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THE CONVECTION COEFFICIENT IN THE REGENERATOR OF STIRLING ENGINES

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Abstract: The performance of Stirling engines can be predicted with accuracy by using a concept of a regenerator losses coefficient, concept used often in the designing precess of new Stirling engines and in predicting the power and efficiency of a particular Stirling engine.
Keywords: *Stirling, cycle, losses, efficiency, regenerator, heat, transfer.*

1. INTRODUCTION

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

$$St \cdot \Pr^{2/3} = \frac{0.79}{p \cdot R_e^{0.576}} \quad (1)$$

where:

$$R_e = \frac{wD}{\nu} \quad (2)$$

$$St = \frac{h}{\rho w c_p} \quad (3)$$

$$P_r = \frac{\nu}{a} = \frac{\rho c_P \nu}{k} \quad (4)$$

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

p = volume of the gas in pores/total volume of the regenerator

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

$$p = 1 - \frac{\pi d}{4(d+b)} \quad (5)$$

The average density of the gas is:

$$\rho_m = \frac{P_m}{RT_m} \quad (6)$$

where:

$$T_m = \frac{T_1(\tau+1)}{2}, P_m = \frac{(\varepsilon+1)(\tau+1)P_1}{4}, \tau = \frac{T_{H,g}}{T_{L,g}} \quad (7)$$

Replacing St from Eq. (3), Re from Eq. (3), the average gas density from Eq. (7) and the porosity from Eq (6) in Eq. (2) results in an expression for h, the convection heat transfer coefficient in the porous medium in the regenerator:

$$h = \frac{0.395(4P_m / RT_L)w_g^{0.424} c_p(T_m)\nu(T_m)^{0.576}}{(1+\tau)\left[1 - \frac{\pi}{4[(b/d)+1]}\right] D_R^{0.576} \cdot P_r^{2/3}} \quad (8)$$

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

Eq. (8) 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.

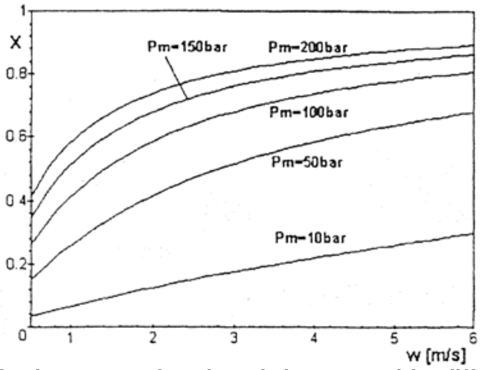

Figure 1: The coefficient of regenerative losses as a function of piston speed for different average working gas pressures (D_C=80mm, D_R=70mm, b/d=1.5, d=0.05mm, S=30mm, τ =2)

2. THE VALIDATION OF THE FINAL FORMULA FOR X, BASED ON COMPARISON WITH THE EXPERIMENTAL DATA

The effect on X_1 and X_2 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: $X = yX_1 + (1-y)X_2$ (*9*)

where the adjusting parameter y is equal to 0.72.

The losses due to incomplete regeneration X as indicated in Eq. (9) 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):

$$\eta_{II,ir,X} = \left[1+\frac{\left[X_1 y + X_2(1-y)\right]\left(1-\sqrt{T_L/T_{H,S}}\right)}{R/c_v(T)\ln\varepsilon}\right]^{-1} \quad (10)$$

which enters in the total efficiency of the Stirling engine:

$$\eta_{SE} = \eta_{CC}\cdot\eta_{II,ir} = \left(1-\frac{T_L}{T_{H,S}}\right)\cdot\left[1+\sqrt{\frac{T_L}{T_{H,S}}}\right]^{-1}\cdot \quad (11)$$

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

where:

$$\eta_{II,ir,\sum\Delta P_i} = 1-\left[\begin{array}{l}\left(\frac{w}{w_{S,L}}\right)\gamma\cdot\left(1+\sqrt{\tau}\right)\ln\varepsilon+5\left(\frac{w}{w_{S,L}}\right)^2 N+\\ +\frac{3(0.94+0.045w)10^5}{4}\end{array}\right]/\left(\tau\eta'\ln\varepsilon\right) \quad (12)$$

3. DISCUSSIONS

The variation of the coefficient of regenerative losses, *X*, with the piston speed for several values of the gas average pressure is shown in Fig. 1.

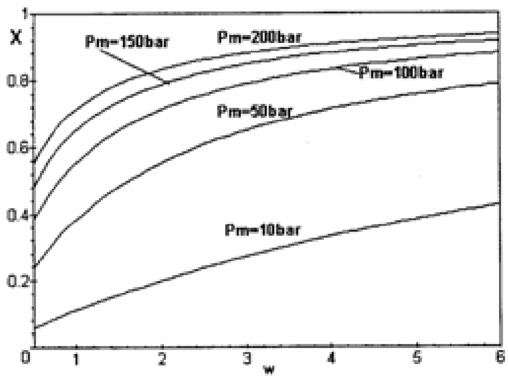

Figure 1: Coefficient of regenerative losses versus the piston speed

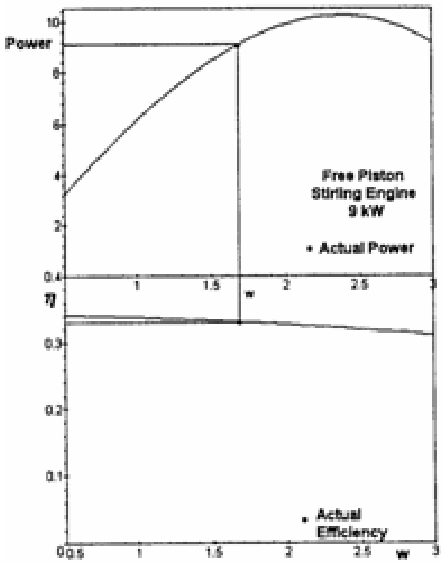

Figure 2: Predicted results versus real data for the Free Piston Stirling engine

The high degree of correlation between the analytic and the operational data shown in these figures indicate that the analysis is capable of accurately predicting Stirling engine performance under a wide range of conditions.

This capability should be of considerable value in Stirling engine design and in predicting the performance of a particular Stirling engine over a range of operating speed.

4. CONCLUSION

The objective of this approach was to closely simulate the operation of actual Stirling engines without losing insight to the mechanisms that generate the irreversibilities. Pressure and work losses generated by finite speed of the actual processes were computed as were the power and efficiency of engines. The first law of thermodynamics for processes with finite speed was used to compute the power losses generated by the pressure losses. The analysis presented was applied to specific operating Stirling cycle engines and results were compared to the measured performance of the engines. The strong correlation between the analytical results and actual engine performance data indicates that the Direct Method of using the First Law for Finite Speed is a valid method of analysis for irreversible cycles.

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