips ADVENCO (ADVanced ENgine COncept) engine were also tested and modeled (3,4,5). The Upgraded MOD-I, an MTI-USAB automotive design, is now being tested. A 1 kW free-piston Stirling engine developed by Sunpower, Inc., the RE-1000, shows promise of being the most valuable engine tested at NASA Lewis for model validation purposes; this is primarily because it is a simple design (one cylinder with small mechanical losses), has electrically heated heater tubes, and operates at a relatively low frequency (30 Hz). The RE-1000 was first tested with a dashpot load (6). It has recently been refitted with a hydraulic load and testing is beginning (7).

A free-piston version of the NASA Lewis performance model was developed under contract by MTI (8); it can operate either in a constrained piston (kinematic) or in an unconstrained (free-piston) mode. This model has been calibrated against the dashpot RE-1000 (9,10). A model of the hydraulic load has been developed. The next step will be to calibrate the hydraulic RE-1000 model against the engine data. The free-piston model has also been used to model the MTI-designed Space Power Demonstrator Engine (SPDE) as part of the SP-100 space power system program (11). So far, this model has been operated only in the constrained piston mode.

Much overall performance data is now available from a number of engines whose geometry is well defined. However, we have found that we can validate our models against data from a specific engine only by calibration of various loss mechanism factors to match overall predicted and measured performances, pressure wave variation over the cycle, and average gas temperatures. Conclusions from our model validation effort are: (1) In general, a model calibrated for one type of Stirling engine does not predict performance well for another type, (2) a model calibrated to predict performance well for several engines cannot reliably be extrapolated to an engine with significantly different geometry, and (3) we do not have a sufficiently good understanding of the heat transfer and fluid flow phenomena or the "loss mechanisms" inside Stirling engines.

*Numbers in parentheses designate references at end of paper.

Our experience in monitoring the work of our contractors tends to reinforce these conclusions. A general consensus had developed that to further improve Stirling engine design capability, a better understanding of the basic fluid flow and heat transfer phenomena occurring inside Stirling engines is needed. Specialized test rigs, not demonstrator engines, are needed to isolate and characterize particular loss mechanisms; this is primarily due to the difficulty of making accurate dynamic measurements in engine working spaces. Instrumentation research is also needed to improve measurement accuracy of dynamic variables in specialized rig and engine tests. While this basic research is underway, efforts should continue to improve analytical models. Periodic meetings of those involved in the various research efforts should be held to discuss the results. These opinions are supported by the conclusions of the Stirling Engine Computer Modeling Workshop sponsored by the Department of Energy (DOE) in Washington, D.C. on August 29, 1985 (12).

The purpose of this report is to review work that is being done now in the areas of loss mechanism characterization and Stirling engine analysis.

STIRLING ENGINE LOSS MECHANISMS

Most Stirling models assume that temperature, pressure, and flow are uniform across a cross section perpendicular to the flow axis. Heat transfer and pressure drop are then calculated from experimental steady-flow correlations; this implies that the nonuniformities and boundary-layer effects that contributed to the form of the steady-flow correlations will make the same contributions in the oscillating flow and oscillating pressure level environment which occurs inside Stirling engines.

The following "loss mechanisms" may produce significant impacts on the performance of Stirling engines: (1) Effects of oscillating flow/pressure level on pressure drop and radial heat transfer in tubes, matrices, and area transitions, (2) flow maldistributions--tube to tube, manifold-regenerator interactions, area transitions in general, (3) gas spring and working space hysteresis (also called cyclic or transient heat transfer) losses, (4) mixing losses (adiabatic volumes, especially, increase losses due to mixing of gases at two different temperatures), (5) appendix gap heat losses experienced in the clearance gap between the cylinder wall and the piston, (6) leakage losses (piston-cylinder, gas spring, free-piston centering port flows), (7) conduction losses (through metal conduction paths and through gas inside the displacer), (8) enhanced axial conductivity through the regenerator due to flow oscillations, (9) losses due to radiation and convection from hot surfaces (losses from engine surfaces to the environment).

Chen, Griffin, and West have noted (13) that three thermodynamic irreversibilities occur inside Stirling engines. These are: (1) heat transfer across a temperature difference, (2) mass flow across a pressure difference, (3) mixing of fluid at different temperatures. Each loss mechanism involves one or more of these irreversibilities.

The key to knowing "all there is to know" about thermodynamic losses inside a Stirling engine, therefore, is knowing as a function of time the: (1) temperature field in the working space and metal walls, (2) flow and pressure fields in the working space, and (3) leakage flows to and from the working space. Experimental mapping of these fields, if possible, would allow characterization of Stirling thermodynamic loss mechanisms. An alternative to the more desirable experimental mapping would be mapping via a multi-dimensional model; the model would need to be carefully formulated to predict results that could be checked via experiment.

PROGRESS IN STIRLING LOSS MECHANISM CHARACTERIZATION

Several grants and contracts are now underway for characterizing one or more loss mechanisms. A review of these efforts follows. Those efforts not specifically identified with Oak Ridge or Argonne National Laboratories are being managed by NASA Lewis. The NASA-managed efforts are being funded by a combination of DOE, Department of Defense, and NASA funds.

OSCILLATING FLOW TEST RIG FOR DEVELOPING CORRELATIONS FOR ONE-DIMENSIONAL MODELS - Sunpower, Inc., under a NASA Phase I Small Business Innovation Research (SBIR) Contract, designed an oscillating flow rig to be used in measuring pressure drops through tubes and matrices. A schematic of the rig is shown in Fig. 1. A linear motor is used to drive the rig at frequencies up to 120 Hz. The unique design of the rig should allow accurate determination of instantaneous mass flows and pressure drops. It was designed to cover the entire range of similarity parameters of interest in Stirling engine design.

Sunpower is now building the rig and will do the testing under a Phase II SBIR contract (which began in April 1986). Fabrication and assembly of the rig is expected to be complete in October 1986. System checkout and some initial testing should be complete by February 1987. The remaining one year and two months of the contract will be used to test and develop pressure drop correlations for various Stirling heat exchanger geometries. A unidirectional flow rig is also being assembled and will be used to test the same heat exchanger geometries under steady-flow conditions.

The initial rig is designed to test for effects of oscillating flow, only, on pressure drop (pressure level will be essentially constant); however, another drive can be added to test for effects of oscillating pressure level. The rig design is flexible so that it can also be modified to test for effects of oscillating flow and pressure level on heat transfer.

ARGONNE NATIONAL LABORATORY--REVERSING FLOW TEST FACILITY - Argonne National Laboratory has constructed a reversing flow test facility. A test rig schematic is shown in Fig. 2. The facility is intended to measure the effects of oscillating flow and pressure level on heat transfer and pressure drop at frequencies up to 50 Hz.

Preliminary results obtained with the test facility are reported in Refs. 14, 15, and 16. The initial tests were conducted with pressurized helium under oscillating flow conditions. Plots are shown of measured pressure drop and calculated mass flow rate (based on piston motions) as functions of crank angle in Ref. 14. Problems that reportedly need resolution are questions regarding accuracy of the pressure drop measurements and flow rate determination. Future plans are to resolve these problems and take data that can be used to develop pressure drop and heat transfer correlations for one-dimension Stirling engine models.

OSCILLATING FLOW TESTS WITH MULTI-DIMENSIONAL MEASUREMENTS - Professor Terry Simon of the University of Minnesota was awarded a grant for "Investigation of Heat Transfer and Hydrodynamics in Oscillating Flow with Application to Stirling Engine Components" in 1986. Professor Simon and Joerg Sueme had completed a search of the oscillating flow literature in 1985, under a previous grant. A summary of the final report on their findings is given in Ref. 17.

The report proposes a set of similarity parameters for characterizing the effects of flow oscillation on wall shear stress, viscous dissipation, pressure drop, and heat transfer rates; operating ranges of eleven Stirling engines are described in terms of these parameters. It is shown that the operating points for several of the engines are in or near the laminar-to-turbulent transition region. Conclusions of the report are that more research is needed to understand: (1) the process of transition, (2) the effect of flow oscillation on turbulent momentum and heat transfer, and (3) the effects of thermal and hydrodynamic entrance lengths on heat transfer and pressure drop in tubes and regenerator matrices.

The 1986 grant renewal was awarded to construct a test rig and begin the recommended research. Tests will be run over ranges of the key similarity parameters which characterize engine conditions; these are the dimensionless frequency or kinetic Reynolds number, Re_{ω}, the Reynolds number based on the maximum flow velocity, Re_{max}, and the flow displacement to tube length ratio, A_R.

A schematic of the proposed test rig is shown in Fig. 3. The test section will be 3 to 4 cm in diameter, maximum frequency will be about 400 rpm, and the working fluid will be air. The relatively large diameter test section (compared to typical Stirling heat exchanger tubes) will permit measurements of multidimensional profiles, using hot wire anemometers. The relatively low maximum frequency should allow accurate dynamic measurements of pressure, velocity, and temperature.

It is expected that the 1986 renewal grant will begin at least a 3 year program of testing. Construction of the facility and operational tests should be complete about February 1987. Shakedown, baseline, and qualification tests, completion of the data reduction program, and uncertainty analysis should be complete by May 1987. Data for the open tube geometry tests are to be taken from May through September of 1987. Tests for the effects of oscillating pressure level are to be conducted in the later phases of the program.

MODELING OF THE UNIVERSITY OF MINNESOTA OSCILLATING FLOW RIG AND THE SPDE - The University of Minnesota was also awarded a grant to develop "One- and Two-Dimensional Stirling Machine Simulations Using Experimentally Generated Reversing Flow Correlations." Under this 1986 grant, Research Fellow Louis Goldberg is to: (1) assist Simon and Seume in determining parametric and normalizing factors for making the test results applicable to Stirling engine design and analysis procedures, and (2) apply the test results to new types of one- and two-dimensional Stirling models of the SPDE.

One-dimensional models of the test rig and the SPDE are operational; Goldberg is currently working on a two-dimensional model of the SPDE.

The SPDE is a 105 Hz, 25 kWe nominal design free-piston engine (consisting of two, mirror image, 12.5 kWe modules). This is the highest frequency Stirling engine ever built. If oscillating flow and pressure level have significant effects on pressure drop or heat transfer in any existing Stirling engine, it is likely they will be significant in this engine. Simon and Seume's data and Goldberg's models should help determine if these effects are significant in the SPDE. The two-dimensional model should help determine if certain flow maldistributions have a significant effect on engine performance.

TWO-DIMENSIONAL COMPUTATIONAL STUDY OF MANIFOLD-REGENERATOR FLOW - Gedeon Associates received a contract in 1986 for "A Computational Study of Two-Dimensional Gas Flow in Stirling Engine Regenerators and Associated

Manifolds." The principal investigator for this contract is David Gedeon, a former Sunpower, Inc. analyst, who is now an independent consultant.

The automotive Stirling engine designs have complex manifolds (or connecting ducts) between some of the heat exchangers and the expansion and compression spaces, due to packaging requirements; improper design of such manifolding could cause very complex flows in the regenerator, with consequent reductions in performance. Also, as a result of initial testing and analyses, there was a concern that the first SPDE regenerator caused "jetting" of flow from the heater tubes into the regenerator matrix, causing reductions in engine performance. After further data analysis, however, MTI now believes there was no significant increase in viscous dissipation. These potential flow maldistribution problems are illustrated in Fig. 4.

The purpose of this contract is to simulate in two-dimensions the fluid dynamics and thermodynamics of regenerators and their associated manifolds. Phase I of the effort, to be complete by December 1986, involves developing a computational method and optimizing it to solve the prototype manifold-regenerator problem shown in Fig. 4(a); two-dimensional pressure, flow, and temperature fields throughout the regenerator matrix and manifolds are solved subject to prescribed inflow mass flux rates and temperatures. A solution method has been developed (using the Beam and Warming implicit finite difference approach) and Phase I goals appear achievable with the model now in use on the contractor's IBM PC-compatible computer.

Contingent upon a successful outcome in Phase I, the Phase II effort would extend the solution method to manifolds of arbitrary shape, refine the software into a complete and portable package, and use the software to derive practical engineering correlations for the loss mechanisms associated with the manifold problem. It is expected that the effort will sooner or later require a sufficiently fine mesh and computational time requirements, such that the problem will require a mainframe computer for practical solution times. Although not contractually obligated to do so, the contractor plans to evaluate the sensitivity of SPDE performance to flow maldistributions such as that illustrated in Fig. 4(b).

The final computer code, which is written in the PASCAL programming language, will become public domain software at the conclusion of the contract.

HYSTERESIS OR CYCLIC HEAT TRANSFER LOSSES - Heat transfer in gas springs, due to the cycling of pressure and temperature, leads to hysteresis or cyclic heat transfer losses. The magnitude of this loss is equal to the work done on the gas spring or the area inside the gas spring P-V diagram. Similar losses also occur in open cylinders, as in the expansion and compression spaces of Stirling engines, due to heat transfer between the gas and the cylinder walls. Some of the known characteristics of this loss are summarized below.

If expansion and compression space processes are adiabatic, as assumed in some Stirling models, or isothermal, then cylinder hysteresis losses are zero. Computations have shown, however (Ref. 13 and undocumented results obtained with the NASA Lewis Stirling model), relatively small rates of heat transfer in the cylinders, as compared to the heater, cause significant reductions in engine performance. That is, cylinder heat transfer rates intermediate between adiabatic and isothermal process rates, produce the worst engine performance losses.

Some results and conclusions of cylinder heat transfer experiments are reported by Faulkner and Smith (18). It was demonstrated that losses due to cylinder heat transfer were greatest at intermediate cylinder average Reynolds numbers for tests made with helium gas. It is noted that in Stirling engines, cylinders tend to operate at high average Reynolds numbers (approach adiabatic processes) and heat exchangers tend to operate at low average Reynolds numbers (approach isothermal). Also, volumes such as connecting passages, which may operate at intermediate Reynolds numbers (with consequent large hysteresis losses), should be minimized.

Faulkner and Smith also demonstrated that the Temperature-Entropy (T-S) diagram is a useful tool for displaying the magnitude and timing of heat transfer processes around the cycle. Experimental T-S diagrams were used to show that the phase lag between cylinder heat transfer and gas-to-wall temperature difference varied from 0° for isothermal to 90° for adiabatic processes.

Heat transfer calculations made with the NASA Lewis Stirling code have, until now, assumed no phase lag between heat transfer and temperature difference. While this should be a good assumption for the heat exchangers, Faulkner and Smith's results suggest it is a poor assumption for cylinder, gas spring, and possibly connecting duct heat transfer calculations.

Analytical correlations for the magnitude and phase lag of cylinder heat transfer are derived by Lee (19). An expression for the Stirling cycle power loss due to cylinder heat transfer is also derived. The loss is shown to approach zero as the heat transfer processes approach either isothermal or adiabatic. The power loss is also shown to be a strong function of the phase angle between the heat transfer and the gas-to-wall temperature difference.

Oak Ridge National Laboratory has recently awarded a grant to Professor Joseph Smith of the MIT for additional experimental and analytical work on the characterization of hysteresis losses.

APPENDIX GAP MODEL AND TESTING - The "appendix gap" is the annular volume between the hot end of the displacer or power piston (depending upon the engine design) and the cylinder wall in a Stirling engine (appendix gap schematics are shown in Fig. 5). The complex fluid flow and heat transfer phenomena which take place in the gap involve several irreversibilities which degrade the performance of the engine.

MIT has developed a detailed appendix gap model (20,21). Three heat loss mechanisms are modeled: (1) axial conduction along the piston and cylinder, (2) radial heat transfer between the gas in the gap and the boundary walls, and (3) leakage enthalpy flow across the cold end seal. The radial heat transfer mechanism is the most complicated and least understood; it can be subdivided into a pure conduction or "shuttle" component and a complicated convection component which is commonly identified as the appendix gap "pumping" loss.

The model is a nodal analysis of the appendix gap region. Inputs to the model are boundary wall temperatures, prescribed piston motions, and prescribed pressure and temperature waves in the expansion and compression spaces. With these boundary conditions given, the model calculates heat flows in the gap, but cannot directly calculate the effect of these heat flows on indicated power (which is essentially determined by the pressure waves). Efforts to validate the model are summarized below.

So far only indirect evaluation of the model has been possible, by comparison with engine performance data. Sensitivity tests were performed, initially on the USAB P-40R Stirling engine, and then on the MTI-USAB Upgraded MOD-I engine. For each of these engines, ranges of data were taken for two different appendix gap configurations. Reference 22 shows that model sensitivity appeared to correlate well with curve fits of the engine sensitivity data; however, considerable data scatter existed and no information is given on the measurement accuracy of the data.

No measurements of the absolute magnitude of the appendix gap losses have been possible. The gap model predicts an appendix gap heat loss of 11.6 kW at full power for one of the P-40R configurations and 7.5 kW at full power for the reference Upgraded MOD-I engine.

The measured pressure waves in the Upgraded MOD-I implied no significant effect on indicated power when the change in gap configuration caused a change in gap heat loss of 1.5 kW (22); for this engine the gap was modified by raising the cold end gap seal to reduce the volume of the appendix gap (by 23 percent). In contrast, when the P-40R engine modification increased the appendix gap pumping heat loss by about 2 kW, the measured shaft power showed a decrease of 0.7 kW. The P-40R gap region was modified by substituting a nickel partition wall for a stainless steel one; the geometry was not changed.

The Upgrade MOD-I at NASA Lewis will soon be fitted with a piston ring at the hot end of the double-acting piston to eliminate or minimize appendix gap pumping losses. The standard piston design for automotive Stirling engines has rings only at the cold end. MTI will evaluate the test data and use it for validation of the appendix gap model. This model will become public domain software.

Appendix gap losses increase with engine pressure ration (P_{max}/P_{min}) and should therefore, other effects being equivalent, be less for free-piston than for the kinematic engines. Nevertheless, a good characterization of these losses is needed for engine design. A dedicated appendix gap test rig will probably be required for satisfactory characterization.

MEASUREMENTS OF REGENERATOR MATRIX THERMAL CONDUCTIVITIES UNDER STAGNANT, STEADY-FLOW, AND OSCILLATING FLOW CONDITIONS - Reasons for investigating regenerator matrix thermal conductivities are summarized here. Stirling heat pump tests at Sunpower, Inc. yielded poor performance for a relatively short regenerator design. Attempts to identify the problem led to the idea that heat losses through the regenerator might be substantially larger than predicted by a model; attempts to resolve the problem by model sensitivity studies did not yield conclusive results (23). Recent analyses by Gedeon (24) suggest that one-dimensional models (but not two-dimensional models) require an assumption of enhanced conductivity under certain conditions to properly predict axial heat flow through regenerators. Since Stirling engines for space power tend to have relatively short regenerators, a concern exists that regenerator losses in these engines may be substantially larger than predicted.

Poor initial performance of the SPDE was at least partly due to the unsintered wire screen regenerator matrix used in the initial build. Replacement of this matrix (after some obvious deterioration of the screens) with a design which insured no vibration of the matrix, produced a significant improvement in engine performance. The new matrix design also included gaps between the matrix and the heater and the cooler tubes where none existed before; these gaps may also have improved the flow distribution and reduced viscous dissipation.

Experiments and analyses by Kurzweg (25,26) suggest a physical explanation of the need for an enhanced conductivity assumption. Kurzweg's results suggest that the primary mode of axial heat transfer in tubes with oscillating flow and an axial temperature gradient is via the interaction of two mechanisms. These mechanisms are: (1) radial heat conduction between the gas core and the boundary layer or wall and (2) the oscillations of the fluid. This interaction causes a "shuttle" heat transfer similar to that which occurs between the displacer and the cylinder wall. To the extent that one-dimensional models do not accurately account for radial heat transfer to or from thermal boundary layers in regenerators, they are subject to errors in predicting axial heat flow.

As a result of regenerator performance concerns, Case-Western Reserve University was awarded a grant in 1986. Professor Alexander Dybbs plans to measure regenerator thermal conductivities under stagnant, steady-flow, and oscillating flow conditions. These tests will require modifications to existing experimental rigs. An oscillating flow rig design is to be ready for review by NASA Lewis by the end of October 1986. The first phase of the test effort is to be complete by June 1987. It is expected that completion of the initial effort will require at least one additional year. Possible additional efforts could include experimental studies of the effects of induced flow maldistributions on regenerator performance.

STIRLING CYCLE ANALYSIS

GENERAL COMMENTS - A number of different Stirling engine models and Stirling computer codes now exist (A code is here defined to be more general than a model. A Stirling code may include other parts of a Stirling power system, optimization algorithms, algorithms for determining system masses and volumes, etc.). A brief description of a common method of model classification will be given with a few examples. A more complete listing and discussion of the various existing models as of 1983 can be found in Ref. 27. References 28 to 31 are also good sources of information on Stirling engine analysis.

Stirling engine models are frequently classified as first, second, or third order models. This method does not have a rigorous mathematical basis. Rather the idea is that lower order models require more simplifying assumptions; therefore the higher order models are mathematically more rigorous and should be accurate. In practice, it has not been established that third-order models are more accurate. Possible reasons for this are that even the third-order models have assumed uniform one-dimensional flow, and have used steady-flow heat transfer and pressure drop correlations; other losses such as appendix gap, hysteresis, and leakage are not well characterized. Thus, even the mathematically more rigorous third-order models are based on questionable physical assumptions. Also, the rigorous partial differential equations must be solved by approximate finite difference, or element, methods on a computer; the errors resulting from these approximations are generally not known for a given Stirling model.

The Schmidt model (29) is classified as a first-order model. The Rios (32), Martini (33) and the harmonic analysis models of MTI (34,35), and Oak Ridge (13) are classified as second-order models; the Philips-United Stirling design codes are also thought to be based on harmonic analysis models. The third-order models are nodal analysis models. The new Gedeon Associates GLIMPS Model (36) and the Goldberg model, to be discussed later, are third-order models that include the coupling of pressure drop with heat and mass transfer. The Urieli (28), NASA Lewis (3), and Giasante-Lewis (9) models are usually classified as third-order models, but pressure drop is decoupled from the heat and mass transfer calculations in these models.

Stirling computer codes, as defined above, are usually classified as design codes or performance codes. A performance code typically consists of a third- or second-order model. A design code typically consists of a second-order model, an optimization algorithm, and other algorithms for sizing the engine for a specified power level. Argonne National Laboratory has developed a nonproprietary design code, SEAMOPT (37), based on the Rios model; this design code appears to be farther along in development than other nonproprietary design codes. Development and validation of a free-piston design code, originally developed for NASA Lewis by Dr. W.R. Martini (38), has made little progress due to lack of funds and manpower.

RECENT STIRLING ANALYSIS DEVELOPMENTS - Gedeon Associates GLIMPS Model - David Gedeon has developed the "Globally Implicit Stirling" or GLIMPS model (36). It is a rigorous third-order nodal analysis model. In a preliminary evaluation at NASA Lewis, GLIMPS was used to simulate the RE-1000 and SPDE engines. The GLIMPS RE-1000 predictions compared well with the RE-1000 data at the engine design point; its SPDE design point predictions compared well with NASA Lewis code and the original MTI design calculations. However, the GLIMPS model has not been validated against data from the SPDE and other engines such as the P-40 and the MOD-I.

Several convenient features of the model were noted. It comes with a well-written user's manual. It is very easy to use ("user friendly"); it was already set up for the RE-1000 engine but was easy to set up for the SPDE. It appears that it could be easily set up for a wide variety of Stirling machine configurations, including automotive engine designs and heat pumps.

The GLIMPS model was run on an IBM PC/AT with a math coprocessor at NASA Lewis; execution time was about 5 min using the recommended time step size and number of control volumes or nodes (and these recommended values were found to be satisfactory). Execution time is proportional to the number of control volumes and to the cube of the number of time steps per cycle. Since only six time steps per cycle are required for accurate performance calculations, this cube relationship could be a disadvantage if an accurate plot of a variable over the cycle is desired. An implicit finite difference solution method was used; the solution method could not be used to study the dynamic response to cycle pertubations. The version evaluated did not provide for separate connecting duct control volumes between the heat exchangers and compression and expansion spaces. GLIMPS is sufficiently fast that, if used on a mainframe, it could probably be coupled with an optimization algorithm and used for machine design.

Goldberg One- and Two-Dimensional Models - Under the previously mentioned University of Minnesota grant, Louis Goldberg is working on one- and two-dimensional models of the SPDE. The one-dimensional model is a rigorous third-order model; a fully implicit integral solution technique is used. In its equilibrium information propagation format, the one-dimensional model had, previous to the grant, been used to simulate the General Motors GPU-3 engine. This simulation was done on a standard 4.77 MHz IBM PC with an 8087 coprocessor with a solution time of approximately 5 min per simulated cycle. Run times on an 8 MHz Intel 80286/80287 processor set (with no memory wait states) are about 3 times faster. Goldberg believes that use of a 32-bit processor (soon to be installed) will enable run times which are 6 to 9 times faster. This model has now been used to simulate Simon and Seume's oscillating flow test rig and the SPDE engine.

The two-dimensional model of the SPDE is reportedly "almost operational;" expansion and compression spaces, heater and cooler are all modeled in two-dimensions; the regenerator, however, is for now still modeled in one-dimension. The basic model has been successfully applied to the problem of air flow in a room in a previous study. A rigorous set of time-dependent compressible flow equations is used. Various finite-difference solution techniques are being tried to optimize the solution technique. The two-dimensional model will help in understanding the effects of oscillating flow/pressure level and the effects of certain flow maldistributions on engine performance. Use of this model requires a mainframe computer.

One-dimensional models require the use of friction factor and heat transfer correlations in both tubes and matrices for laminar and turbulent flow regimes. In the two-dimensional model, no friction factor correlation is required for laminar flow in tubes; tube profiles can be calculated from the basic equations and properties of the fluid by assuming "no slip" at the tube walls. However, in the turbulent regime a turbulence model must be assumed. Simulation of two-dimensional flow in the regenerator requires specialized assumptions and techniques, since the grid cannot be made small enough (it would require too much computational time) to resolve the details of flow through the matrix.

Both one- and two-dimensional codes will become public domain software at the conclusion of the grant. These codes are written in FORTRAN.

Oak Ridge National Laboratory Linear Harmonic Analysis Model - Oak Ridge National Laboratory has been working on a linear harmonic analysis model for several years (13,39,40). A basic assumption in this type of analysis is that all engine variables can be represented as harmonic functions. Oak Ridge's work seems to indicate that harmonic functions consisting of a constant plus a fundamental give satisfactory accuracy for many or most engines. The harmonic function could include higher order terms but this would increase the complexity of the model.

Oak Ridge has published a listing of their harmonic analysis model (40); the model does not include an appendix gap loss calculation. Ref. 40 shows the result of one prediction made with the model for the RE-1000 engine and compares it with data.

A significant feature of the harmonic analysis models have been their calculation speed, which allows them to be used in design codes; nodal analysis models have been too slow for this application. However, the new models of Goldberg and Gedeon appear to be closing the computational speed gap; these nodal analysis models may be sufficiently fast for use in design codes.

Harmonic analysis also permits closed form equations to be derived for calculation of each thermodynamic loss. Nodal analysis loss calculations have typically been an integral part of the basic cycle calculations so that specific loss values were not calculated; thus it was not straight forward to determine how significant some losses were in reducing engine performance.

The Oak Ridge model appears unique among Stirling models in using a second law of thermodynamics analysis to separate out each of the losses. This technique could also be used to separate out the losses in nodal analysis models.

Computer Aided Thermodynamics (CAT) - Computer Aided Thermodynamics (CAT) is a new concept in thermodynamic system modeling. The description below is derived from Ref. 41 received from Gilberto Russo and Professor Joseph Smith of MIT.

Generalized dynamic analysis modeling codes such as CSMP (Continuous System Modeling Program) and EASY5 require the user to figure out a set of equations to model a given system. The user then specifies a network of the available symbolic elements (such as integrators, summers, multipliers, etc.) to represent the set of equations. The modeling code then uses a numerical solution technique (default or specified) to solve the system of equations.

CAT is "...a methodology of thermodynamic analysis based on a new formulation of classical thermodynamics in a numerical computation environment" (41). CAT's implementation, still in the development stage, is in the form of a generalized computer code for modeling thermodynamic systems. The user specifies a network or mesh of the available symbolic thermodynamic elements to represent the system of interest. These elements are usually either storage or interconnection elements. Examples of storage elements, which model parts of the system where energy may vary, are fluid elements, thermal capacities, and pistons. Examples of interconnection elements, which model the interactions between storage elements, are mechanical and thermal interconnections. Special reservoir and/or equilibrating mechanism elements are used to represent external work and heat interactions. Therefore no mass, energy or entropy crosses the external boundary; so, all CAT problems are closed and isolated.

The network of elements is created by using a "mouse" to select symbolic elements (or icons) from a menu area of the CAT terminal screen and place them in a work area. A simple CAT network or mesh is shown "on screen" in Fig. 6. CAT then generates the equations required to model the specified system and solves the equations numerically. Interacting with the user via a user interface, CAT interprets and displays the results on the terminal screen.

CAT is operational and ready to solve closed equilibrium system problems at the undergraduate text book level. The code and a user's manual are available from the authors of Ref. 41.

Recent updates to CAT include introduction of rate processes via a new heat rate interconnection element (42). This element is required to relate energy flux between storage elements to the difference in temperature. Plans are to use this updated version of CAT to model Stirling engine problems. A kinematic mesh or Lagrangian representation of the fluid nodes has also been implemented (that is, the fluid nodes or control volumes move relative to the solid boundary). CAT is currently being extended to allow modeling of systems which involve gas mixtures and chemical reactions.

CONCLUDING REMARKS

Good Stirling engines are being designed and built via existing design "tools." Frequently, however, the "first build" engine hardware needs much modification before its performance approaches the design goals. Improved understanding of Stirling engine loss mechanisms should result in improved design tools. These tools should help produce designs that require less expensive hardware modification to achieve performance goals. Better design tools should also allow consideration of innovative designs with greater confidence.

Several new Stirling models are, or will soon be, generally available. Taken together, they represent a significant advancement in computational speed combined with mathematical rigor. Computer Aided Thermodynamics may, eventually, make it easy for any "technical" person to set up an accurate model of a Stirling or other complex thermodynamic system. However, a major improvement in design capability and predictive accuracy should not be expected until the results of loss mechanism research is available and can be factored into the models.

Several areas of Stirling loss mechanism research are getting underway. A sustained effort of three to five years must be maintained in these areas to have a reasonable hope of obtaining conclusive results.

Satisfactory characterization of the appendix gap loss will probably require a specialized test rig; none is yet planned. The Sunpower, Inc. oscillating flow rig requires modification to allow testing for the combined effects of oscillating flow/pressure level on pressure drop and heat transfer. Leakage losses can be modeled by well-known equations; however the accuracy of the resulting calculations for Stirling machine performance is not generally known. Better characterization of leakage losses may also require special test rigs. Solid conduction losses and radiation and convection losses from engine external surfaces are relatively straight forward calculations, provided engine and environment temperatures and engine geometry are sufficiently well known.

The idea of building a general purpose test engine has been considered in the past to permit testing of a wide variety of engine components and more accurate measurements. One such engine was designed several years ago, but was never built. Whether such engines would provide capabilities significantly beyond the oscillating flow, oscillating pressure level test rigs should be given further consideration.

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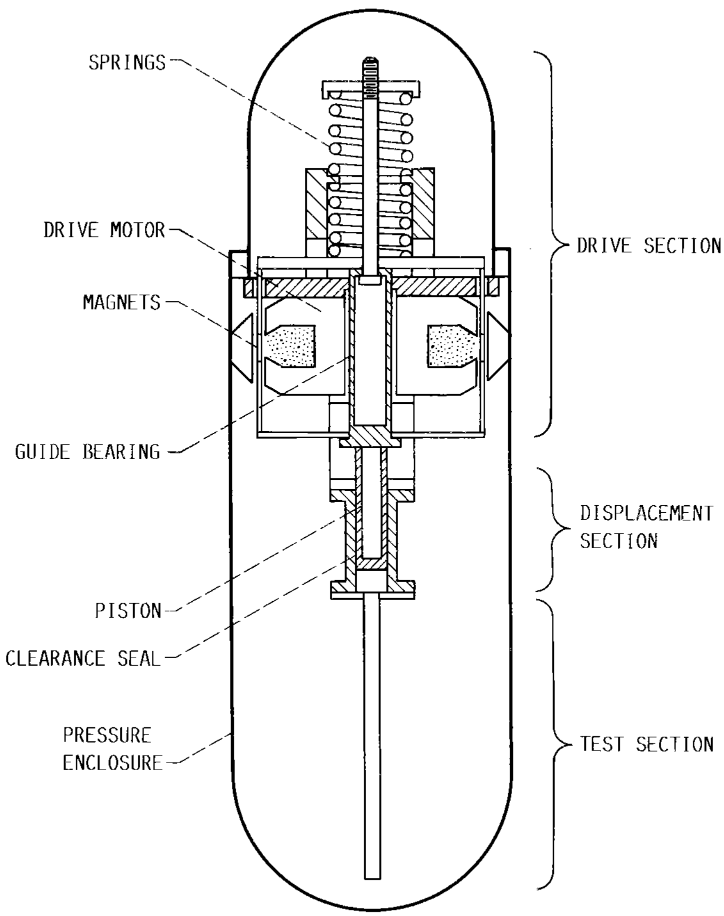


FIGURE 1.- SUNPOWER DESIGNED OSCILLATING FLOW TEST RIG.

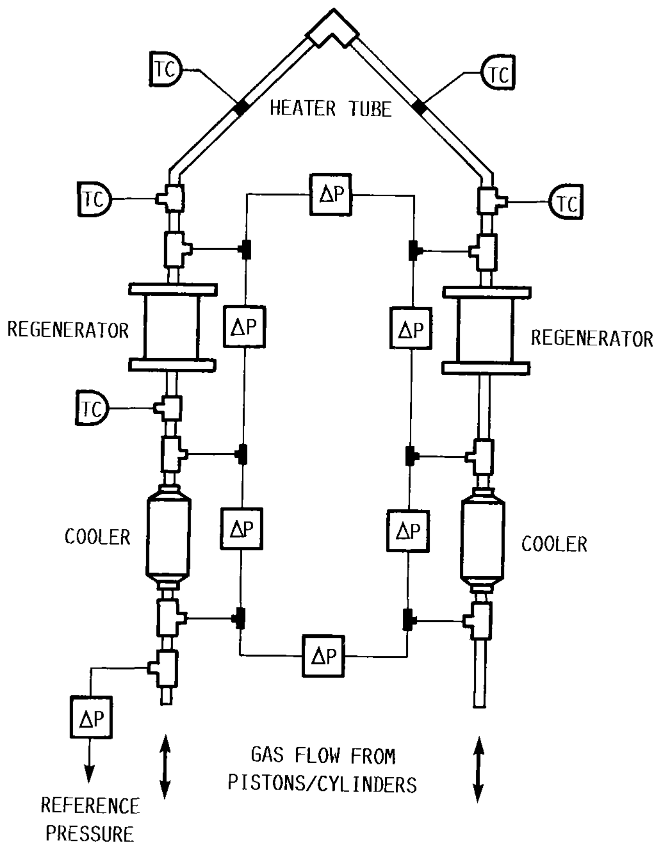


FIGURE 2.- SCHEMATIC OF ARGONNE NATIONAL LABORATORY REVERSING FLOW TEST FACILITY.

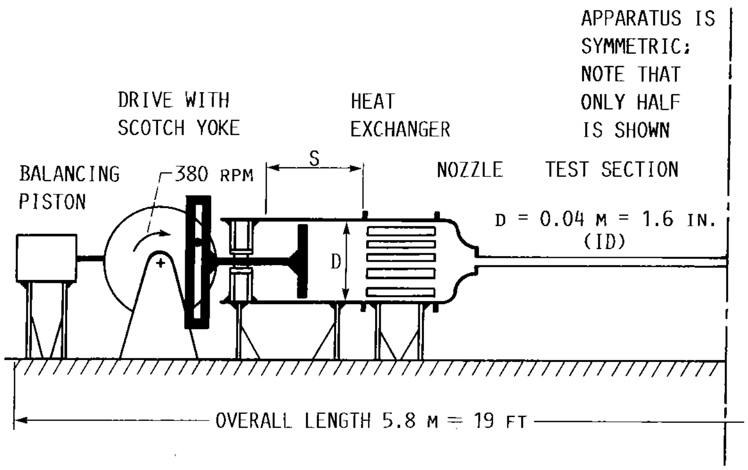
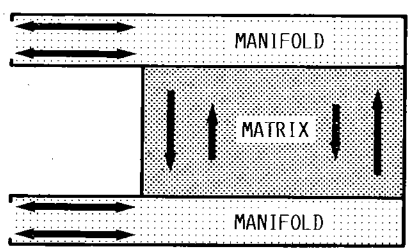
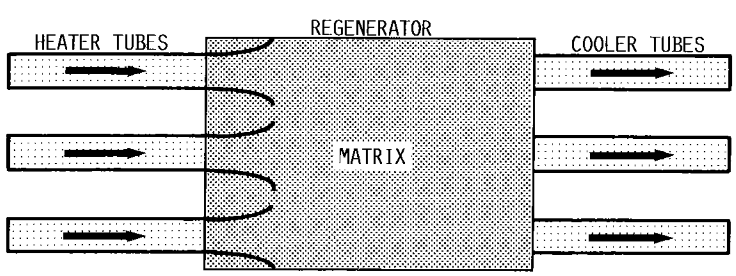


FIGURE 3.- SCHEMATIC OF UNIVERSITY OF MINNESOTA OSCILLATING FLOW TEST RIG FOR OBTAINING MULTI-DIMENSIONAL MEASUREMENTS.

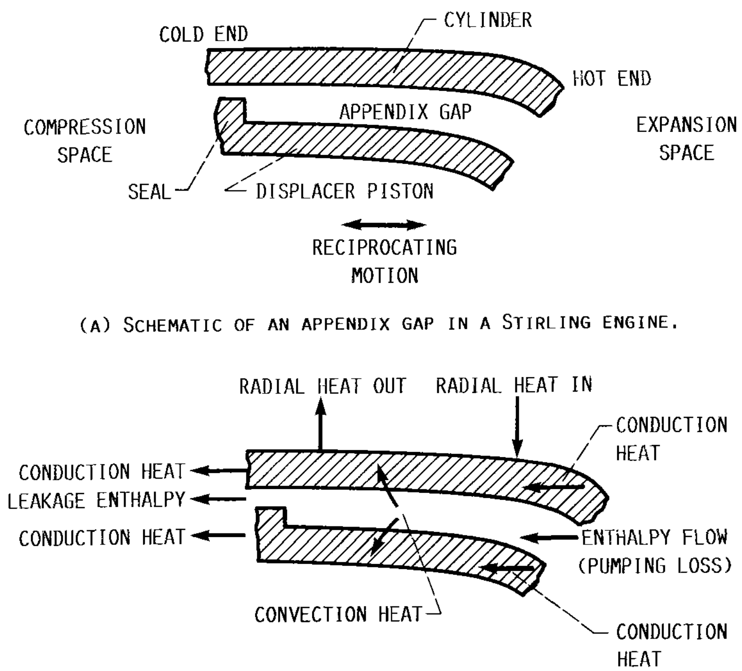


(A) REGENERATOR WITHMANIFOLD FLOW FROM SIDES SHOWS POSSIBLE MAL- DISTRIBUTIONS (DEPENDENT UPON FLOW DIRECTION).



(B) ORIGINAL SPDE CONFIGURATION WITH "JETTING" FROM TUBES INTO MATRIX.

FIGURE 4.- MANIFOLD-REGENERATOR MODEL SCHEMATICS, SHOWING POSSIBLE FLOW MALDISTRIBUTIONS.



(A) Schematic of an appendix gap in a Stirling engine.

(B) Heat flows in the appendix gap region.

Figure 5.

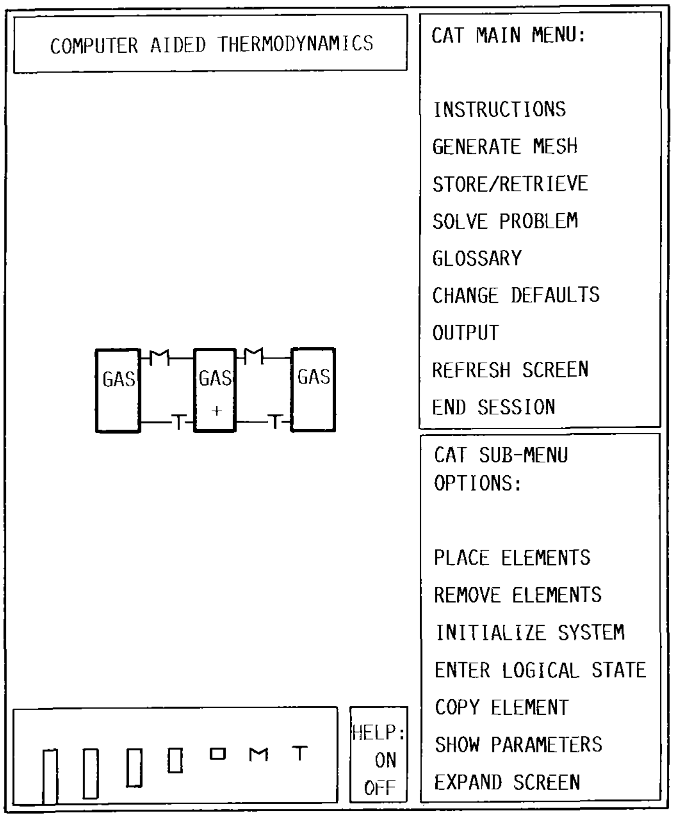


FIGURE 6.- A SIMPLE CAT NETWORK OR MESH.

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16. Abstract
An assessment of Stirling engine thermodynamic modeling and design codes shows a general deficiency; this deficiency is due to poor understanding of the fluid flow and heat transfer phenomena that occur in the oscillating flow and pressure level environment within the engines. Requirements for improving modeling and design are discussed. Stirling engine thermodynamic loss mechanisms are listed. Several experimental and computational research efforts now underway to characterize various loss mechanisms are reviewed. The need for additional experimental rigs and rig upgrades is discussed. Recent developments and current efforts in Stirling engine thermodynamic modeling are also reviewed.

17. Key Words (Suggested by Author(s))
Stirling engine; Stirling cycle;
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