"Mircea cel Batran" Naval Academy Scientific Bulletin, Volume XVII – 2014 – Issue 2
Published by "Mircea cel Batran" Naval Academy Press, Constanta, Romania // The journal is indexed in:
PROQUEST SciTech Journals, PROQUEST Engineering Journals, PROQUEST Illustrata: Technology, PROQUEST Technology Journals, PROQUEST Military Collection PROQUEST Advanced Technologies & Aerospace

DETERMINATION OF THE COEFFICIENT OF REGENERATIVE LOSSES IN STIRLING ENGINES

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Abstract: *In this paper, we intend : (1) to present a method for the calculus of the coefficient of regenerative losses in Sterling engines and (2) to use this coefficient for the determination of the efficiency and the power output of Sterling engines.*
Key words: *Sterling engine, regenerative loss, correction coefficient.*

1. Introduction

The coefficient of regenerative losses. X, is the term that includes all the losses due to incomplete heat transfer in the regenerator of a Stirling machine. This parameter clearly depends on a large number of variables. The relationship expressing the regenerative losses as a function of all. parameters has been evaluated using first law and heat transfer principles applied to both the regenerator and the gas. The analysis resulted in differential equations that were then integrated. This integration is based on (1) a lump sum analysis, which tends to predict higher values of the regenerative losses, X_1; or (2) on a linear distribution of the temperature in the regenerator matrix and gas, which tends to predict lower value of the regenerate losses X_2. The results of computations of regenerator heat losses, efficiency and power output based on this analysis are compared to the performance, data from the twelve operating Stirling engines. A high degree of correlation is found over a wide range of operating conditions for all the engines.

The P-v/P-X diagram has been presented previously and has been shown to be an effective tool for analyzing the Stirling Cycle, both theoretical and actual (Petrescu et al. 1999, 2000a, 2000b, 2000c; Florea 1999). In this paper, a T-x diagram has been added to the P-v/P-X diagram in order to more clearly present and explain the processes that take place in the regenerator.

An equation is presented for calculating the regenerative losses, *X,* in Stirling engines based on using the P-v/P-X/T-X diagram for insight and using the First Law of Thermodynamics as a basis for calculations. This equation for *X* has been found to accurately predict the coefficient of regenerative losses for twelve engines under sixteen conditions of operation (Allen 1987, Fujii 1990, Fared 1988, Geng 1987, Stine and Diver 1994).

2. Using the P-v/P-X/T-X diagram as an aid in understanding the Stirling Engine Cycle

The PV diagram in Fig. 1 illustrates how the isothermal compression process 1-2 and the isothermal expansion process 3-4 occur in the Stirling Engine Cycle. The P-X and T-X diagrams in Fig. 1 illustrate the operation of the regenerator during the isometric processes 2-3 and 4-1. The T-X diagram serves to clarify the operation of the regenerator.

Referring now to the P-v diagram in Fig. 1, the isothermal compression process 1-2 takes place at temperature (T_L) with the regenerator stationary at R_2 while the working piston, P moves from P_t to P_2. Heat, Q_L is rejected to the cooler during this process.

The isometric process 2-3 occurs next. During this process, the working piston remains stationary at (P_2) while the regenerator moves from R_2 to R_1 in the displacer cylinder. During this process, the pressure variation, assuming no losses, is shown on P-x coordinates as 2'-3', while the actual pressure is shown by the process line 2'-$3'_R$ - The gas is heated from 2 to only 3_R, not 3, due to incomplete regeneration in the regenerator. This incomplete regeneration or heat loss is accounted for through use of the regenerator heat loss coefficient X, defined by Feidt (1987) as:

$$X=\frac{Q_{R,id}-Q_{R,lost}}{Q_{R,id}}=\frac{Q_{23}-Q_{3_R3}}{Q_{23}}=1-\frac{mc_v\left(T_3-T_{3_R}\right)}{mc_v\left(T_3-T_2\right)} \quad (1)$$

$$X=1-\frac{T_3-T_{3_R}}{T_3-T_2}=1-\frac{T_4-T_{1_R}}{T_4-T_1} \quad (2)$$

The **T-X** diagram in Fig. 1 includes curves showing tire ideal (complete regeneration) and the real (incomplete regeneration) temperature distributions in the gas and the real temperature distribution in the regenerator with the regenerator at R_1 and also with the regenerator at R_2. On the **T-X** diagram:

$T_{R,ideal,g}$ is the ideal temperature distribution of the gas contained in the regenerator porous matrix, $T_{R,real,g}$ is the real temperature distribution of the gas contained in the regenerator porous matrix, and $T_{R,real}$ is the real temperature distribution in the regenerator matrix.

With this distribution in mind, the **T-X** diagram aids in clarifying the processes taking place in the regenerator during the isometric process 4-1 (ideal) and 4-I_R (real) as shown on the **P-v** diagram. This process takes place with the working piston stationary at P, while the regenerator moves from R_1 to R_2. When the regenerator is at R_1 the temperature distribution in the regenerator is shown on the **T-X** diagram. During the process 4-1, the curve CDA traces the ideal temperature variation of the gas, the line CBA traces the real temperature in the gas and the line CR traces die real temperature variation of the matrix material in the regenerator.

After the regenerator moves from R_1 to R_2 the ideal temperature distribution in the gas is shown by curve AD'C, the real temperature in the gas is shown by curve AB'C and the real temperature in the regenerator matrix is shown by curve AR'.

The isothermal expansion process 3-4 take place at temperature (T_H) with the regenerator stationary at R_1 while the working piston moves from P_2 to P_1.

The T-x diagram shows how the temperature of the gas in the regenerator oscillates between the temperatures CBA and AB'C during each complete cycle and how the temperature of the matrix oscillates between temperatures CR and AR'. Using the temperatures illustrated on this diagram and based on a lump sum analysis of the thermal interaction between the gas and the regenerator matrix, equations for X will be formulated. These equations for X, in one case, include worst-case assumptions and hence tend to overestimate losses. In the other case, the equations for X include best-case assumptions arid tend to underestimate these losses. These two equations eventually will be combined into a single equation for X by bringing the losses calculated analytically into consistency with experimental data (Allen 1987, Fujii, 1990; Farell, 1988; Geng, 1987, Stine and Diver, 1994).

3. Regenerative Loss, X, Based on High Loss Assumptions

In a lump sum analysis of the heat transfer processes between the gas and the metal matrix in the regenerator, the First Law may be written as follows:
Matrix Internal Energy Variation = Gas Internal Energy Variation = Heat transfer between the Gas and Matrix.
Upon substitution for the general terms in the above relationship:

$$m_R c_R \left(T_R - T_{R,i}\right) = m_g c_{v,g} \left(T_g - T_{g,i}\right) = \int h A_R \left(T_g - T_R\right) dt \quad (3)$$

Solving for T_R and substituting for Min Eq. (3), gives:

$$T_R = T_{R,i} + M\left(T_{g,i} - T_g\right) \quad (4)$$

with:

$$M = \frac{m_g c_{v,g}}{m_R c_R} \quad (5)$$

where m_g is the mass of the gas passing through the regenerator, m_R is the mass of the porous matrix in the regenerator; and A_R is the heat transfer surface area of the wires in the regenerator:

$$m_R = \frac{\pi \cdot 2D_R \cdot 2dL\rho_R}{16\left(b + d\right)} \quad (6)$$

$$A_R = \frac{\pi \cdot 2D_R \cdot 2L}{4\left(b + d\right)} \quad (7)$$

Upon substitution of the above into Eq. (3) and Eq. (4) and after rearrangement

$$\frac{-dT_g}{T_g\left(1 + M\right) - T_{R,i} - MT_{g,i}} = \frac{hA_R}{m_g c_{v,g}} dt \quad (8)$$

This differential equation is then integrated and solved for the temperature at 1_R:

$$T_{1_R} = \frac{\left(T_H - T_L\right)\exp\left(\frac{-B}{2}\right) + \frac{T_H + T_L}{2} + MT_H}{1 + M} \quad (9)$$

where

$$B = \left(1 + M\right)\frac{hA_R}{m_g c_{v,g}} \frac{S}{w} \quad (10)$$

The temperature T_{1_R} is then substituted in Eq. (2), the expression for X, This expression for X, based on a lump sum analysis of the regenerator processes, predicts relatively high losses and is designated X_1. It may be referred to as a "pessimistic" expression for X.

$$X_1 = \frac{1 + 2M + e^{-B}}{2\left(1 + M\right)} \quad (11)$$

The values of X_1 were found to be less than 0.5 in a first approximation.

4. Regenerative loss, X, Based on Low Loss Assumptions

In an analysis predicting low losses, the gas is hypothesized to be permanently in contact with the heater at point A and also in permanent contact with the cooler at point B on the **T-X** diagram of Fig. 1. Under these conditions and with the regenerator at R_1, the real temperature of the gas in the regenerator is represented by the line ABC. After the regenerator moves to R_2, the temperature profile in the regenerator is represented by the line CBA. During operation of the engine, the temperature of the gas in the regenerator oscillates between ABC and CBA with each cycle. By comparison, the ideal temperature of the gas would oscillate between lines ADC and CD A if there were no losses.

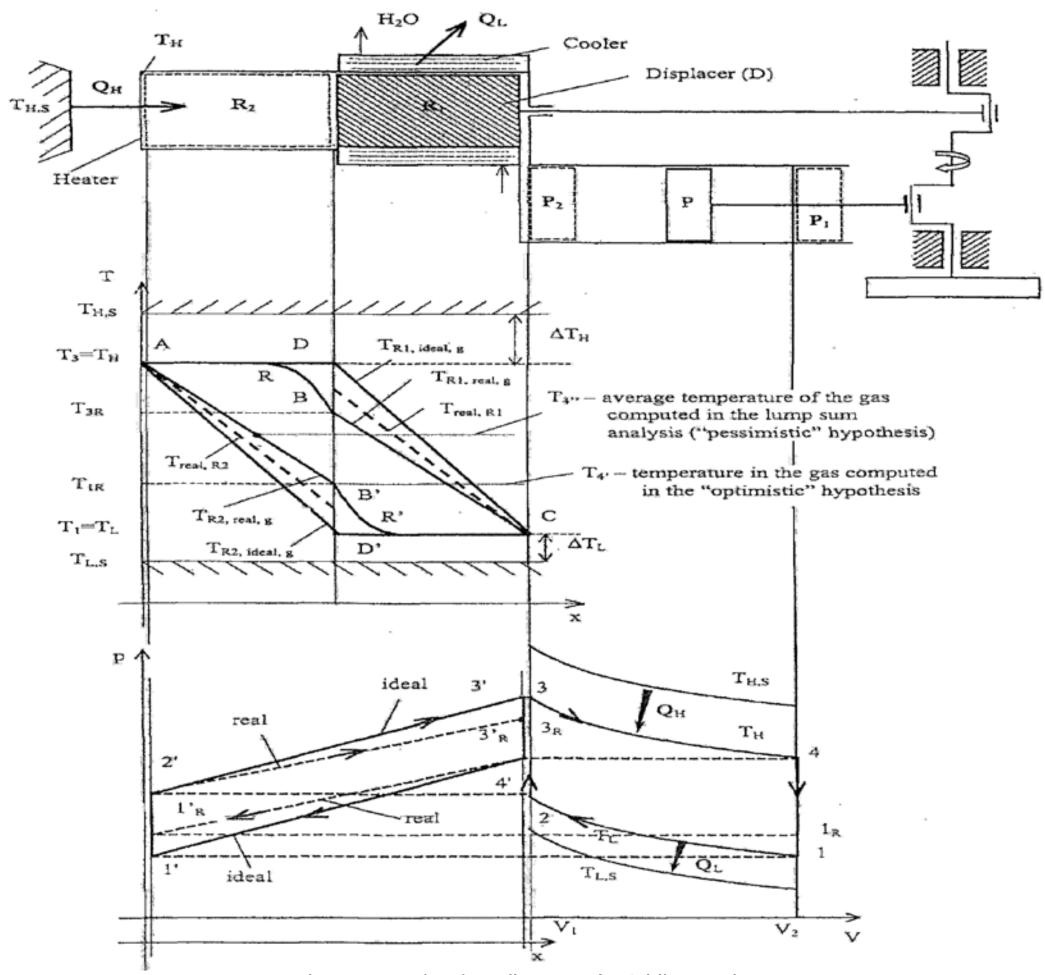

Figure 1. P-V/P-x/T-x diagram of a Stirling engine

In formulating the low loss equation for X, the temperature T_4" shown on the T-x diagram of Fig.1 is considered equal to the temperature T_{1_R} which was obtained in the "high loss" or "pessimistic" analysis given in Eq. (9). Based on the above hypothesis the temperature T_4 is as follows:

$$T_{4'} = T_H - 2(T_H - T_{4''}) = \frac{(T_H - T_L)\exp(-B) + T_L + MT_H}{1+M} \quad (12)$$

With die temperature $T_{4'}$ assumed equal with T_{1_R}, substitution into Eq. (2) for *X* and letting X_2 equal X for condition of low regenerator losses, we get

$$X_2 = \frac{M + e^{-B}}{1+M} \quad (13)$$

Eq. (13) represents the low losses or "optimistic" equation for X.

5. The Convection Coefficient in the Regenerator

The Incropera and De Witt correlation formula (Incropera and De Wirt, 1996) for analysis of the heat transfer processes between the gas and porous matrix in the regenerator results in the following equations:

$$St \cdot \Pr^{2/3} = \frac{0.79}{p \cdot R_e^{0.576}} \quad (14)$$

where:

$$R_e = \frac{wD}{v} \quad (15)$$

$$St = \frac{h}{\rho w c_p} \quad (16)$$

$$P_r = \frac{v}{a} = \frac{\rho c_P v}{k} \quad (17)$$

The porosity of the regenerator matrix, p, is given by:

p = volume of the gas in pores/total volume of the regenerator (18)

A regenerator made up from N pressed screens having d, diameter of the wire and b, distance between wires has a porosity:

$$p = 1 - \frac{\pi d}{4(d+b)} \quad (19)$$

The average density of the gas is

$$\rho_m = \frac{P_m}{RT_m} \quad (20)$$

where

$$T_m = \frac{T_1(\tau+1)}{2},\ P_m = \frac{(\varepsilon+1)(\tau+1)P_1}{4},\ \tau = \frac{T_{H,g}}{T_{L,g}} \quad (21)$$

Replacing St from Eq. (16), Re from Eq. (15), the average gas density from Eq. (20) and the porosity from Eq. (19) in Eq. (14) results in an expression for h, the convection heat transfer coefficient in the porous medium in the regenerator:

$$h = \frac{0.395\left(4P_m / RT_L\right)w_g^{0.424}c_p\left(T_m\right)\nu\left(T_m\right)^{0.576}}{\left(1+\tau\right)\left[1-\frac{\pi}{4\left[\left(b/d\right)+1\right]}\right]D_R^{0.576}\cdot P_r^{2/3}} \tag{22}$$

where c_P, ν and Pr are computed at the average temperature T_m.

Eq. (22) shows that the convection coefficient is influenced by the average pressure of the gas in the engine P_m, low temperature in the gas T_L, ratio of temperatures τ, speed of the gas w_g, gas properties, c_p, ν and Pr, and also by constructive parameters (b, d, D_R). This in turn affects the engine efficiency and the power output through X.

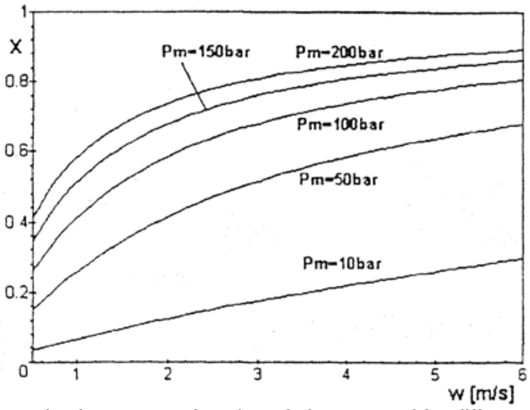

Figure 2. The coefficient of regenerative losses as a function of piston speed for different average working gas pressures (D_C=80mm, D_R=70mm, b/d=1.5, d=0.05mm, S=30mm, τ =2,

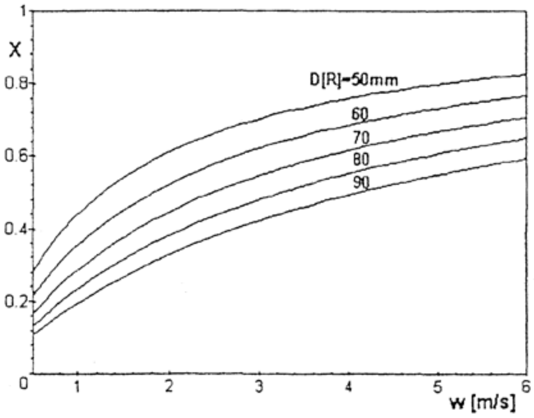

Figure 3. The coefficient of regenerative losses as a function of piston speed for different values of the regenerator diameter (D_C=80mm, P_m=50bar, b/d=1.5, d=0.05mm, S=30mm, τ =2, N=700).

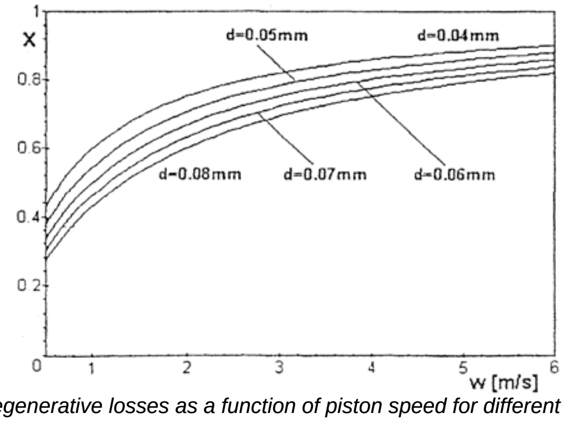

Figure 4. The coefficient of regenerative losses as a function of piston speed for different values of the regenerator wire diameter (Dc=80mm, D_R=70mm, P_m=50bar, b/d=L5, S=30mm, τ =2, N=700).

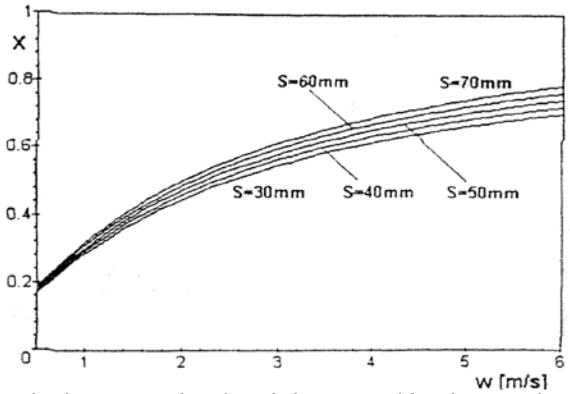

Figure 5. The coefficient of regenerative losses as a function of piston speed for piston strokes (D_C=80mm, D_R=70mm, b/d=1.5, d=0.05mm, P_m=50mm, τ =2, N=700).

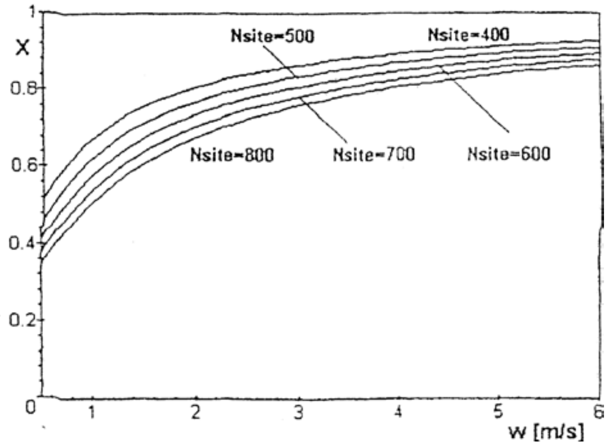

Figure 6. The coefficient of regenerative losses as a function of piston speed for various number of matrices wires (D_C =80mm, D_R=70mm, b/d=1.5, P_m=150bar, S=50mm, τ =2, N=700).

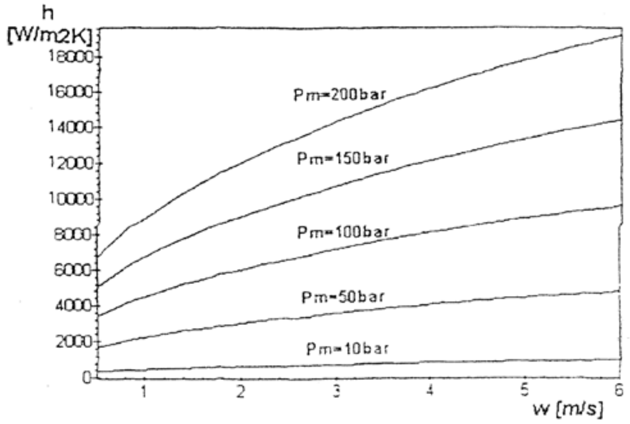

Figure 7. The convective heat transfer coefficient in the regenerator as a function of piston speed for several values of the medium pressure of the working gas (D_R=70mm, b/d=1.5, τ =2).

6. The Validation of the Final Formula for X, based on comparison with the experimental data

The effect on X_1 (Eq. 11) and X_2 (Eq. 13) of the operating variables such as piston speed and all the other parameters and properties of the gas, cycle and regenerator was determined. The computed values of X_1 and X_2 were found to accurately predict the values of X determined from experimental data available in the literature (Allen and Tomazic 1987, Farell 1988, Fujii 1990, Geng 1987, Stine and Diver 1994) using the following equation: $X = yX_1 + (1-y)X_2$ (23)

which enters in the total efficiency of the Stirling engine: where the adjusting parameter y is equal to 0.72.

The losses due to incomplete regeneration X as indicated in Eq. (23) cause a decrease in the efficiency of the Stirling engine through The Second Law Efficiency factor (Petrescu et al. 1999, 2000a, 2000b, 2000c, Florea 1999):

$$\eta_{II,ir,X} = \left[1+\frac{[X_1 y + X_2(1-y)]\left(1-\sqrt{T_L / T_{H,S}}\right)}{R / c_v(T)\ln\varepsilon}\right]^{-1} \quad (24)$$

$$\eta_{SE} = \eta_{CC} \cdot \eta_{II,ir} = \left(1 - \frac{T_L}{T_{H,S}}\right) \cdot \left[1 + \sqrt{\frac{T_L}{T_{H,S}}}\right]^{-1} \cdot \left[1 + \frac{X\left(1 - \sqrt{T_L / T_{H,S}}\right)}{R / c_v(T) \ln \varepsilon}\right]^{-1} \cdot \eta_{II,ir,\sum \Delta P_i} \quad (25)$$

where:

$$\eta_{II,ir,\sum \Delta P_i} = 1 - \left[\left(\frac{w}{w_{S,L}}\right)\gamma \cdot \left(1 + \sqrt{\tau}\right)\ln \varepsilon + 5\left(\frac{w}{w_{S,L}}\right)^2 N + \frac{3(0.94 + 0.045w)10^5}{4}\right] / \left(\tau \eta' \ln \varepsilon\right) \quad (26)$$

Fig. 2 shows the variation of the regenerative loss coefficient, X, versus the piston speed for several values of the average pressure of the working gas. Figs. 3-6 present the variation of the coefficient of regenerative losses as a function of the piston speed for several values of the analysis parameters (D_R-regenerator diameter, d-wire diameter, S-stroke, N-number of gauzes).

Fig. 7 illustrates the convection heat transfer coefficient dependence on piston speed, for several values of the average pressure of the working gas.

The final analytic expression for the power output of actual Stirling engines is:

$$Power_{SE} = \eta_{SE} \cdot zmRT_{H,g}\left(w / 2S\right)\ln \varepsilon \quad (27)$$

This expression accurately predicts the power output of twelve Stirling engines under 16 operating conditions (Allen 1987, Fujii 1990, Farell 1988, Geng 1987, Stine and Diver 1994) when the adjusting parameter z equals 0.8.

7. Discussion

The operating processes of the Stirling engines are presented in a comprehensive yet intuitive manner using a **P-v** and **P-X**coordinate system (Petrescu et al. 1999, 2000a, 2000b, 2000c, - Florea 1999) to which the **T-X** diagram has been added. The addition of the **T-X** diagram to Fig. 1 aids in understanding and explaining the processes in the regenerator. An analysis and a technique for calculating of the regenerator losses that occur in Stirling engines and a method of predicting the effect of regenerative losses on engine performance is presented. This analysis provides insight into the processes involved since it utilizes the First Law of Thermodynamics for Processes with Finite Speed (Stoicescu and Petrescu 1964a, 1964b, 1965a, 1965b, 1965c, Petrescu 1969a, 1971, 1974, 1991, Petrescu et al. 1992, Petrescu and Stanescu 1993, Petrescu and Harman 1994, Petrescu et al. 1996b) in conjunction with the Direct Method. (Stoicescu and Petrescu 1964a, 1964b, 1965c, Petrescu 1969, 1991, Stanescu 1992, Petrescu and Stanescu 1993, Petrescu et al. 1993a, 1993b, Petrescu and Harman 1994, Petrescu et al. 1994, 1996a, 1996b, Costea 1997, Costea et al. 1999, Florea 1999, Petrescu et al. 1999, 2000a, 2000b, 2000c, 2000d). The method simulates die operation of actual Stirling engines while intuitively suggesting the mechanisms that generate the irreversibilities. A method for calculating these losses based on actual regenerator components is presented in Eq. (23) for the regenerator loss coefficient *X.* This relationship was validated by comparison with experimental data on known components and engine configurations (Allen 1987, Fujii 1990, Farell 1988, Geng 1987, Stine and Diver 1994). The results of computations based on this analysis are compared to performance data taken from a number of operating Stirling engines in Figs. (8-9) and Table 1.

Table 1 Comparison between analytical results and actual engine performance data (Fujii, 1990; Allen and Tomazic, 1987; Geng, 1987; Stine and Diver, 1994; Farell et al., 1988; Organ, 1992)

Stirling engine	Actual Power [kW]	Calculated Power [kW]	Actual Efficiency [-]	Calculated Efficiency [-]
NS-03M, regime 1 (max. efficiency)	2.03	2.182	0.359	0.339
NS-03M, regime 2 (max. power)	3.81	4.196	0.310	0.329
NS-30A, regime 1 (max. efficiency)	23.20	29.450	0.375	0.357
NS-30A, regime 2 (max. power)	30.40	33.820	0.330	CB-36
NS-30S, regime 1 (max. efficiency)	30.90	33.780	0.372	0.366
NS-30S, regime 2 (max. power)	45.60	45.620	0.352	0.352
STM4-120	25	26.360	0.400	0.401
Y-160	9	8.825	0.300	0.30S
4-95 MKII	25	28.400	0.294	0.289
4-275	50	48.610	0.420	0.412
MP 1002 CA	200W	193.900W	0.156	0.153
Free Piston Stirling engine	9	9.165	0.330	0.331
RE-1000	0.939	1.005	0.258	0.228

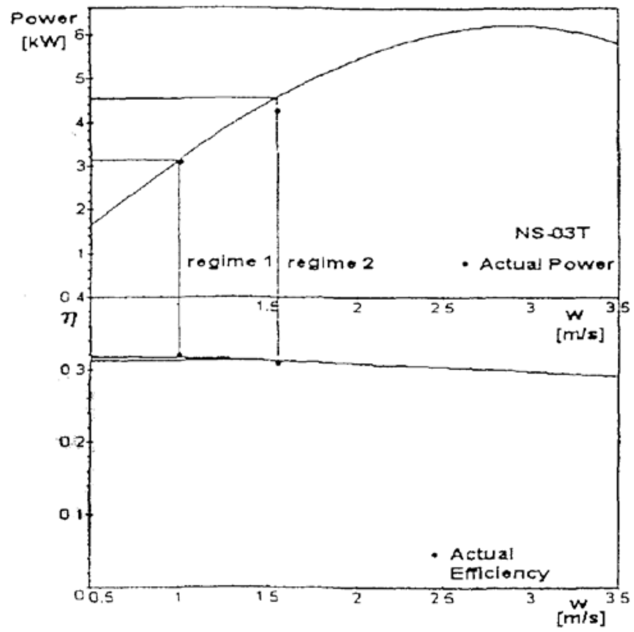

Figure 8. Comparison of the analysis results with actual performance data for the NS-03T Stirling engine.

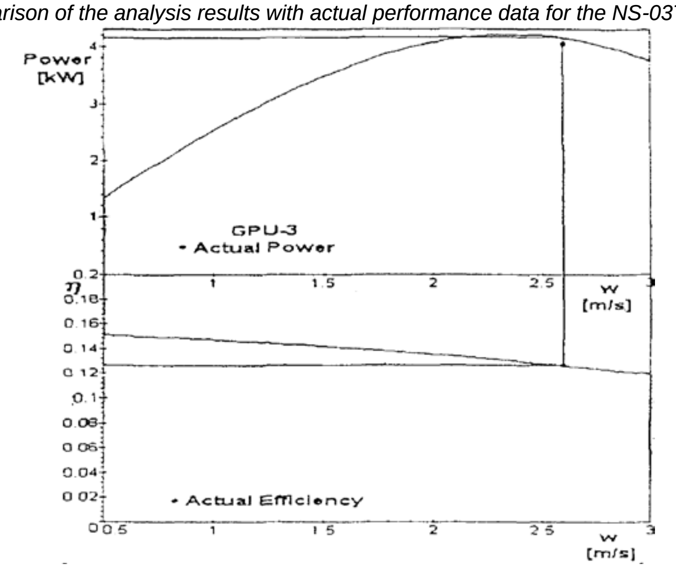

Figure 9. Comparison of the analysis results with actual performance data for the GPU-3 Stirling engine.

8. Conclusion

The high degree of correlation between the analytic and the operational data shown in Figures (8-9) and Table 1 indicates that the analysis presented using the concept of a coefficient of regenerator losses *X* accurately predicts the performance in terms of power and efficiency for Stirling engines over the range of conditions. This capability has value in the design of new Stirling engines and in predicting the power and efficiency of a particular Stirling engine.

Nomenclature

A area, m^2
b distance between the regenerator matrix wire, m
CC Carnot Cycle
c_P, c_v specific heats, J kg^{-1} K^{-1}
D diameter, m
d wire diameter, m
h heat transfer coefficient, W m^{-2} K^{-1}
k gas thermal conductivity, W m^{-1} K^{-1}
m mass, kg
N number of gauzes
P pressure, Pa
p porosity
Pr Prandtl number
Q heat, J
R gas constant, J kg^{-1} K^{-1}
Re Reynolds number
S stroke, m

St Stanton number
T temperature, K

T time, s
U internal energy, J
V volume, m^3
W work, J
w piston speed, m s^{-1}
w_R gas speed in the regenerator, m s^{-1}
w_{SL} speed of the sound at temperature T_L,(m s^{-1})
X regenerative losses coefficient
y adjusting parameter
z adjusting parameter

Greek symbols
ε compression ratio (VI/V2)
γ ratio of the specific heats
η first law efficiency
η_{II} second law efficiency
ν viscosity of the gas, m^2 s^{-1}
τ ratio of the extreme temperatures

Subscripts
g gas
H,g gas, at the hot-end of the engine
H,S source, at the hot-end of the engine
i instantaneous
L sink
m average
R regenerator
S,L sink, at the cold-end of the engine
SE Stirling engine

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