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RESEARCH ARTICLE OPEN ACCESS

Analysis of Coefficient of Performance & Heat Transfer Coefficient on Sterling Cycle Refrigeration system.

*Narendra .N .Wadaskar[1], Dr S.K.Choudhary[2], Dr R.D.Askhedkar[3]
Ph.D. student in Mechanical Engineering, Nagpur University, MaharashtraINDIA[1]
Prof in K.D.K College of Engineering, Professor in Mechanical Engineering Nagpur, Maharashtra, INDIA[2,3]
Corresponding Author: Narendra .N .Wadaskar

ABSTRACT
Concerns about the environmental impact of refrigerants used in vapour-compression refrigerators, have prompted the Stirling-Cycle Research to investigate the feasibility of low-cost Stirling-cycle machines that use air as the refrigerant. Such machines theoretically have the highest efficiency possible for any practical thermodynamic system, and thus provide a tempting alternative to traditional vapour- compression technology. This paper outlines the working principles of Stirling-cycle on refrigeration system. The focus of research is kept on analysis of effect of regenerator length, regenerator Diameter, wire mesh size, wire mesh arrangement, and wire mesh material on Coefficient of Performance and Heat Transfer Rate.

Keywords: Stirling engines; Performance; optimal value; C.O.P.; Regenerator; Heat Transfer Coefficient.

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I.INTRODUCTION

Air-Conditioning and refrigeration are the parts of day-today life in economically developing countries. Presently, almost all the refrigeration systems are working on vapour compression refrigeration system (VCRS).In VCRS, heat is absorbed and rejected by changing the phase of refrigerants i.e. liquid to vapour and vapour to liquid**.**

Drawbacks of present vapour compression refrigeration system

The heat transfer through refrigerants in VCRS is in the form of latent heat; so the refrigerants used in this system should have the property to change their phase at the desired pressure and temperature conditions. The refrigerant having the above properties is Cloro-Fluoro-Carbon (CFC). The CFC refrigerants have very high ozone depletion potential and also cause global warming

Montreal protocol

Montreal protocol was signed in U.K. in the year 1987 with the aim to protect the ozone layer from further depletion. As per Montréal protocol CFC group of refrigerant, which is the main culprit for ozone layer depletion should be banned by the year 2010. Dr. Devotta[1] discusses the implications of Montreal protocol and the changes required in the present refrigeration system.

Kyoto protocol

Though HCFC refrigerants do not cause ozone layer depletion, they lead to global warming. The temperature of the atmosphere is increasing slowly because the use of HCFC/CFC refrigerants. The objective of the Kyoto protocol, signed in 1997, is to prevent global warming and as per this protocol use of HCFC should be banned by year 2020.

II.WORKING PRINCIPLES OF STIRLING-CYCLE REFRIGERATION SYSTEM

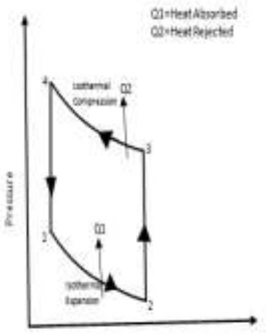


Fig. : IdealP-V Diagram

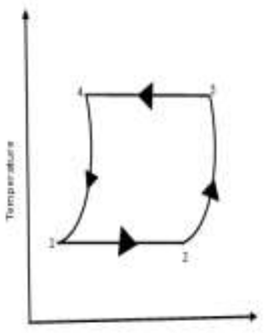


Fig. : IdealT-S Diagram

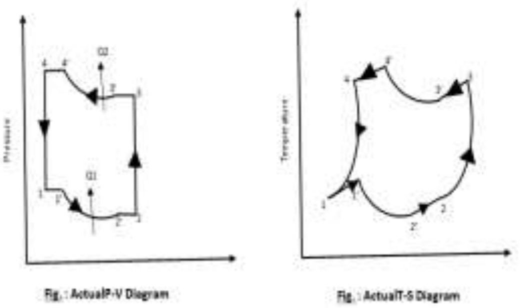


Figure 2. Thermodynamic processes in the ideal Stirling-cycle refrigerator. (A) Pressure- volume diagram (B) Temperature-entropy diagram..

1 **2**→: Isothermal expansion – the low-pressure working gas expands isothermally at cold end temperature, hence absorbing heat from the cold space (via the heat absorbing heat-exchanger) and doing work to the expansion piston.

2 **3**→: Isochoric displacement – both pistons move together to transfer all the working gas isochorically through the regenerator to the hot end of the machine. Heat is delivered to the gas as it passes through the regenerator, thus raising the temperature of the gas to that of the hot space. As the temperature rises, the gas pressure increases significantly.

3 **4**→ : Isothermal compression – the compression piston does work to the gas and compresses it isothermally at hot end temperature, hence rejecting heat to the hot space (via the heat rejecting heat-exchanger). Because the gas is at high pressure, more work is required for compression than was obtained from the gas during expansion (in 1 2). The cycle therefore has a net work input.

4 **1** : Isochoric displacement – both pistons move together to transfer all the working gas isochorically through the regenerator to the cold end of the machine. Heat is absorbed from the gas as it passes through the regenerator, thus lowering the temperature of the gas to that of the cold space. As the temperature reduces, the gas pressure drops significantly, and the system returns to its initial conditions (at 1).

Figure 1

There are five main components in a Stirling-cycle machine, as shown in Figure 1.

(a) *Working gas* – the Stirling Cycle is a closed cycle and the various thermodynamic processes are carried out on a working gas that is trapped within the system.

(b) *Heat-exchangers* – two heat exchangers are used to transfer heat across the system boundary.

A *heat absorbing heat-exchanger* transfers heat from outside the system into the working gas, and a *heat rejecting heat-exchanger* transfers heat from the working gas to outside the system. For example, on a refrigerator the heat absorbing heat-exchanger would transfer heat from the cold space into the working gas, and the heat rejecting heat-exchanger would transfer heat from the working gas to the ambient environment.

(c) *Displacer mechanism* – this moves (or displaces) the working gas between the hot and cold ends of the machine (via the regenerator).

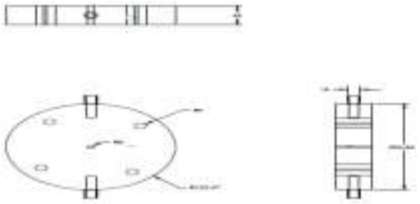
(d) *Regenerator* – this acts both as a thermal barrier between the hot and cold ends of the machine, and also as a “thermal store” for the cycle. Physically a regenerator usually consists of a mesh material (household pot scrubbers have even been used in some engines), and heat is transferred as the working gas is forced through the regenerator mesh. When the working gas is displaced from the hot end of the machine (via the regenerator) to the cold end of the machine, heat is “deposited” in the regenerator, and the temperature of the working gas is lowered. When the reverse displacement occurs, heat is “withdrawn” from the regenerator again, and the temperature of the working gas is raised.

(e) *Expansion/compression mechanism* – this expands and/or compresses the working gas. In an engine this mechanism produces a net work output. In a refrigerator a net work input is required to move the heat from a low to a high temperature regime (in accordance with the Second Law of Thermodynamics)

III.COMPONENTS OF STERLING CYCLE REFRIGERATION SYSTEM

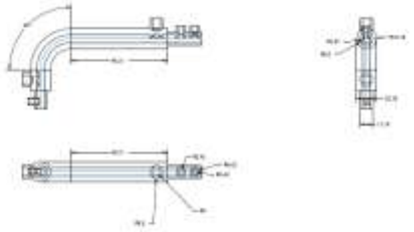
3.1WATER JACKETS

In α configuration Stirling cycle machines the major efforts are for the adequate provisions for removal of heat on the compressor side and supply of cooling load on the expander side to ensure isothermal compression & expansion processes. Water cooling was preferred to air cooling because the heat transfer co-efficient with water are greater than the air, moreover here water also acted as a secondary refrigerant in the expander side of the machine. The dimensional drawing of water jacket is shown in fig. no. 5.2 and its photograph is shown in image no. 5.2.The water jacket is having a provision to pass 12mm outer diameter tube for passage of refrigerant. Four holes are provided to each water jacket to insert the bolts to connect the water jacket to water jacket connector on compressor and expander cylinder. To, fulfill this requirement water jackets of 65 mm diameter and 30 mm height were fabricated .The metal used for the water jackets was mild steel. These water jackets were fixed on the compressor and expander above the 10 mm thick copper plates.



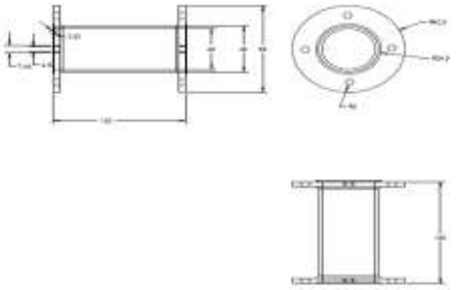
3.2 DOUBLE PIPE HEAT EXCHANGER

In α configuration Stirling cycle machine the whole system is divided into two temperature regions T_C and T_E by the regenerator. So to maintain these two temperatures constant, adequate provision of cooling and heating is required. So for this purpose apart from water cooling jackets two double pipe heat exchanges were also fabricated. Fig. No. 4.3 shows the detailed drawing and image no.4.3 is the photograph of double pipe heat exchangers. The heat exchanger is fabricated by brazing a copper tube of 30 mm inner diameter to 12mm outer diameter tube through which refrigerant passes. Provisions are made to double pipe heat exchangers for connecting entry and exit of water. The material used in double pipes heat exchangers were selected as copper due to its high thermal conductivity.



3.3 REGENERATOR

The regenerator alternately stores and rejects heat in a manner, which theoretically is thermodynamically reversible. The regenerator for α configuration Stirling cycle machines is generally made of packs of wire mesh in a hollow cylinder with flange on both sides. This mesh material should have high thermal conductivity, so copper wire meshes of minimum available five diameters i.e. 0.09, 0.1, 0.2 & 0.4 mm were selected.The material for outer body of regenerator was selected as stainless steel because of its high strength and low thermal conductivity. So nine numbers of regenerators of outer body of sizes as given in plan of experimentation were fabricated. Fig No. 4.4, image no. 4.4 gives the details of regenerator body. The regenerator body is fabricated by welding flanges at both ends of hollow cylinders.



IV.DIMENSIONAL ANALYSIS FOR α CONFIGURATION STIRLING CYCLE REFRIGERATION SYSTEM

For present research work, the Buckingham π-Theorem is used for dimensional analysis. The variables, their types, symbols and dimensions of α – configuration Stirling cycle refrigeration system are given below.

Table No. 3.1 Independent and Dependent variables

S.N.	Description of variable	Types of	Symbol	Dimension
1.	Dead volume	Independent	V_D	L^3
2.	Expansion space volume	Independent	V_E	L^3
3.	Compression space volume	Independent	V_C	L^3
4.	Diameter of Mesh wire	Independent	Dm	L
5.	Compaction ratio	Independent	V_M/ V_R	$M^0L^0T^0$
6.	Regenerator volume	Independent	V_R	L^3
7.	Length of regenerator	Independent	L_R	L
8.	Diameter of regenerator	Independent	D_R	L
9.	Speed of the machine	Independent	N	1/T
10.	Charging Pressure	Independent	P	M/LT^2
11.	Phase angle	Independent	α	$M^0L^0T^0$
12.	Mass flow of water	Independent	m_w	M/T
13.	Compressionspace	Independent	Tc	K
14.	Heat extracted	Dependant	Q_E	ML^2/T^3
15.	Power consumed	Dependant	W	ML^2/T^3
16.	Coefficient of Performance	Dependant	COP	$M^0L^0T^0$
17.	Expansion space temperature	Dependant	T_E	K
18.	HeatTransfer Coefficient	Dependant	HTC	$ML^0K^{-1}T^{-3}$

Dimensional analysis is carried out to establish dimensionless equations in terms of various independent and dependent dimensionless groups of physical quantities affecting the system.

Table 3.2 Planning of experimentation

Sr. No.	**Dimensionless Ratio**	**Test Envelop**	**Test Points**	**Test Sequence**
1.	$\pi_1 = L_R/V_E^{1/3}$	2.130-3.347	2.130,2.434,2.738,3.043, 3.347	Random
2.	$\pi_2 = D_R/V_E^{1/3}$	0.71-1.11	0.71,0.81,0.91,1.01,1.11	Random
3.	$\pi_3 = D_M/V_E^{1/3}$	0.001826-0.010143	0.001826,0.004057,0.006086,0.008114,0.010143	Random
4.	$\pi_4 = V_M/V_R$	0.1232-0.216	0.1232,0.1465,0.1698,0.186,0.216	Random
5.	$\pi_5 = Nm_w/PV_E^{1/3}$	0.195-0.13	0.13,0.142,0.1560,0.1733, 0.195	Random
6.	π_6 to π_8	Constant	Constant	Constant

V.FORMULATION OF POLYNOMIAL MODEL

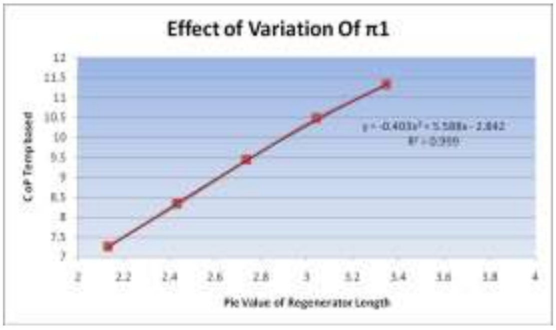
a) COP and HTC on Regenerator

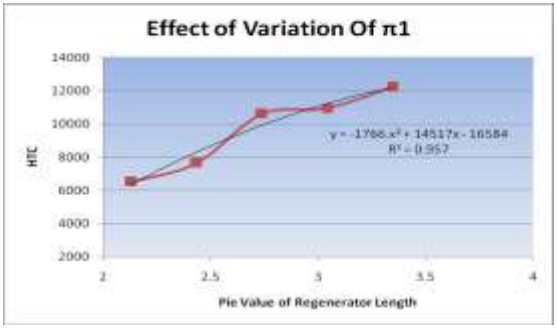
$$COP_T = -31.71 - 0.403\pi_1^2 + 5.588\pi_1 + 0.421\pi_2^2 + 10.82\pi_2 + 1155\pi_3^2 - 148.6\pi_3 + 3.59\pi_4^2 + 11.06\pi_4 - 434.4\pi_5^2 + 1727\pi_5 \text{...(a)}$$

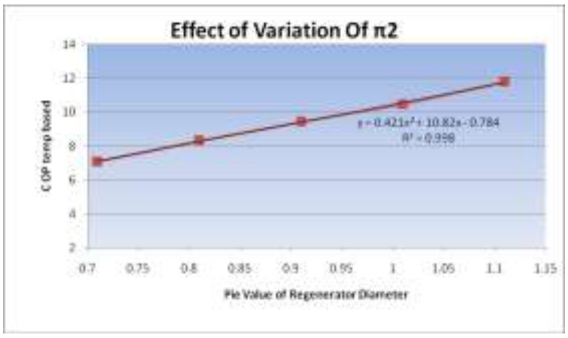
$$COP_T = -31.71 + 0.404\left[\frac{L_R}{(V_E)^{\frac{1}{3}}}\right]^2 + 5.586\left[\frac{L_R}{(V_E)^{\frac{1}{3}}}\right] + 0.421\left[\frac{D_R}{(V_E)^{\frac{1}{3}}}\right]^2 + 10.82\left[\frac{D_R}{(V_E)^{\frac{1}{3}}}\right] + 1155\left[\frac{D_M}{(V_E)^{\frac{1}{3}}}\right]^2 - 148.6\left[\frac{D_M}{(V_E)^{\frac{1}{3}}}\right] + 3.59\left[\frac{V_W}{V_R}\right]^2 + 11.06\left[\frac{V_W}{V_R}\right] - 434.4\left[\frac{Nm_W}{P(V_E)^{\frac{1}{3}}}\right]^2 + 172.7\left[\frac{Nm_W}{P(V_E)^{\frac{1}{3}}}\right] \text{.......(b)}$$

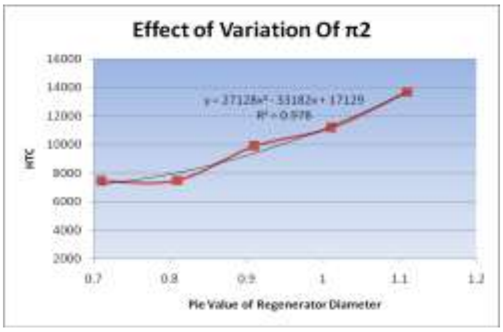
$$HTC_T = -916.5 - 1766\pi_1^2 + 14517\pi_1 + 27128\pi_2^2 - 33182\pi_2 + 92238\pi_3^2 - 35786\pi_3 + 28843\pi_4^2 - 59864\pi_4 - 73199\pi_5^2 + 25192\pi_5 \text{...(a)}$$

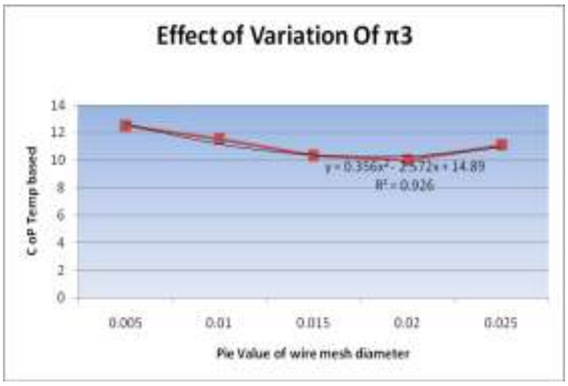
$$HTC_T = -916.5 - 1766\left[\frac{L_R}{(V_E)^{\frac{1}{3}}}\right]^2 + 14517\left[\frac{L_R}{(V_E)^{\frac{1}{3}}}\right] + 27128\left[\frac{D_R}{(V_E)^{\frac{1}{3}}}\right]^2 - 33182\left[\frac{D_R}{(V_E)^{\frac{1}{3}}}\right] + 92238\left[\frac{D_M}{(V_E)^{\frac{1}{3}}}\right]^2 - 35786\left[\frac{D_M}{(V_E)^{\frac{1}{3}}}\right] + 28843\left[\frac{V_W}{V_R}\right]^2 - 59864\left[\frac{V_W}{V_R}\right] - 73199\left[\frac{Nm_W}{P(V_E)^{\frac{1}{3}}}\right]^2 + 25192\left[\frac{Nm_W}{P(V_E)^{\frac{1}{3}}}\right] \text{.......(b}$$

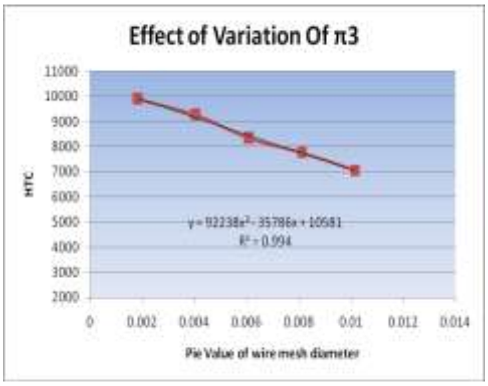


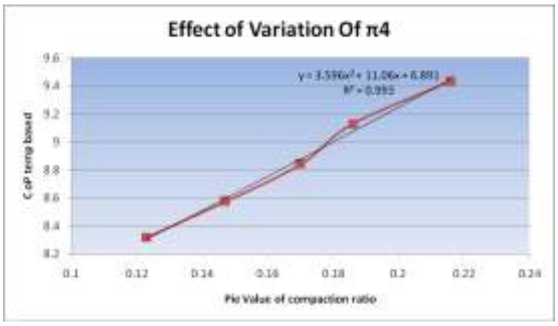


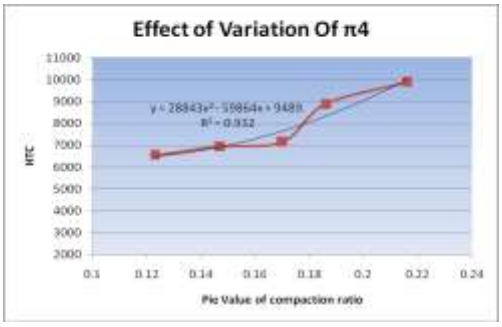

Effect of Variation Of π2

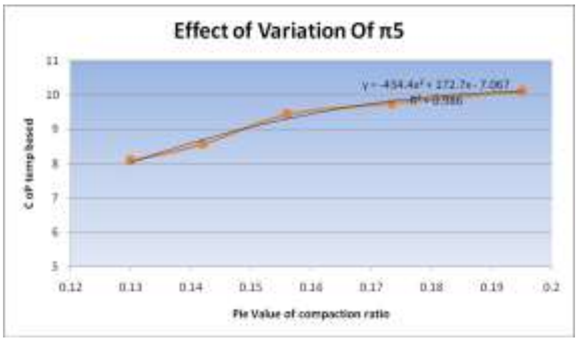

Effect of Variation Of π2

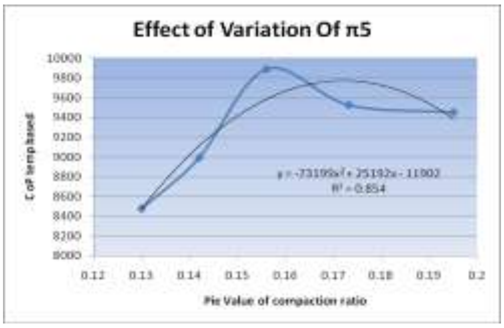

Effect of Variation Of π3


Effect of Variation Of π3


Effect of Variation Of π4


Effect of Variation Of π4


Effect of Variation Of π5


Effect of Variation Of π5

b) COP and HTC on Heat Exchanger

$$COP_A = -12.04 - 0.236\pi_1^2 + 2.224\pi_1 - 1.65\pi_2^2 + 6.452\pi_2 - 1121\pi_3^2 - 109.4\pi_3 - 27.65\pi_4^2 + 20.14\pi_4 - 20.76\pi_5^2 + 15.56\pi_5 \ldots\text{(a)}$$

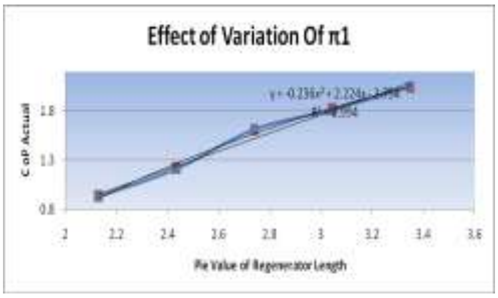
$$COP_A = -12.04 - 0.236\left[\frac{L_R}{(V_E)^{\frac{1}{3}}}\right]^2 + 2.224\left[\frac{L_R}{(V_E)^{\frac{1}{3}}}\right] - 1.65\left[\frac{D_R}{(V_E)^{\frac{1}{3}}}\right]^2 + 6.452\left[\frac{D_R}{(V_E)^{\frac{1}{3}}}\right] - 1121\left[\frac{D_M}{(V_E)^{\frac{1}{3}}}\right]^2$$

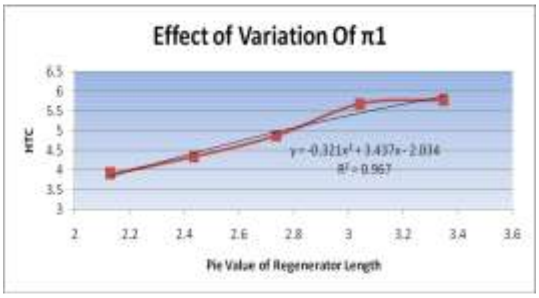
$$-109.4\left[\frac{D_M}{(V_E)^{\frac{1}{3}}}\right]-27.65\left[\frac{V_W}{V_R}\right]^2+20.14\left[\frac{V_W}{V_R}\right]-20.76\left[\frac{Nm_W}{P(V_E)^{\frac{1}{3}}}\right]^2+15.56\left[\frac{Nm_W}{P(V_E)^{\frac{1}{3}}}\right] \text{.......}\textbf{(b)}$$

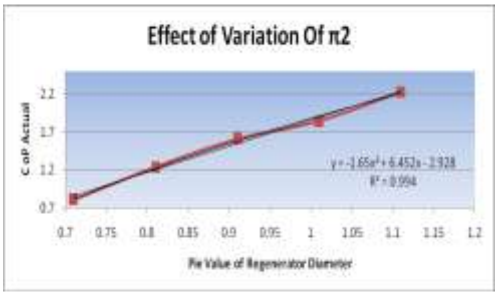
$$HTC_A= -0.2894-0.321\pi_1^2+3.437\pi_1+1.171\pi_2^2+0.557\pi_2-16986\pi_3^2+10.95\pi_3-36.29\pi_4^2+29.73\pi_4+359.4\pi_5^2-107.5\pi_5 \text{...}\textbf{(a)}$$

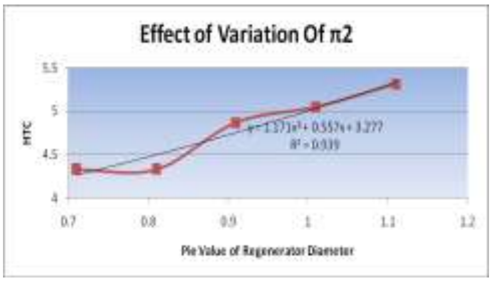
$$HTC_A = -0.2894 - 0.321\left[\frac{L_R}{(V_E)^{\frac{1}{3}}}\right]^2+3.437\left[\frac{L_R}{(V_E)^{\frac{1}{3}}}\right]+1.171\left[\frac{D_R}{(V_E)^{\frac{1}{3}}}\right]^2+0.557\left[\frac{D_R}{(V_E)^{\frac{1}{3}}}\right]-16986\left[\frac{D_M}{(V_E)^{\frac{1}{3}}}\right]^2$$

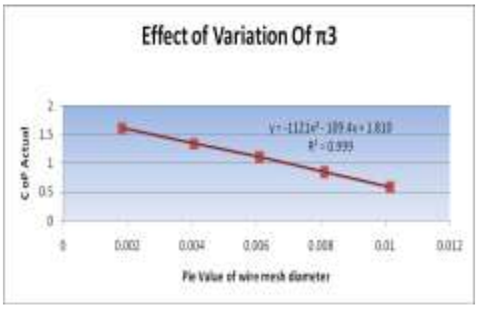
$$+10.95\left[\frac{D_M}{(V_E)^{\frac{1}{3}}}\right]-36.29\left[\frac{V_W}{V_R}\right]^2+29.73\left[\frac{V_W}{V_R}\right]+359.4\left[\frac{Nm_W}{P(V_E)^{\frac{1}{3}}}\right]^2-107.5\left[\frac{Nm_W}{P(V_E)^{\frac{1}{3}}}\right] \text{.......}\textbf{(b}$$

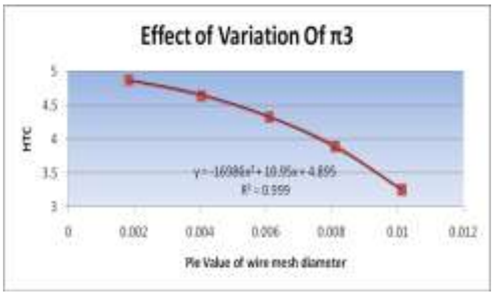


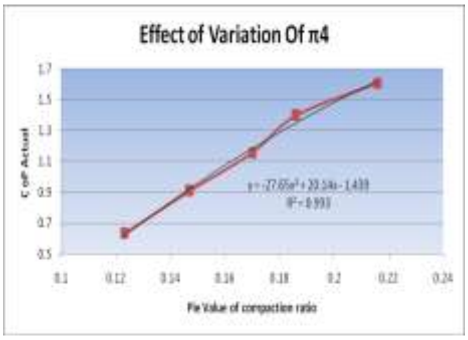


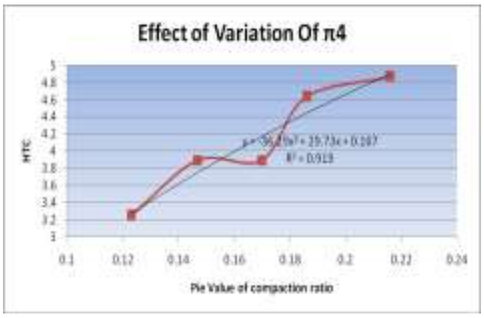


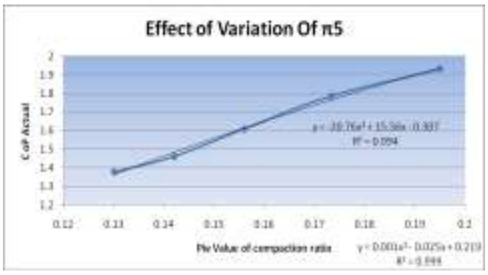


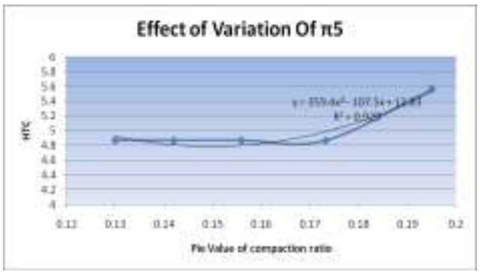












Sr.	Dimensionless pie term	Test envelope
1.	$\pi_1=L_R/V_E^{1/3}$	3.347-6.0
2.	$\pi_2=D_R/V_E^{1/3}$	1.11-2.79
3.	$\pi_3=D_m/V_E^{1/3}$	0.005-0.025
4.	$\pi_4=V_m/V_E^{1/3}$	0.25-0.45

VI.CONCLUSION

As well as their role as high-efficiency low-noise engines, Stirling-cycle machines offer an environmentally-friendly alternative to vapour-compression systems, by virtue of their ability to use air as a refrigerant (the ultimate environmentally-safe chemical).

The heat transfer process in a regenerator & heat exchanger that work between the intake of air and the exhaust gas in a power plant is very complex. It is also very hard to find a numerical solution with a high accuracy that considers all those facts that have a high influence of the result

The Stirling-Cycle are working on the development of low-cost high-performance machines. Initially these systems will probably be introduced in niche applications for small markets, where they can offer improved performance at similar cost to vapour-compression systems.

Stirling Engines”,G.Walker(1980),Clarenden Press,Oxford,page.1”A sterling engine is a mechanical device which operates on a closed egenerative thermodynamic cycle,with cyclic compression and expansion of the woring fluid at different temperature level.

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