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Efficiency Terms for Stirling Engine Systems

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ABSTRACT

Thermal efficiencies are the primary indicators of the quality of design and performance of any energy system. However, in the case of Stirling engine systems, there is no widely accepted standard terminology in use, which would allow valid comparative evaluations to be made. Discussions with Department of Energy staff and with the Stirling machine research community have confirmed that this lack of standard terms is giving rise to severe problems in comparing the results of different research programs. To help overcome these problems, 14 efficiency terms that describe the performance of 6 combinations of the basic system components — the heat source, the engine, and the load — are proposed. The efficiency terms are defined in terms of an energy accounting flowchart, which allows individual components or the entire system to be reported consistently so that the results of various research groups may be properly compared. The appendixes contain three sets of sample calculations, two of which use test run data from an actual free-piston and a kinematic Stirling engine.

1. INTRODUCTION

There is no widely accepted terminology or method available for describing the performance of the Stirling engine. Researchers are obliged to devise (but often fail to define properly) their own terms for describing the results obtained in testing Stirling systems. Efficiency being the common denominator of the numerous variations in Stirling engine size and configuration, it is difficult to compare the results of various research groups due to the use of inconsistent efficiency terms.

The problem of inconsistency of efficiency terms is not unique to Stirling engines, of course. Inconsistency in the definition and application of efficiency terms exists to a certain extent even in common energy systems, such as power plants, where the terms and system boundaries are fairly well defined.[1] A large part of this problem for some Stirling systems is caused by the lack of clearly defined boundaries between the engine, its heat source, and its load, due to the necessarily close coupling between components. The steam engine, on the other hand, has easily defined boundaries separating it from the boiler and the load. Standardized steam engine efficiency terms[2] do not include the boiler, for example. In contrast, the free-piston Stirling engine has no clearly defined separation between heat source and engine or between engine and load.

It is not likely that everyone will agree with the definitions given in this report. Because of the variety of viewpoints on these terms, as evidenced by the variety of terms presently in use, this report has been given as extensive a review as time would allow. It was first reviewed internally at the Oak Ridge National Laboratory (ORNL) by staff members knowledgeable about Stirling engines. Appropriate comments by these reviewers were incorporated in the text, and the second draft was sent outside the Laboratory to reviewers in ten organizations as follows: Martini Engineering; General Electric Company; University of Washington; National Aeronautics and Space Administration—Lewis Research Center; Data Trace, Inc.; Energy Conversion Equipment Branch of the Department of Energy; University of Calgary; Sunpower, Inc.; Mechanical Technology, Inc.; and University of Minnesota. At the time this report was written, five responses had been received and were incorporated where appropriate. It is intended that the use of this tabulation of efficiency terms will help to provide a larger measure of consistency in the subsequent reporting of Stirling engine performance and thus improve communication within the Stirling research community.

2. OBJECTIVE AND SCOPE

The purpose of this report is to provide a common basis for reporting efficiencies of Stirling engines and their supporting systems. Providing calculational procedures and specifying units are not objectives of this report; it is assumed that the researchers using the efficiency terms given herein will choose the appropriate units. If the terminology proposed in this report is widely adopted, it will provide a consistent method of accounting for the various paths traveled by the fuel energy supplied to the Stirling engine system. However, it is likely that there will be engine systems with exceptions that are not readily adaptable to the energy accounting given here. In such special cases the researcher should carefully define his terms and explain the special considerations so that other researchers may be fully informed.

Dividing the Stirling engine system into its three basic components (heat source, engine, and load) results in six equipment combinations for efficiency determination. These six combinations (shown in Fig. 1) are the basis for the grouping of the efficiency terms discussed in this report. Fourteen efficiency terms sufficiently descriptive to characterize

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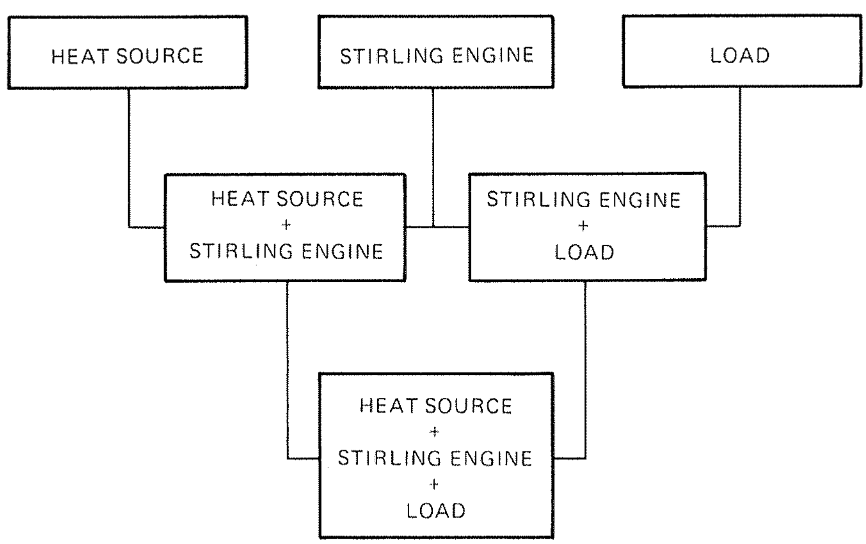

Fig. 1. Equipment combinations for efficiency determination.

the three basic components separately and in any combination are tabulated in Table 1 according to the six combinations shown in Fig. 1.

If both low and high fuel heating values (LHVs and HHVs) and both gas and metal temperatures for Carnot efficiency were used, there would be 10 additional terms for a total of 24 efficiency terms. To minimize the confusion that would result from attempting to incorporate such a large number of terms, these options were excluded to maintain the number of efficiency terms at 14. It is therefore necessary at the outset to state that the HHV should be used in the fuel energy term and that maximum metal and coolant supply temperatures should be used in the Carnot

Table 1. Efficiency terms for the three components of the Stirling engine system

Efficiency term	Symbol
Heat source	
Combustion system efficiency	η_{hs}
Stirling engine	
Carnot efficiency	η_{ca}
Ideal Stirling cycle efficiency	η_{cy}
Indicated thermal efficiency	η_{it}
Indicated engine efficiency	η_{ie}
Brake thermal efficiency	η_{bt}
Mechanical efficiency	η_{me}
Load	
Load efficiency	η_{ℓ}
Heat source and engine	
Indicated gross engine efficiency	η_{ige}
Indicated gross thermal efficiency	η_{igt}
Brake gross thermal efficiency	η_{bgt}
Stirling engine and load	
System thermal efficiency	η_{st}
Heat source, engine, and load	
Gross thermal efficiency	η_{gt}
Net thermal efficiency	η_{nt}

efficiency term. Note that the use of the HHV is inconsistent with the use of LHV as proposed for heat pump systems.[3] However, the use of HHV will result in a more conservative efficiency number. In addition, because of the improvements being made in combustion systems, such as the pulsed jet furnace, using the LHV could result in furnace efficiencies greater than 100%. The 14 efficiency terms in Table 1 are the basis for the discussion in the remainder of this report.

Definitions of power, temperature, and efficiency terms are given in Sects. 3 and 4; these terms are used in three sets of example calculations, which are presented in the appendixes. Appendix A gives an example using a fictitious engine for the purpose of illustrating the use of 13 of the 14 efficiency terms. Appendixes B and C contain example calculations of efficiency terms, using test run data obtained from an actual free-piston and a kinematic Stirling engine.

3. DEFINITION OF POWER AND TEMPERATURE TERMS

Table 2 presents descriptions of the power and temperature terms that are used later in the definition of efficiency terms. It is obvious that all of these terms cannot be the result of direct measurements. It would not be possible or desirable to attempt to delineate here all the possible ways to measure or calculate these terms. It is thus the responsibility of the individual researcher to indicate in his/her technical reports how the values were determined and, if possible, to give an indication of the confidence level in the values so determined. In Table 2 each term is given a number. Subsequent use of these terms will be by reference to this term number. In Sect. 4 these terms will be used in the definition of the 14 efficiency terms selected for application to the Stirling engine system.

Figure 2 is an energy balance flowchart, which represents most Stirling engine systems. The circled numbers represent the power and

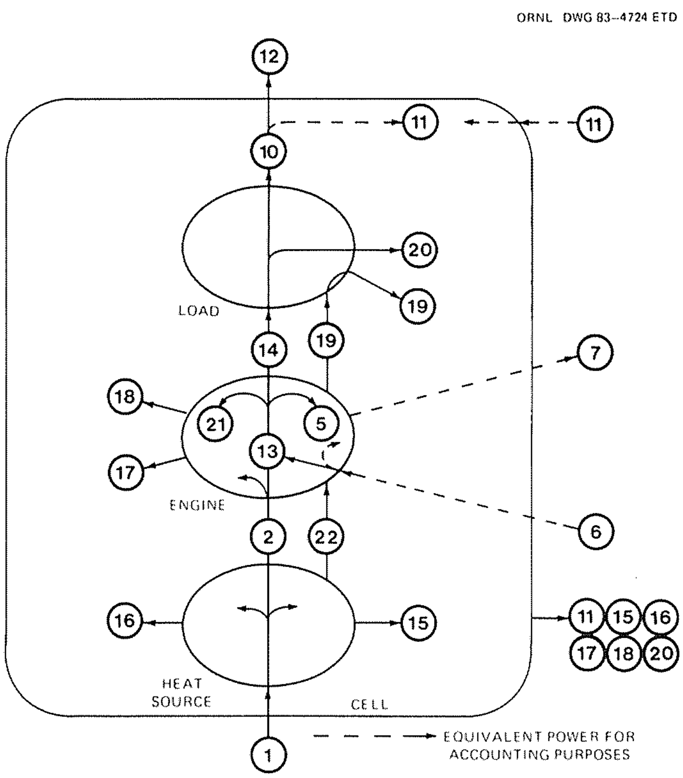

Fig. 2. Power accounting in the Stirling engine system. See Table 2 in Sect. 3 for an explanation of the numbered terms.

Table 2. Description of power and temperature terms

Term No. (see Fig. 2)	Term	Description
(1)	Heat source total energy, Q_{SOURCE}	Total input to solar collector, total output of isotopic source, or total input to furnace in the form of fuel at the HHV. If input is electrical, use source efficiency of 0.3.
(2)	Power input to engine head, Q_{HEAD}	That portion of total input which is effectively transferred to the engine head
(3)	Coolant temperature, T_{COOL}	Absolute temperature at which coolant enters the engine cooler
(4)	Metal temperature, T_{HEAD}	Maximum absolute temperature of metal at the interface between furnace and engine head
(5)	Engine-supplied power to auxiliaries	The power supplied by the power piston for such auxiliaries as frequency control gas spring, gas bearing supply, etc. This loss term, when combined with the friction loss term (21), determines the difference between indicated power (13) and brake power (14).
(6)	Externally supplied input to engine	The equivalent power supplied to the engine contributing directly to the energy conversion chain (such as a motor-driven displacer). The equivalent power supplied is the actual input modified by the efficiency terms of all the components in the energy conversion chain from its source. Use a source efficiency of 0.3 for electrical power unless otherwise justified. This equivalent power is to be treated as input (denominator) in the efficiency term.
(7)	Equivalent power loss from (6) above	Equivalent loss from (6); (7) = (6) x (1 − source efficiency).

Table 2 (continued)

Term No. (see Fig. 2)	Term	Description
(8)	Ideal cycle output	The calculated ideal Stirling cycle work output with no losses, as defined by the user
(9)	Ideal cycle input	The calculated ideal Stirling cycle total work input, as defined by the user. Total work consists of output above (8) plus ideal cycle reject heat.
(10)	Gross load power output	Gross power output from the engine load
(11)	Externally supplied auxiliary power	Auxiliary power that is separately supplied to auxiliaries such as fans and pumps required for the operation of any Stirling system component not situated directly in the power conversion chain. This power is treated as negative output in the efficiency term.
(12)	Net load power output	Net load power output equals gross load power minus auxiliary power: (12) = (10) − (11).
(13)	Indicated power	The sum of all induced pressure-volume (or force-stroke) variations, per unit time, contributing to the movement of the power piston
(14)	Brake (or shaft) power	The useful power crossing the boundary between engine and load. Brake power is the indicated power less any friction, pumping, gas spring, or other loss from the power piston on the engine side of the load boundary. (14) = (13) − [(21) + (5)], (14) = (10) + (20).
(15)	Loss from heat source to cell	Power loss from heat source as heat transfer to the cell, which is not included in measurement of term (16)

Table 2 (continued)

Term No. (see Fig. 2)	Term	Description
(16)	Exhaust gas loss from heat source	Power loss from heat source as exhaust gas
(17)	Loss from engine housing to cell	Power loss from engine housing as heat transfer to the cell
(18)	Reject heat from engine cooler	Power loss as reject heat from the engine cooler
(19)	Loss from engine to load	Heat loss between engine and load such as heat transfer
(20)	Load/transmission inefficiency	Power loss from load due to inefficiency of transmission, alternator, or pump. Does not include heat transfer from engine, term (19). [(20) = (14) − (10)]
(21)	Loss from power piston	Friction loss from the power piston and linkage between the compression space interface and the engine output shaft (or equivalent). This loss term, when combined with the gas spring hysteresis loss of term (5), determines the difference between indicated power (13) and brake power (14).
(22)	Loss from heat source to engine housing	Power loss (i.e., nonproductive heat transfer) from the heat source to the engine cooler
(23)	Source efficiency	The assumed efficiency used to establish the equivalent auxiliary power [such as term (6)] supplied from an outside source. Assume a source efficiency of 0.3 unless otherwise justified.

temperature terms described in this section. An energy balance can be established for individual components, pairs of components, or the entire system. Reference to Fig. 2 will help the reader to understand the definition of efficiency terms in Sect. 4 and the sample calculations in the appendixes.

4. DEFINITION OF EFFICIENCY TERMS

Following is a list of the 14 efficiency terms of Table 1 together with a summarized definition. The term numbers in parentheses refer to the definitions given in Table 2 of Sect. 3. The use of "thermal" or "engine" in the Stirling engine efficiency terms is consistent with common usage in other types of engine systems as follows: "thermal" efficiency compares actual work to actual heat rate, whereas "engine" efficiency compares actual work to Carnot or ideal work.

4.1 Heat Source*

Combustion system efficiency, η_{hs}:

$$\eta_{hs} = \frac{(2)}{(1)} = \frac{Q_{HEAD}}{Q_{SOURCE}}$$

4.2 Stirling Engine

Carnot efficiency, η_{ca}:

$$\eta_{ca} = 1 - \frac{(3)}{(4)} = 1 - \frac{\text{coolant temperature}}{\text{maximum head temperature}}$$

Ideal cycle efficiency, η_{cy}:

$$\eta_{cy} = \frac{(8)}{(9)} = \frac{\text{ideal Stirling cycle work output}}{\text{total ideal cycle work input}}$$

Indicated thermal efficiency, η_{it}:

$$\eta_{it} = \frac{(13)}{(2) + (6)} = \frac{\text{indicated power}}{Q_{HEAD} + \text{engine aid power at source efficiency}}$$

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*Where applicable, "furnace" is used in place of the generic term "heat source" elsewhere in this report.

Indicated engine efficiency, η_{ie}:

$$\eta_{ie} = \frac{\eta_{it}}{\eta_{ca}} = \frac{\text{indicated thermal efficiency}}{\text{Carnot efficiency}}$$

Brake thermal efficiency, η_{bt}:

$$\eta_{bt} = \frac{(14)}{(2) + (6)} = \frac{\text{brake power}}{Q_{HEAD} + \text{engine aid power at source efficiency}}$$

Mechanical efficiency, η_{me}:

$$\eta_{me} = \frac{(13) - [(21) + (5)]}{(13)} = \frac{(14)}{(13)} = \frac{(10) + (20)}{(13)} = \frac{\text{brake power}}{\text{indicated power}}$$

4.3 Load

Load efficiency, η_{ℓ}:

$$\eta_{\ell} = \frac{(10)}{(14)} = \frac{\text{gross load output power}}{\text{brake power}}$$

4.4 Heat Source and Engine

Indicated gross engine efficiency, η_{ige}:

$$\eta_{ige} = \frac{\eta_{igt}}{\eta_{ca}} = \frac{\text{indicated gross thermal efficiency}}{\text{Carnot efficiency}}$$

Indicated gross thermal efficiency, η_{igt}:

$$\eta_{igt} = \frac{(13)}{(1) + (6)} = \frac{\text{indicated power}}{Q_{SOURCE} + \text{engine aid power at source efficiency}}$$

Brake gross thermal efficiency, η_{bgt}:

$$\eta_{bgt} = \frac{(14)}{(1) + (6)} = \frac{\text{brake power}}{Q_{SOURCE} + \text{engine aid power at source efficiency}}$$

4.5 Stirling Engine and Load

System thermal efficiency, η_{st}:

$$\eta_{st} = \frac{(10)}{(2) + (6)} = \frac{\text{gross load power}}{Q_{HEAD} + \text{engine aid power at source efficiency}}$$

4.6 Heat Source, Engine, and Load

Gross thermal efficiency, η_{gt}:

$$\eta_{gt} = \frac{(10)}{(1) + (6)} = \frac{\text{gross load power}}{Q_{SOURCE} + \text{engine and power at source efficiency}}$$

Net thermal efficiency, η_{nt}:

$$\eta_{nt} = \frac{(10) - (11)}{(1) + (6)} = \frac{\text{gross load power} - \text{auxiliary power}}{Q_{SOURCE} + \text{engine aid power at source efficiency}}$$

5. SUMMARY AND RECOMMENDATIONS

The most important objective of this tabulation of efficiency terms is to provide standardized terms which, when accepted and utilized by the Stirling research community, will result in more consistency in the technical descriptions of Stirling engine systems. It is obviously unnecessary to use all 14 terms in every technical presentation. Therefore, this report recommends the use of certain key efficiency terms, which will allow realistic comparisons of various Stirling systems among the many variations in existence.

At the top of this list of key efficiency terms is the brake thermal efficiency, η_{bt}. The four most important efficiency terms are tabulated in Table 3. When the gross thermal efficiency is quoted, it would be most helpful if the auxiliary power [power term (11) in Fig. 2] were also listed. Giving both the auxiliary power and the gross thermal efficiency, η_{gt}, would be more informative than giving only the net thermal efficiency, η_{nt}.

Table 3. Key efficiency terms

Components	Efficiency term
Stirling engine	Brake thermal, η_{bt}
Stirling engine	Indicated thermal, η_{it}
Heat source and engine	Brake gross thermal, η_{bgt}
Heat source, engine, and load	Gross thermal, η_{gt}

As previously stated, Appendixes A, B, and C present three examples of efficiency term calculations. The example in Appendix A is a fictitious free-piston Stirling engine, while test data obtained from actual free-piston Stirling and kinematic Stirling engines were used in the examples in Appendixes B and C. A summary of the efficiency term calculations for the two actual engines is given in Table 4. Although the two

Table 4. Tabulation of calculated efficiency terms for a free-piston Stirling Engine (see Appendix B) and a kinematic Stirling engine (see Appendix C)

(The four key efficiency terms are printed in italic type.)

	Free-piston engine (Appendix B)	Kinematic engine (Appendix C)
Furnace		
Furnace efficiency, η_{hs}	0.55	0.62
Engine		
Carnot efficiency, η_{ca}	0.73	0.74
Indicated thermal efficiency, η_{it}	0.24	0.28
Indicated engine efficiency, η_{ie}	0.33	0.37
Brake thermal efficiency, η_{bt}	0.19	0.19
Mechanical efficiency, η_{me}	0.79	0.70
Load		
Load efficiency, η_{ℓ}	0.84	0.81
Furnace and engine		
Indicated gross thermal efficiency, n_{igt}	0.13	0.17
Indicated gross engine efficiency, n_{ige}	0.18	0.23
Brake gross thermal efficiency, n_{bgt}	0.10	0.12
Engine and load		
System thermal efficiency, η_{st}	0.16	0.16
Furnace, engine, and load		
Gross thermal efficiency, η_{gt}	0.09	0.10

engines are listed side by side, it is not the purpose of Table 4 to demonstrate any relative merit one engine may have over the other. The primary consideration in the selection of these data points was data quality, not engine performance. Both of these engines were highly instrumented, and the test runs were selected to make maximum use of measured values rather than calculated values.

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Appendix A

FICTITIOUS STIRLING ENGINE

Presented below is a list of test parameters from a fictitious Stirling engine, with examples of the efficiency terms as defined in this report. To make maximum use of the terms, this fictitious engine is assumed to be a free-piston Stirling with the displacer sprung to the power piston, the power piston sprung to the housing, and the displacer driven by a linear electric motor.

Following the tabulation of fictitious data in Table A.1, the efficiency terms as defined in Sect. 4 are calculated.

Using the efficiency definitions of Sect. 4 and the engine parameters of Table A.1, the following efficiencies are calculated:

<u>Furnace</u>

Furnace efficiency:

$$\eta_{hs} = \frac{(2)}{(1)} = \frac{10{,}500}{16{,}500} = 0.64$$

<u>Engine</u>

Carnot efficiency:

$$\eta_{ca} = 1 - \frac{(3)}{(4)} = 1 - \frac{300}{1{,}172} = 0.74$$

Indicated thermal efficiency:

$$\eta_{it} = \frac{(13)}{(2) + (6)} = \frac{2{,}790}{10{,}500 + 670} = 0.25$$

Indicated engine efficiency:

$$\eta_{ie} = \frac{\eta_{it}}{\eta_{ca}} = \frac{0.25}{0.74} = 0.34$$

Table A.1. Fictitious Stirling engine parameters used in the sample calculations

Term No.	Term	Value
(1)	Total power input to furnace, fuel rate at HHV	16,500 W
(2)	Furnace input to engine head, Q_{HEAD}	10,500 W
(3)	Cooling water inlet temperature, 80°F	300 K
(4)	Maximum metal temperature in head, 1650°F	1,172 K
(5)	Power loss due to hysteresis in the frequency adjustment gas spring	180 W
(6)	Electrical input to displacer motor, 201 W; equivalent input at source efficiency: 201 ÷ 0.3 = 670 W	670 W
(7)	Equivalent loss = 0.7 x (6) = 0.7 x 670 = 469 W	469 W
(10)	Load power; gross output of linear alternator on the shaft	2,205 W
(11)	Auxiliary power; input to fan on load is 167 W	167 W
(12)	Net power output: (10) – (11) = 2,205 – 167 = 2,038 W	2,038 W
(13)	Indicated power: displacer gas spring, 600 W, plus working space, 2,190 W = 2,790 W	2,790 W
(14)	Brake power = indicated power minus friction and gas spring losses: (14) = (13)– [(21) + (5)] = 2,790 – (160 + 180) = 2,450 W	2,450 W
(15)	Heat transfer loss from furnace	500 W
(16)	Exhaust gas loss from furnace	5,300 W
(17)	Heat transfer loss from engine	300 W
(18)	Reject heat from cooler	7,851 W
(19)	Heat transfer between engine and load	300 W
(20)	Alternator efficiency = 0.9: loss due to inefficiency = 0.1(14) = 0.1 x 2,450 = 245 W	245 W
(21)	Friction and pumping loss from power piston	160 W
(22)	Heat transfer between furnace and engine (nonproductive)	200 W
(23)	Source efficiency	0.3

Brake thermal efficiency:

$$\eta_{bt} = \frac{(13) - [(21) + (5)]}{(2) + (6)} = \frac{2790 - [160 + 180]}{10,500 + 670} = 0.22$$

Mechanical efficiency:

$$\eta_{me} = \frac{(14)}{(13)} = \frac{2,450}{2,790} = 0.88$$

Load

Load efficiency:

$$\eta_{\ell} = \frac{(10)}{(14)} = \frac{2,205}{2,450} = 0.90$$

Furnace and engine

Indicated gross thermal efficiency:

$$\eta_{igt} = \frac{(13)}{(1) + (6)} = \frac{2,790}{16,500 + 670} = 0.16$$

Indicated gross engine efficiency:

$$\eta_{ige} = \frac{\eta_{igt}}{\eta_{ca}} = \frac{0.16}{0.74} = 0.22$$

Brake gross thermal efficiency:

$$\eta_{bgt} = \frac{(14)}{(1) + (6)} = \frac{2,450}{16,500 + 670} = 0.14$$

Stirling engine and load

System thermal efficiency:

$$\eta_{st} = \frac{(10)}{(2) + (6)} = \frac{2,205}{10,500 + 670} = 0.20$$

Furnace, engine, and load

Gross thermal efficiency:

$$\eta_{gt} = \frac{(10)}{(1) + (6)} = \frac{2,205}{16,500 + 670} = 0.13$$

Net thermal efficiency:

$$\eta_{nt} = \frac{(12)}{(1) + (6)} = \frac{2,038}{16,500 + 670} = 0.12$$

Appendix B

FREE-PISTON STIRLING ENGINE

Presented below is a list of test parameters from an actual free-piston Stirling engine, with examples of the efficiency terms as defined in this report. This engine has the displacer sprung to the power piston and the power piston sprung to the housing.

Following the tabulation of data in Table B.1, which was obtained from an actual test run, the efficiency terms as defined in Sect. 4 are calculated.

Sample calculations of efficiency terms using data from Table B.1:

Furnace

Furnace efficiency:

$$\eta_{hs} = \frac{(2)}{(1)} = \frac{10,554}{19,225} = 0.55$$

Engine

Carnot efficiency:

$$\eta_{ca} = 1 - \frac{(3)}{(4)} = 1 - \frac{297.5}{1,088} = 0.73$$

Indicated thermal efficiency:

$$\eta_{it} = \frac{(13)}{(2)} = \frac{2,530}{10,554} = 0.24$$

Indicated engine efficiency:

$$\eta_{ie} = \frac{\eta_{it}}{\eta_{ca}} = \frac{0.24}{0.73} = 0.33$$

Brake thermal efficiency:

$$\eta_{bt} = \frac{(14)}{(2)} \quad \frac{2,000}{10,554} = 0.19$$

Table B.1. Data obtained from the operation of an actual free-piston Stirling engine and used in the sample calculations

Term No.	Term	Value	Comments
(1)	Total power input to furnace, fuel rate at HHV	19,225 W	Measured directly
(2)	Furnace input to engine, Q_{HEAD}	10,554 W	Term (1) minus loss from combustor
(3)	Cooling-water inlet temperature	297.5 K	Measured
(4)	Maximum metal temperature in head	1,088 K	Fin temperature
(5)	Power loss due to hysteresis in the frequency adjustment gas spring	220 W	Measured as $\int Pdv$
(10)	Load power	1,670 W	Measured as $\int Fdx$ in the two pumping chambers of the inertia piston compressor
(12)	Net power output	1,670 W	
(13)	Indicated power: displacer gas spring (865 W) plus compression space (1,665 W)	2,530 W	Measured as $\int Fdx$ on power piston-displacer gas spring and compression space
(14)	Brake power	2,000 W	Measured as $\int Fdx$ in four gas volumes of compressor plus estimated 50-W friction loss from the compressor inertia piston: (14) = (10) + (20) = 1,950 + 50 W
(15)	Heat transfer loss from furnace	3,405 W	Calculated
(16)	Exhaust gas loss from furnace	5,265 W	Measured
(17)	Heat transfer loss from engine	225 W	Measured with heat flux transducer
(18)	Reject heat from cooler	8,552 W	Measured
(19)	Heat transfer between engine and load	300 W	Calculation based on thermocouple mesurements
(20)	Power loss from load	330 W	Measured as $\int Fdx$ in compressor gas springs (280 W) plus estimated (50 W) friction of the compressor piston
(21)	Loss from power piston	310 W	Indicated power minus brake power and gas spring loss: (21) = (13) − [(14) + (5)] (21) = 2,530 W − (2,000 + 220 W)

Mechanical efficiency:

$$\eta_{me} = \frac{(14)}{(13)} = \frac{2,000}{2,530} = 0.79$$

Load

Load efficiency:

$$\eta_{\ell} = \frac{(10)}{(14)} = \frac{1,670}{2,000} = 0.84$$

Furnace and engine

Indicated gross thermal efficiency:

$$\eta_{igt} = \frac{(13)}{(1)} \quad \frac{2,530}{19,225} = 0.13$$

Indicated gross engine efficiency:

$$\eta_{ige} = \frac{\eta_{igt}}{\eta_{ca}} = \frac{0.13}{0.73} = 0.18$$

Brake gross thermal efficiency:

$$\eta_{bgt} = \frac{(14)}{(1)} \quad \frac{2,000}{19,225} = 0.10$$

Stirling engine and load

System thermal efficiency:

$$\eta_{st} = \frac{(10)}{(2)} \quad \frac{1,670}{10,554} = 0.16$$

Furnace, engine, and load

Gross thermal efficiency:

$$\eta_{gt} = \frac{(10)}{(1)} \quad \frac{1,670}{19,225} = 0.09$$

Appendix C

KINEMATIC STIRLING ENGINE

Presented below is a list of test parameters from an actual kinematic Stirling engine together with examples of the efficiency terms as defined in this report. This engine has a rhombic drive with a buffer gas spring between the power piston and the crank case.

Following the tabulation of data in Table C.1, which was obtained from an actual test run, the efficiency terms, as defined in Sect. 4, are calculated.

Sample calculations of efficiency terms using data from Table C.1:

<u>Furnace</u>

Furnace efficiency:

$$\eta_{hs} = \frac{(2)}{(1)} = \frac{13,812}{22,440} = 0.62$$

<u>Engine</u>

Carnot efficiency:

$$\eta_{ca} = 1 - \frac{(3)}{(4)} = 1 - \frac{285}{1,105} = 0.74$$

Indicated thermal efficiency:

$$\eta_{it} = \frac{(13)}{(2)} \quad \frac{3,799}{13,812} = 0.28$$

Indicated engine efficiency:

$$\eta_{ie} = \frac{\eta_{it}}{\eta_{ca}} = \frac{0.275}{0.742} = 0.37$$

Brake thermal efficiency:

$$\eta_{bt} = \frac{(14)}{(2)} = \frac{2,649}{13,812} = 0.19$$

Table C.1. Data obtained from the operation of an actual kinematic Stirling engine and used in the sample calculations

Term No.	Term	Value	Comments
(1)	Total power input to furnace, fuel rate at HHV	22,440 W	An LHV of 43.2 x 10^6 J/kg had been used in the data report from which this number was obtained. For the purpose of these sample calculations, an HHV of 46.5 x 10^6 J/kg was assumed.
(2)	Furnace input to engine, Q_{HEAD}	13,812 W	
(3)	Cooling water inlet temperature	285.5 K	
(4)	Maximum metal temperature	1,105 K	Heater tube temperature
(5)	Power loss due to hysteresis in the buffer space gas spring	1,014 W	Measured in cooling water to this area
(10)	Alternator output	2,151 W	Alternator output measured; alternator efficiency given as 0.812
(13)	Indicated power	3,799 W	Obtained by adding mechanical losses to measured brake power: (13) = (21) + (5) + (14); (13) = 138 + 1,014 + 2,649
(14)	Brake power	2,649 W	Measured alternator power divided by alternator efficiency: $(14) = \dfrac{(10)}{\text{alternator efficiency}} = \dfrac{2{,}151}{0.812} = 2{,}649\ \text{W}$
(18)	Reject heat from cooler	8,280 W	Measured value
(20)	Load inefficiency loss	498 W	Loss equals brake power minus alternator output: (20) = (14) − (10)
(21)	Mechanical loss from linkage between power piston and alternator	138 W	Measured value in the oil cooler

Mechanical efficiency:

$$\eta_{me} = \frac{(14)}{(13)} = \frac{2,649}{3,799} = 0.70$$

Load

Load efficiency:

$$\eta_{\ell} = \frac{(10)}{(14)} = \frac{2,151}{2,649} = 0.81$$

Furnace and engine

Indicated gross thermal efficiency:

$$\eta_{igt} = \frac{(13)}{(1)} = \frac{3,799}{22,440} = 0.17$$

Indicated gross engine efficiency:

$$\eta_{ige} = \frac{\eta_{igt}}{\eta_{ca}} = \frac{0.169}{0.742} = 0.23$$

Brake gross thermal efficiency:

$$\eta_{bgt} = \frac{(14)}{(1)} = \frac{2,649}{22,233} = 0.12$$

Stirling engine and load

System thermal efficiency:

$$\eta_{st} = \frac{(10)}{(2)} = \frac{2,151}{13,812} = 0.16$$

Furnace, engine, and load

Gross thermal efficiency:

$$\eta_{gt} = \frac{(10)}{(1)} = \frac{2,151}{22,440} = 0.10$$

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