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Recent Stirling Engine Loss-Understanding Results

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ABSTRACT

For several years, the National Aeronautics and Space Administration and other U.S. Government agencies have been funding experimental and analytical efforts to improve the understanding of Stirling thermodynamic losses. NASA's objective is to improve Stirling engine design capability to support the development of new engines for space power. An overview of these efforts was last given at the 1988 IECEC. Recent results of this research are reviewed here.

INTRODUCTION

NASA and other U.S. Government agencies have been funding several efforts to improve the understanding and characterizations of Stirling engine thermodynamic losses. These efforts were started because it seemed likely that shortfalls in engine performance were in part due to poor design code loss characterization. Frequently, the procedure used in validating codes for a particular engine is to calibrate engine thermodynamic losses until performance predictions match measured engine performance. At one time it was thought that the primary reason for discrepancies between predictions and data was underestimation of fluid viscous losses; thus it became common to use pressure drop weighting factors to calibrate codes against engine data. It was found, however, that a code calibrated in this manner for one engine could not accurately predict the performance of another engine. Experimental data has, in recent years, convinced researchers that for some engines the standard steady-flow friction factor correlations actually overpredict fluid viscous losses. More recently weighting factors have been applied to cylinder heat transfer (to enhance hysteresis losses) and to seal leakage losses to get agreement between codes and data. Although such empirical factors may work, and may be appropriate, in calibrating a code to fit the particular characteristics of one engine design, significantly different weighting factors are generally needed to calibrate a particular code for two different engines.

Over the last several years, new information about fluid flow in Stirling engines has been generated via experiments. For example, laminar/turbulent transition data has been taken for oscillating flow about a zero mean and has been used to check turbulence model predictions. And, tubular and regenerator pressure drops have been compared for steady- and oscillating-flow experiments. Experiments to characterize heat transfer and losses in gas springs have continued and some initial experiments on heat transfer in variable volumes with inflow/outflow (cylinders) have been done. Some of the insights developed as a result of the oscillating-flow tests and modeling have been used to develop a new cylinder-heat-transfer model. Several two-dimensional (2-D) modeling efforts are underway which, when coupled with experiments, should eventually provide a better understanding of Stirling engine fluid-flow and temperature fields. Insights from these efforts and new engine test results are impacting the continued development of one-dimensional (1-D) Stirling engine design codes.

This report gives an overview of these results relative to NASA's goal of developing Stirling engines for space power.

LOSS UNDERSTANDING EFFORTS

Two engines are referred to in the discussion below. The RE-1000 is a 1 kW free-piston engine, built by Sunpower, Inc. It has been extensively tested, modeled and reported by NASA Lewis Research Center and others [1-3]. The space power demonstrator engine (SPDE) was a nominal 25 kW, two-cylinder free-piston engine with linear alternators that was built by Mechanical Technology, Inc. (MTI) [4]; initially indicated power, indicated efficiency, and alternator efficiency were well below the design goals [5]. The SPDE has been divided into two space power research engines (SPRE). One of these is being tested at MTI and the other at Lewis [6]. MTI has rebuilt the surrounding structure of their SPRE alternator to reduce eddy current losses and has now achieved their original design goal of 90 percent alternator efficiency. However, SPRE power is still short of the design goal by about 1 kW, out of 12.5 kW.

Sunpower Oscillating Flow Rig Test Results

Sunpower's oscillating-flow rig design [7] allowed accurate measurement of pressure drop and viscous dissipation in tubes and regenerator matrices (with small pressure variation). A steady-flow rig provided consistent steady-flow results. A description of the rigs, test results, and data reduction procedures are being reported in a NASA Contractor's Report [8]. Some of the important test results are summarized below.

For steady flow in tubes, measured entrance/exit loss coefficients and friction factors seemed consistent with existing steady-flow correlations for both flush-mounted and protruding square-edged tubes and for tubes with rounded entrances.

For oscillating flow in tubes, it was not possible to separate entrance/exit-friction and core-friction losses. Thus results were presented in terms of a total dissipation factor (measured total frictional losses in oscillating flow/total frictional losses predicted with steady-flow correlations). For fluid displacement ratios, A_r (fluid displacement/tube length), <1, measured pressure-drop loss was less than that predicted with steady-flow correlations (as much as 35 percent less). Having $A_r > 1$ or 2, seemed to ensure that the steady-flow correlations were adequate for prediction of the viscous losses. These results are illustrated by Fig. 1 for a square-ended tube in Helium at 82 Hz and Valensi number, $Re_\omega = 100$ for several length/diameter ratios.

One possible explanation of the above results is as follows: For $A_r < 1$, where much of the fluid never exits the tube, the flow remains laminar over a larger portion of the cycle than implied by the steady-flow correlations due to acceleration effects. With $A_r > 1$, all of the fluid exits the tube during the oscillation, and the fluid is predominately turbulent over the cycle, as a result of boundary layer separation at the tube entrances and ingested turbulent fluid from the cylinder; this would produce fluid physics more consistent with the assumptions of the steady-flow correlations.

For steady flow in regenerators, measured friction-factor correlations were roughly consistent with GLIMPS [9] steady-flow correlations for sintered-wire screen and for Metex. However, for Brunswick felt metal and for unsintered-wire screen, the measured friction factors were up to two times higher than predicted by the GLIMPS correlations. Some of these results are shown in Figs. 2 and 3 (plotted as a function of Reynolds number, Re).

For oscillating flow in regenerators, measured pressure drop was as much as 25 percent less than that predicted from steady-flow correlations over the intermediate portion of the maximum-Reynolds-number range. This is illustrated in Fig. 4 for sintered-wire screen. If correct, it is surprising that oscillating-flow pressure drop would be smaller than that for steady flow in the regenerators, since Re_ω here is small, less than 0.4 in Fig. 4; such a small Re_ω in tubes would imply a negligible acceleration effect. For low maximum Reynolds numbers, measured losses were larger than the predicted steady-flow values. It should be noted that the measurement error became increasingly larger as the maximum Reynolds number decreased. For the regenerator oscillating-flow results, as shown in Fig. 4, the referenced steady-flow losses were based on friction factors measured in the steady-flow tests rather than on GLIMPS correlations. Results were qualitatively similar to Fig. 4 for Brunswick felt metal and other sintered-screen wire diameters. For the one Metex wire diameter tested, oscillating- and steady-flow losses were in good agreement (data was taken only in the high Re_{max} range). For stacked (unsintered) wire screen, the results varied significantly with wire diameter.

University of Minnesota - Simon, Seume, and Friedman

This work will also be reported in a paper in this session [11]. Some of the results, and their implications for Stirling engine design, are summarized here.

In an early effort, the design point operating regimes of the heaters, coolers, and regenerators of many Stirling engines were characterized in terms of three dimensionless parameters. These are maximum Reynolds number over the cycle, Re_{max}; the Valensi number or kinetic Reynolds number, Re_ω; and. the ratio of fluid displacement to flow passage length, A_r. A large scale, single-drive oscillating-flow rig was designed and built to cover appropriate ranges of these dimensionless parameters. Testing has been under way for several years.

Test results seemed to confirm that flow acceleration retards laminar-to-turbulent transition and flow deceleration retards the reverse transition. This suggests that, in general, flow will be laminar over a larger portion of the high Reynolds number part of the cycle than predicted by steady-flow correlations. It was also concluded, with smooth transitions or nozzles between the smaller diameter test section and the larger diameter of the adjacent components, that, apparently: (1) fluid in the large diameter plenums at the exits of the test section was turbulent during outflow and remained so upon reentering the tube after flow reversal, and (2) a heat exchanger on the upstream end (upon inflow) of a plenum tended to "straighten" the flow or dissipate the turbulence of the flow passing through the heat exchanger. Consequently, even when values of the dimensionless parameters would "normally" suggest laminar flow conditions, hot-wire measurements revealed passage of a turbulent slug of fluid that had, apparently, resided in the plenum which supplied the flow upon flow reversal. Hot-wire determination of the time that the turbulent slug had passed coincided with the computed time of arrival of quiescent fluid that had passed through a heat exchanger and a plenum before entering the test section. These results are discussed in Seume's thesis [12]. A recent plot which illustrates the above is shown in Fig. 5 where velocity fluctuation is plotted as a function of crank angle. The large peak on the left (near 106°) is thought to be due to boundary-layer transition which resulted from instability of the boundary layer inside the tube; the rightmost peak is thought to be due to the passage of a turbulent slug down the tube from one of the adjacent plenums.

More recently, careful measurements of velocities and velocity fluctuation profiles taken radially across the test section, at various axial locations, have provided information to aid the development of an oscillating-flow turbulence model by Patankar, Ibele, and Kohler at the University of Minnesota [13].

The Sunpower oscillating flow rig results suggest that a sharp-edged or slightly rounded transition (as used at the ends of most Stirling engine heaters and coolers), would tend to produce turbulence during inflow to the tube (provided $A_r > 1$ or 2). In the next several months, Simon, and Friedman will be testing for the hydrodynamic effect of several different types of tube entrance/exit geometries. After that, heat transfer testing will provide information needed by Patankar and Ibele to verify turbulence model heat transfer predictions.

University of Minnesota - Patankar, Ibele, and Kohler

This work will also be addressed in a separate paper in this session [14]. A brief review of some of the results is given here.

Patankar, Ibele, and Kohler are using a 2-D model of the Minnesota oscillating-flow rig test section in an attempt to develop a turbulence model which can predict laminar/turbulent transitions under oscillating flow conditions. A high Reynolds number (HRN) κ-ε turbulence model was ruled out because it did not do a good job of modeling velocity gradients near the wall and was not capable of modeling transition.

Results from attempts to model transition with a LRN κ-ε model look more promising. Two remaining problems that need resolution are: (1) in accelerating flow fields, laminar-to-turbulent transition is predicted too early; (2) when a turbulent slug was input at the inflow boundary, in accordance with test data, the turbulence dissipated much too quickly. The problem here seemed to be that the inflow boundary condition on turbulence dissipation was much too large.

Using the current LRN model, the 2-D model of the test rig was used to calculate friction factors and Nusselt numbers for oscillating flow. When comparisons were made with steady-flow correlations, the following results were observed: (1) When the maximum Reynolds number was sufficiently large (on the order of 10^5 for Valensi numbers in the range 80 to 230), both friction factors and Nusselt numbers for oscillating flows agreed with the established turbulent steady-flow correlations. These results are illustrated in Figs. 6 and 7 as taken from Kohler's Ph.D. thesis [13]; (2) When Re_{max} (maximum Reynolds number) was moderate (same order of magnitude as in the SPDE heater and cooler), there was significant deviation from both the turbulent and laminar steady-flow correlations. These results are shown in Figs. 8 and 9. The deviation at moderate Reynolds number may have been due to (1) delay in prediction of transition relative to steady-flow criteria, and (2) neglect of acceleration effects on the laminar-flow friction factor. Calculations also showed that for oscillating flow, as for steady flow, the developing (entrance) region is much shorter for turbulent flow than for laminar flow.

Entropy generation calculations were made and illustrated with three-dimensional plots and with video animation. These results show that for operating conditions similar to the SPDE heater and cooler, except for the temperature level (which is an important difference), the irreversibility due to heat transfer between the wall and gas was far greater than that for fluid viscous loss. If this were correct for the SPDE heater and cooler (that is, at the higher temperature levels that occur in the SPDE), then it would suggest that the SPDE heat exchanger design could have been "stretched" further in the direction of improving heat transfer (at the expense of increased viscous losses). However, in engine design, a trade-off must be made among the various losses for all engine components, including end effects losses at area transitions between components.

University of Minnesota - Goldberg

Goldberg supported development of the Minnesota oscillating flow rig by modeling it in one and in two dimensions. He also developed a 1-D model of the SPDE and a 2-D model of the SPDE heater that was inserted in an otherwise 1-D engine model. These models are based on integral equation forms of the conservation equations. The 1-D model runs efficiently on an IBM/AT microcomputer.

Goldberg also made use of preliminary oscillating flow rig "turbulence model" data to test a κ-ω turbulence model; this model was based on "chaotically" generated turbulence. The qualitative comparison with the early data seems promising. The results of Goldberg's grant work is being published in considerable detail in a NASA Contractor's Report [15].

Goldberg also investigated whether or not pressure information propagation (acoustic) effects were of significance in Stirling engines, such as the relatively high frequency SPDE (where Mach numbers are quite low, usually much less than 0.2). He showed that an additional dimensionless parameter is needed to address this effect. Goldberg's choice of dimensionless parameter is the "characteristic number," which is defined as the number of times a pressure pulse traverses the path length during one engine cycle. Goldberg showed that for a characteristic number > 20, acoustic effects should be negligible for a transmission line of uniform diameter with a small cavity volume. If the SPDE is thought of as a pressure transmission line with small cavity volumes, then its characteristic number at design is about 24; this would suggest that acoustic effects for the SPDE are negligible.

However, the SPDE has very large cavity volumes. In a recent paper [16], Miller developed an approximate equation which shows the effect of cavity-to-transmission-line volume ratios up to 15. The equation shows that increasing this volume ratio decreases the resonance frequency. Goldberg calculated that, in the SPDE, there are cavity-to-tube volume ratios as large as 522. While Miller's approximate equation cannot be extrapolated with confidence to large volume ratios, it does make one wonder whether high frequency engines such as the SPDE, with complicated "tube and cavity" geometries, might be capable of significant acoustic effects if the right (or wrong) volume ratios are chosen.

Although there does not appear to be any U.S. Stirling engine data which have been identified as exhibiting acoustic effects, such effects were found to be a problem at low strokes (for certain tube lengths over certain frequency ranges) in testing of the Sunpower oscillating flow rig [17]. David Rix and Alan Organ reported on engine pressure-drop test results taken at Cambridge University (with a variety of gases), which may have showed the influence of acoustic phenomena [18,19].

A recent paper by Organ [19] attempts to approximate the effect of longitudinal path area changes, including those due to each layer of regenerator screen, on engine acoustic effects, via linear acoustic analysis. Application of this analysis to geometry and operating conditions approximating those of the SPDE would be interesting.

Massachusetts Institute of Technology - Smith, Kornhauser, and Wang

Recent gas spring and "two-space" experiments are summarized in Alan Kornhauser's Ph.D. thesis [20]. The results of this work, which was supported by Oak Ridge National Laboratory (ORNL), are summarized below.

Earlier experiments at MIT demonstrated that, in general, the variation in heat transfer leads that of the wall-to-mean gas temperature in gas springs. Kornhauser significantly extended the data base to different geometries, gases and operating conditions and refined the heat transfer model. This heat transfer phase lead increases with increasing "oscillating flow Peclet number," Pe_{ω} (Prandtl number × Valensi number) to a maximum of 45°. It was found that heat transfer could be predicted with a complex Nusselt number model in which heat flux consists of a real part which is proportional to temperature difference and an "imaginary" part proportional to the rate of change of temperature.

In "two-space" experiments (a variable cylinder volume connected via an area change to an adjacent fixed annular volume), the phase shift observed for oscillating pressure alone (gas spring tests) was also present with the combined oscillating pressure and oscillating flow in the fixed annular volume. It was concluded that although the complex Nusselt number model was effective for predicting heat transfer in the annular volume, its usefulness in conditions of rapidly changing turbulence would be uncertain. The experiments showed that, at least, one other dimensionless parameter was important. Dimensional analysis showed that the other variable must be either a ratio of gas thermal properties-to-wall thermal properties or a Mach number.

One of the conclusions of the above work was that there was a need for tests to characterize heat transfer under various combinations of oscillating pressure and flow. Such a rig has been designed and is under construction. A schematic of the rig is shown in Fig. 10. The phase between the two drive pistons can be changed to produce various combinations of oscillating pressure and flow. First, baseline tests will be conducted with the annular test section that was used in the two-space experiments. Next a tubular test section for testing over a wide range of operating conditions will be designed and tested. Correlations will be developed for use in Stirling design codes. The current year's work is being jointly funded by ORNL and Lewis.

Albert Wang, at MIT, has modeled cylinder heat transfer for Stirling cryocoolers using a complex Nusselt number model of the type refined by Kornhauser and Smith [21]. This work will be reported on in a separate paper in this session [22].

Wang calculated entropy generation for several control volumes so that losses due to various irreversibilities could be separated. Losses for mixing during gas inflow, mixing during gas outflow, and gas-to-wall heat transfer were considered.

Two cylinder design conditions were considered: (1) an "isothermal" wall case, where the cylinder acts as an extension of the adjacent heat exchanger by assuming the heat exchanger temperature, and (2) an "adiabatic" case where the cylinder wall attains the temperature for which the net heat transfer per cycle in the cylinder is zero, even though there is instantaneous heat transfer throughout the cycle.

The results suggest that the various cylinder irreversibilities should be separated (via entropy calculations) during the design process, so that it can be determined what cylinder design is appropriate for the Stirling operating conditions under consideration. For example, in the low Peclet number (low frequency) range, cylinder heat transfer losses are small but mixing losses can be large unless the cylinder wall is "isothermal" (as defined above). Although cylinder heat transfer losses predominate in the intermediate Peclet number range, an "isothermal" wall is advantageous because it reduces mixing losses (relative to the "adiabatic" case). In the high Peclet number range, it made little difference whether the "isothermal" or "adiabatic" cylinder design was used.

It should be remembered that the complex Nusselt number model used in Wang's study exhibits increasing phase shift between heat transfer and wall-to-mean gas temperature as the frequency increases. Gedeon's cylinder heat transfer model, discussed below, which predicts greatly reduced phase shift, might produce a different trade-off of irreversibilities.

Gedeon Associates

Gedeon has developed a new cylinder heat transfer model [10] which introduces the effect of turbulence into the analysis of cylinders with inflow/outflow. In Gedeon's model, turbulence enhances apparent gas conductivity, thereby reducing the phase shift between heat transfer and temperature difference that was found in the MIT gas spring tests. (The turbulence also increases effective viscosity, which reduces effective Valensi number.) For most of the engines Gedeon investigated, he concluded that the phase shift should be negligible.

Gedeon has incorporated the new cylinder heat transfer model into version 3.0 of GLIMPS [10]. Steve Geng of Lewis had previously calibrated version 2.0 of GLIMPS against SPRE and RE-1000 data [23]; cylinder heat transfer multiplication factors of 11 for the RE-1000 and 4 for the SPRE were required. The factor of 11 reduced RE-1000 performance by about 40 percent and the factor of 4 reduced SPRE performance by about 20 percent. Gedeon's new cylinder heat transfer model produces good agreement with RE-1000 data and fair agreement with SPRE data, without the need for additional calibration factors.

MTI's 1-D Stirling design code, HFAST, uses Kangpil Lee's heat transfer model (based on MIT gas spring tests) to evaluate cylinder hysteresis loss. HFAST is believed to calculate much smaller hysteresis losses than GLIMPS version 3.0 [24].

Wolf Kohler calculated oscillating-flow Nusselt number correlations that agree with steady-flow correlations for sufficiently high Re_{max} (Fig. 7); this seems to provide some support for Gedeon's reduced phase shift result. One of Alan Kornhauser's conclusions [20] was that experiments were needed to investigate heat transfer in open cylinders with oscillating pressure level and with inflow and outflow of hotter or cooler gas. Previous thought given to such tests suggests they would present very difficult instrumentation problems. Further evaluation of the problem and consideration of the need for such tests is needed.

Cleveland State University - Ibrahim

Cleveland State University (CSU) is assisting the Lewis Stirling Technology Branch by (1) developing 2-D models of Stirling engine components to aid in better understanding the pertinent hydrodynamics, heat transfer, and related thermodynamic losses, (2) assisting in following and understanding the loss related research ongoing at other organizations, and (3) helping to understand the limitations of Stirling 1-D design codes that are in current use. CSU has permitted Professor Mounir Ibrahim to work onsite at Lewis approximately half-time; he also supervises the work of several CSU graduate students who are also working onsite.

Ibrahim has followed a very systematic approach in developing a generalized 2-D heat exchanger model. The model can be switched between tubular and parallel-plate configurations. Although many Stirling heaters and coolers are tubular, parallel-plate data and analyses are more plentiful and have been very useful for checking the accuracy of the model. The parallel-plate configuration can also be used for simulation of foil regenerators. The first stage of the work was reported at last year's IECEC [25]. Recent work will be updated in a paper later in this session [26].

The heat exchanger code has been used for calculation of friction-factor correlations for laminar flow. The results showed that a complex friction-factor relationship exists which is consistent with increased friction factor during fluid acceleration (relative to the same steady-flow Reynolds number) and decreased friction factor during fluid deceleration, as indicated by previous closed-form analyses. Work now underway includes (1) incorporation of a turbulence model into the 2-D heat-exchanger model, and (2) development of a sudden expansion/contraction model that can be used in joining together two components of different cross-sectional areas. Plans for the coming year are to (1) bring the model closer to the real engine environment by assuming compressibility and properties that are variable with temperature and pressure, (2) incorporate end effects from the sudden expansion/contraction work, and (3) simulate a "subchannel" that runs through all three heat-exchanger components (i.e., single tube heater and cooler and a portion of a regenerator matrix).

University of Pittsburgh - Hall and Porsching

Dr. John Goodrich of the Lewis Internal Fluid Mechanics Division proposed evaluation of an existing multidimensional code, ALGAE (ALgorithms for GAs Equations), for Stirling engine simulation. ALGAE's computational technique is thought to be particularly efficient in use of computer time and, thus, it may be practical for use in eventual 2-D simulation of an entire Stirling engine working space.

A feasibility study was conducted last summer by the developers of the code, Drs. Charles Hall and Tom Porsching of the University of Pittsburgh. The results of that study were promising and, consequently, a grant is now underway; the initial goal is to use ALGAE to perfect the simulation of the SPDE heater-regenerator-cooler that was developed last summer. Video animation will be used to aid in interpretation of the computational results; initially, video animation of the gas temperature field and fluid particle motion are planned. GLIMPS has been used to compute boundary conditions for input to the ALGAE model. Initial results of this work will be presented in a paper later in this session [27].

CONCLUDING REMARKS

Heater/Cooler Performance

A combination of Sunpower and University of Minnesota oscillating-flow rig test results suggest that: (1) If fluid displacement/tube length, A_r, < 1 and Re_{max} is not too large, flow can remain laminar over a significant portion of the high Reynolds number part of the cycle. Thus, viscous losses would be less, but, heat transfer would be worse than predicted with existing steady-flow correlations, and (2) If A_r > 1 or 2 or Re_{max} is sufficiently high, then flow can remain turbulent over essentially all of the cycle (except for points near flow reversal) and steady-flow correlations can be used for oscillating-flow predictions.

If current Stirling space power engine performance is more sensitive to changes in heat transfer than to viscous losses in the heater and cooler, as indicated by Mechanical Technology, Inc. calculations, then it would seem best to keep A_r > 1 or 2 and Re_{max} sufficiently high so that flow in the heaters and coolers is essentially always turbulent. This might ensure that heater and cooler steady-flow correlations are adequate for oscillating-flow predictions and make performance predictions more reliable. This would be true because accurate prediction of transition and the effects of acceleration/deceleration on laminar flow correlations would not be important.

Gedeon reported that modification of the GLIMPS transition criterion for ductlike heat exchangers, in an attempt to reflect some of the University of Minnesota findings, showed no significant impact on performance predictions for the RE-1000 and SPDE (relative to predictions made with the GLIMPS steady-flow correlations). Steve Geng of Lewis (with a NASA Stirling code) extrapolated the delay in laminar-to-turbulent transition beyond that observed in the University of Minnesota findings. In what should represent a worst case for engine performance, he showed that if the laminar-to-turbulent transition point is shifted from the steady-flow transition criterion to the point of maximum Reynolds number in the heater and cooler, then SPRE power would drop by 1.5 kW (or more than 10 percent of the nominal PV power). In engine tests, the SPDE heater and cooler appeared to exhibit lower viscous losses and poorer heat transfer performance than predicted during the design process. It appears that further investigation of potential improvements in engine performance, by attempting to ensure turbulence in heaters and coolers, is needed.

Cylinder Heat Transfer

The complex Nusselt number model developed at MIT for gas springs and Gedeon's new cylinder heat transfer model appear to produce significantly different predictions, for cylinders with inflow/outflow, of how instantaneous heat transfer varies over the engine cycle. Further investigation/

comparison of these models is needed and cylinder heat transfer experiments (with inflow/outflow), as recommended by Kornhauser, may be required. If Gedeon's model should prove accurate, then it might be desirable to attempt to minimize turbulence in the cylinders.

Entropy Calculations

MTI has added a postprocessor to their 1-D design code, HFAST, to calculate entropy generation and thus allow separation of the various irreversibilities. GLIMPS now has all irreversibilities separated out except for mixing losses. We should soon be able to make an "irreversibility by irreversibility" comparison of GLIMPS and HFAST losses and, thus, have a much better understanding of how these codes compare than was possible when many irreversibilities were not separately evaluated. These entropy calculations will also be useful in helping to decide which losses are most significant with regard to engine performance. Wang of MIT made use of entropy calculations in his analysis of cylinder heat transfer loss. It should become routine for all Stirling codes to do this type of second Law analysis.

Multidimensional calculation of entropy generation with video animation can very graphically illustrate where, in space and time, the irreversibilities which are having the greatest impact are located. Kohler has already done this for the University of Minnesota oscillating flow rig; his calculations showed that for the operating point considered (similar to the SPDE heater/cooler operating regime except for temperature level) practically all of the irreversibility was due to heat transfer in a thin boundary layer near the wall of the test section.

Acoustic Effects

When Stirling engines are treated as though they were transmission lines with small cavity volumes, acoustic ("organ pipe") resonance frequencies are an order of magnitude above those of the highest frequency Stirling engines. However, increasing cavity-to-tube volume ratio shifts acoustic resonances to lower frequencies. Thus, consideration of the large cavities and the complicated "tube and cavity" volumes that exist in Stirling engines suggests that vigilance should be maintained in Stirling engine and oscillating-flow rig testing for the possible impact of acoustic effects on test results.

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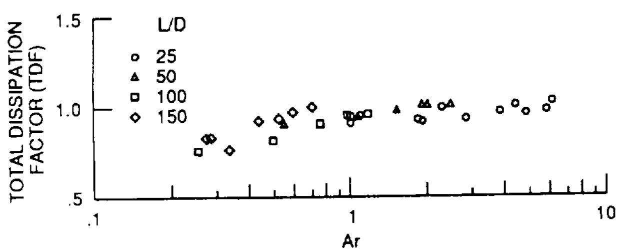

Figure 1. - Oscillating flow test results for square ended tubes TDF versus Ar and L/D. All points are from Test Runs 92,97, 101, 102, 117 and 119. Helium at 82 Hz and Re ω = 100.

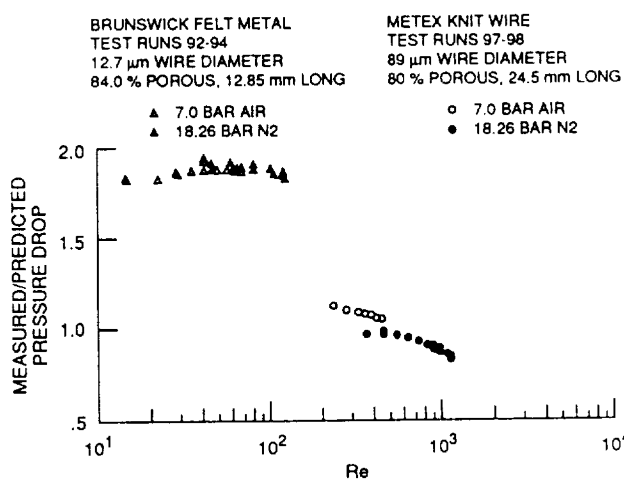

Figure 3. - Steady flow test results for random fiber regenerator Pratio versus Re and wire diameter.

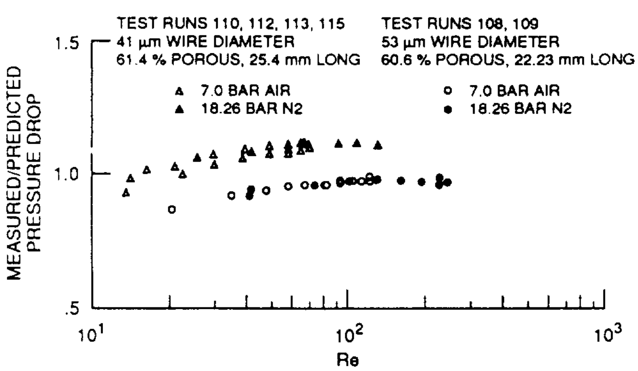

Figure 2. - Steady flow test results for sintered screen regenerator Pratio versus Re and wire diameter.

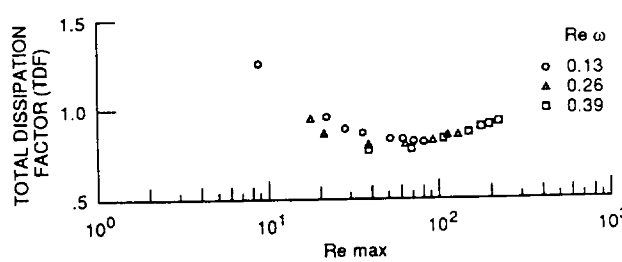

Figure 4. - Oscillating flow test results for 53 μm sintered screens TDF versus Re max and Re ω. All points are from Runs 137-138. Tests at 90 Hz using Helium.

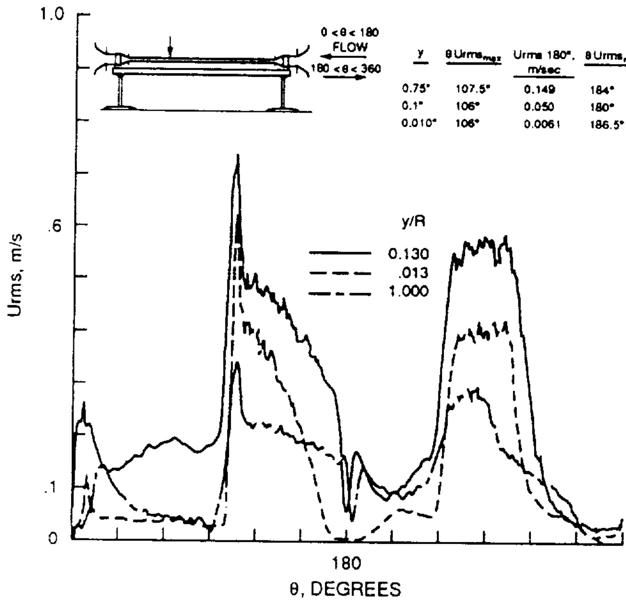

Figure 5. - Plot of velocity fluctuations, Urms, measured at axial location, x/d = 44 (Urms ensemble averaged over 500 cycles).

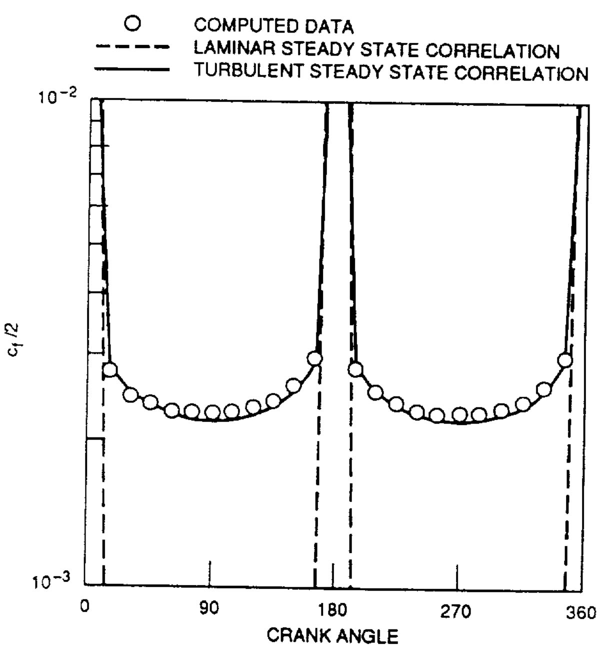

Figure 6. - Comparison of computed fully developed friction coefficient with steady state correlations. Data point d: $Re_{max} = 1.32 \times 10^5$, $Re\ \omega = 81$, $L/D = 60$.

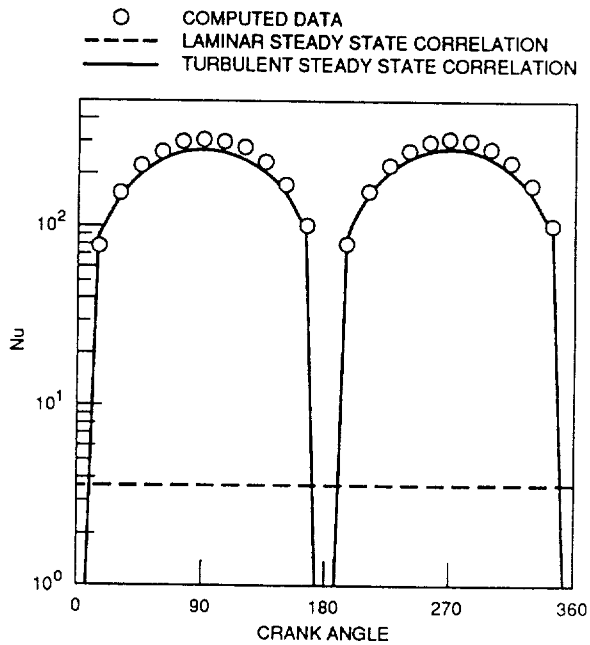

Figure 7. - Comparison of computed fully developed Nu number with steady state correlations. Data point d: $Re_{max} = 1.32 \times 10^5$, $Re\ \omega = 81$, $L/D = 60$.

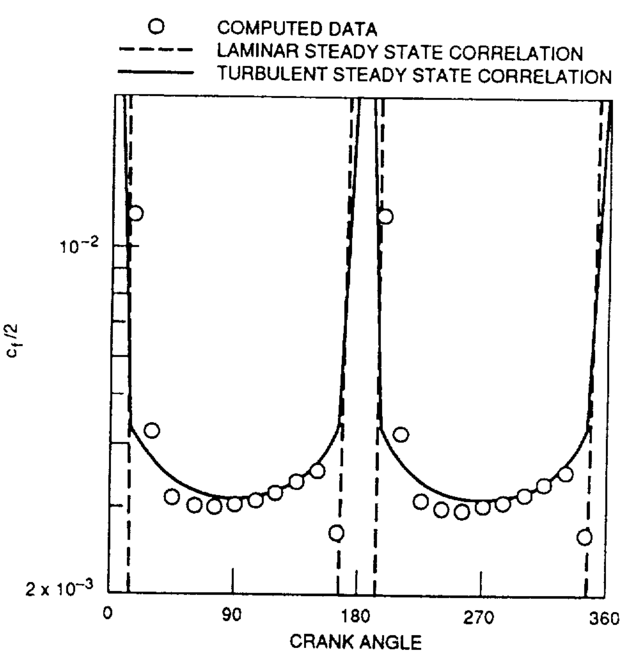

Figure 8. - Comparison of computed fully developed friction coefficient with steady state correlations. Data point m: $Re_{max} = 2.39 \times 10^5$, $Re\ \omega = 230$, $L/D = 68.5$.

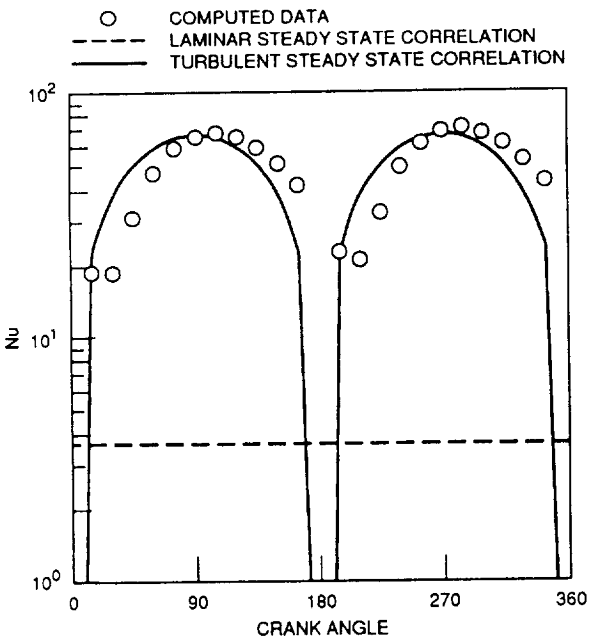

Figure 9. - Comparison of computed fully developed Nu number with steady state correlations. Data point m: $Re_{max} = 2.39 \times 10^4$, $Re\ \omega = 230$, $L/D = 68.5$.

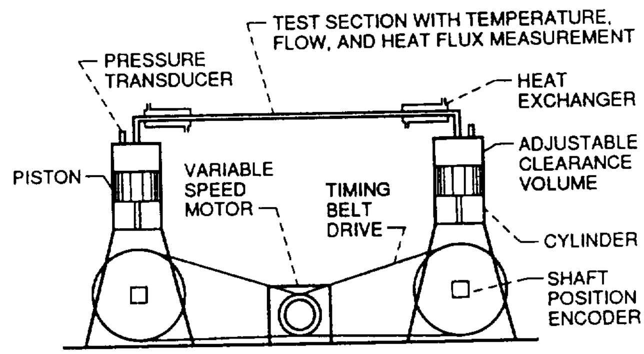

Figure 10. - Schematic of MIT test rig.

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15. Supplementary Notes

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16. Abstract

For several years, the National Aeronautics and Space Administration and other U.S. Government agencies have been funding experimental and analytical efforts to improve the understanding of Stirling thermodynamic losses. NASA's objective is to improve Stirling engine design capability to support the development of new engines for space power. An overview of these efforts was last given at the 1988 IECEC. Recent results of this research are reviewed here.

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