CREEP CHARACTERISTICS OF AUSTENITIC STAINLESS STEEL FOILS UNDER OXIDATIVE AND NON-OXIDATIVE ENVIRONMENT

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***Dedicated** to*

*My dearest country **IRAQ***

*My parents, **Mohammed Kadhim (Late)** and **Hekma Attallah**,*

*My respected supervisor **Professor Dr Mohd Nasir Tamin***

All my family and friends for their immeasurable support and love throughout my journey for education.

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ABSTRACT

Compact and high efficiency recuperator with thin foil corrugated air cell as the primary surface is employed in clean and efficient microturbine system (100 kW). Current primary surface recuperators are made of AISI 347 austenitic stainless steel foils that operate at gas inlet temperature of less than 650 ℃ and attain approximately 30 percent of efficiency. Efficiency of greater than 40 percent is possible with the increase in turbine inlet temperature to 1230 ℃, and as a result recuperator inlet temperature increase to 843 ℃. This study establishes base line creep rupture behaviour of AISI 347 austenitic stainless steel foils at operating temperature of 700 ℃ and applied stresses of 150,182 and 221 MPa in air as oxidation environment, and in inert gas (Argon gas) as non-oxidation environment. Creep behaviour of the foil shows that the primary creep stage is short and creep life of the foil is dominated by secondary and tertiary creep deformation. The time to rupture for the foil specimen is 78 hours with the corresponding rupture strain of 18.42 percent in air and 102 hours with the corresponding rupture strain of 15 percent in Argon gas for the applied stresses of 150,182 and 221 MPa at 700 ℃. Creep curves for AISI 347 austenitic stainless steel foil at 700 ℃ and at 150,182 and 221 MPa are well represented by the modified Theta-Projection concept model with hardening and softening terms. The creep coefficients, $\theta 1$ and $\theta 3$, and the exponent α are 0.0355, 0.04645 and 1.39 respectively in air and 0.0035, 0.048 and 1.3 respectively in Ar gas environment. Theta-Projection parameter values of the creep curves at temperature of 700 ℃ and applied stress of range 150,182 and 221 MPa shows a sudden gradient change at applied stress of 150 MPa possibly due to different mechanism of dislocation movements and microstructure changes. the creep curves for AISI 347 austenitic stainless steel foil at 700 ℃ and at 150,182 and 221 MPa in inert gas are represented by the power-law model and parameters of this model A, n and Q are $7.947(10^{10})$, 1.73 and 556.4KJ/mol., respectively. Two different creep failure mechanisms for austenitic stainless steel foils are possible since the creep failure data falls very close to the boundary of dislocation and diffusion creep regions in the creep mechanism map for bulk material.morphology of fractured foil surface revealed intergranular fracture with shallow network of faceted voids. The formation of creep cavities is significant. Post test phase analysis indicates the formation of carbides, namely $Cr_{23}C_6$, NbC and Fe_3Nb_3C.

ABSTRAK

Pemulih padat serta berkecekapan tinggi dengan kerajang tipis sel udara beralun sebagai permukaan utama digunakan dalam sistem mikroturbin bersih dan cekap (100 kW). Pemulih permukaan utama semasa diperbuat daripada AISI 347 kerajang austenit keluli tahan karat yang beroperasi pada suhu gas masuk kurang daripada 650 ℃ serta mencapai kira-kira 30 peratus kecekapan. Kecekapan yang lebih besar daripada 40 peratus adalah mungkin dengan peningkatan suhu masuk turbin hingga 1230 ℃, dan hasilnya suhu masuk pemulih meningkat hingga 843 ℃. Kajian ini menetapkan garis asas kelakuan rayapan pecah AISI 347 austenit kerajang keluli tahan karat pada suhu operasi pada 700 ℃ dan tekanan yang digunakan adalah 150.182 dan 221 MPa dalam udara persekitaran pengoksidaan dan dalam gas lengai (gas Argon) sebagai persekitaran bukan-pengoksidaan. Kelakuan rayapan kerajang menunjukkan bahawa peringkat rayapan utama adalah pendek dan jangka hayat rayapan kerajang dikuasai oleh pengubahbentuk rayapan sekunder dan tertier. Masa untuk pecah bagi spesimen kerajang adalah 78 jam dengan ketegangan kepecahan yang sepadan sebanyak 18.42 peratus di udara dan 102 jam dengan ketegangan kepecahan yang sepadan sebanyak 15 peratus dalam gas Argon. Lengkung rayapan bagi kerajang austenit keluli tahan karat AISI 347 pada 700 ℃, 150,182 dan 221 MPa diwakili dengan menggunakan model konsep Unjuran Theta yang diubah suai daripada segi pengerasan dan pelembutan. Pekali rayapan, θ1 dan θ3, dan α eksponen adalah 0,0355, 0,04645 dan 1.39 masing-masing di udara dan 0,0035, 0,048 dan 1.3 masing-masing dalam gas lengai. Nilai parameter-parameter Unjuran Theta rayapan eksperimen pada suhu 700 ℃ dan tekanan digunakan daripada julat 150,182 dan 221 MPa menunjukkan perubahan secara tiba-tiba pada kecerunan tekanan gunaan pada 150 MPa mungkin disebabkan oleh mekanisma yang berbeza daripada pergerakan kehelan dan perubahan-perubahan mikrostruktur dan juga lengkuk rayapan bagi kerajang austenit keluli tahan karat AISI 347 pada 700 ℃, 150,182 dan 221 MPa dalam gas lengai diwakili oleh model kuasa-hukum dan parameter-parameter model ini adalah A, n dan Q iaitu masing-masing 〖7,947 * 10 〗 ^ 10, 1.73 dan 556.4KJ/mol. Dua mekanisme kegagalan rayapan yang berbeza bagi austenit kerajang keluli tahan karat adalah mungkin kerana data kegagalan rayapan berada sangat dekat dengan sempadan kehelan dan kawasan resapan rayapan dalam peta mekanisme rayapan untuk bahan pukal.

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LIST OF ABBREVIATIONS

AISI	-	American Iron and Steel Institute
ASME	-	American Society of Mechanical Engineers
ASTM	-	American Society for Testing and Materials
CHP	-	Combined Heat and Power
DG	-	Distributed Generation
EDX	-	Energy Dispersive X-ray Spectroscopy
FESEM	-	Field Emission Scanning Electron Microscope
HHV	-	Higher Heating Value
LVDT	-	Linear Variable Differential Transformer
MTG	-	Microturbine Generation
PID	-	Proportional-Integral-Derivative

LIST OF SYMBOLS

ε_0	-	Instantaneous strain
ε_{cr}	-	Creep strain
$\varepsilon_{primary}$	-	Primary creep
ε_t	-	Total strain
$\varepsilon_{tertiary}$	-	Tertiary creep
$\dot{\varepsilon_{ss}}$	-	Strain rate
t	-	time
T	-	Operating temperature
T_m	-	Melting temperature
wt. %	-	Weight percentage
α	-	Rate constant
θ_1 , θ_3	-	Parameters describing the primary and tertiary stages
θ_2 , θ_4	-	Rate parameters characterize the curvature of the primary and tertiary stages
n	-	Creep exponent
A	-	Creep coefficient
Q	-	The activation energy for creep
R	-	The gas constant, R = 8.314 J/mol.K

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Distributed Generation (DG) is expected to play an important role in the electric power system in the near future. The insertion of DG systems into existing electric systems has a great impact on real-time system operation and planning. It is widely accepted that Microturbine Generation (MTG) systems are currently attracting much attention for meeting customers' needs in the distributed-powergeneration market. The challenges facing the power industries companies are to provide clean, efficient, affordable and reliable heat and power supplies. Microturbines with their compact size, modularity and potential for relatively low cost, efficient and clean operations are emerging as a leading candidate meeting these needs.

Microturbines are suitable for distributed generation applications due to their flexibility in connection methods, ability to be stacked in parallel to serve larger loads, ability to provide stable and reliable power, and low emissions. Microturbines run at high speed and can be used either in power-only generation or in combined heat and power (CHP) systems. The size range for microturbines currently available and in development is from 30 to 250 kilowatts (kW), while conventional gas turbine sizes range from 500 kW to 250 megawatts (MW) [1].

Single-shaft microturbine based generation system [2, 6] Figure 1.1 shows the basic components of a microturbine generation system consist of a compressor, turbine, recuperator, high speed generator and power electronics interface. Microturbines, like large gas turbines, operate based on the thermodynamic cycle known as the Brayton cycle [2]. In this cycle, a) the inlet air is compressed in a radial (or centrifugal) compressor, b) fuel is mixed with the compressed air in the combustor and burned, and c) the hot combustion gas is then expanded in the turbine section producing rotating mechanical power to drive the compressor and the electric generator, mounted on the same shaft.

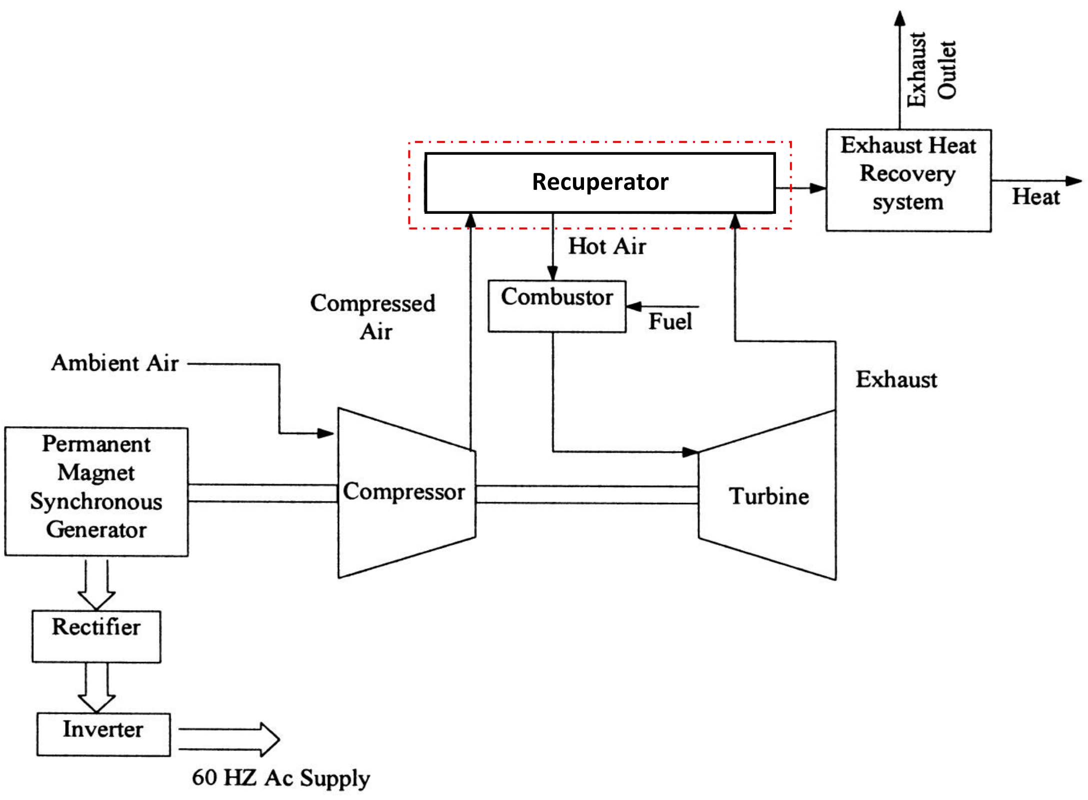

Figure 1.1 Microturbine based CHP System [5]

In a typical microturbine, an air- to- gas heat exchanger (called a recuperator) is added to increase the overall efficiency. The recuperator uses the heat energy available in the turbine's hot exhaust gas to preheat the compressed air before the compressed air goes into the combustion chamber, thereby reducing the fuel needed during the combustion process.

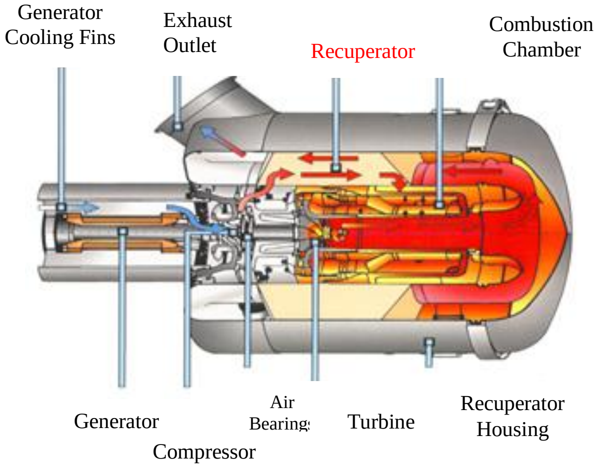

Figure 1.2 Microturbine Generation (MTG) Components [8]

Clean and efficient microturbine system (100 KW) employs compact, high efficiency heat-exchanger or recuperator with thin-foil folded air cell as the primary surface [7]. Figure 1.3 illustrates the corrugated air cell construction in a typical recuperator. The corrugated pattern of the cell maximizes the primary surface area that is in direct contact with turbine exhaust gas on one side and compressor discharge air on the other.

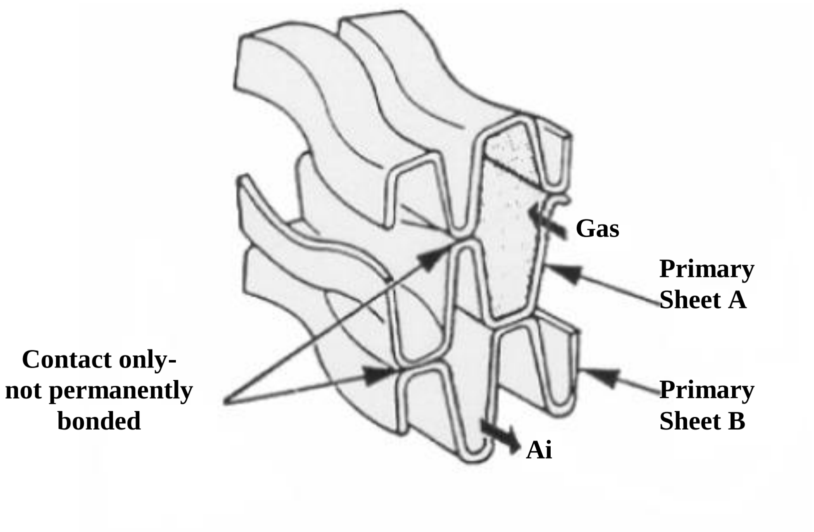

Figure 1.3 Schematic of corrugated air-cell in thin foils primary surface recuperator [7]

Combined heat and power system efficiency of a microturbine is a function of the exhaust heat temperature. Recuperator effectiveness strongly influenced by the microturbine exhaust temperature. Effectiveness in heat exchanger industry is for ratio of the actual heat transferred to the maximum achievable. Most microturbines include built in recuperator. The inclusion of a high effectiveness (90 percent) recuperator essentially doubles the efficiency of a microturbine with a pressure ratio of 3.2, from about 14 percent to about 29 percent depending on component details [1]. With the addition of the recuperator, a microturbine can be suitable for intermediate duty or price-sensitive base load service.

The efficiency of heat exchanger or recuperator depends on arranging and profile since the efficiency increase with increase surface area that clear in figure 1.4.

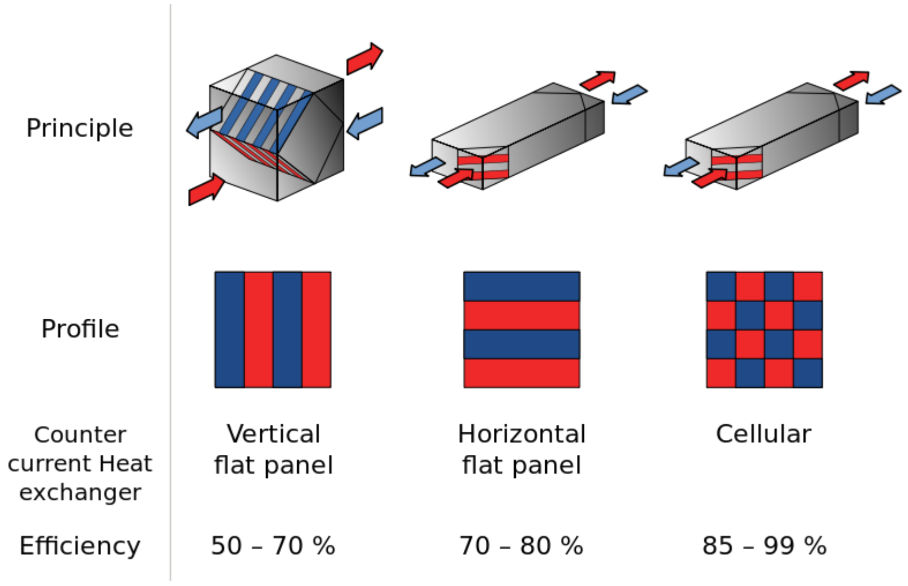

Figure 1.4 Efficiency as a Function of profile [4]

Current primary surface recuperators are made of AISI 347 stainless steel foils that operate at gas inlet temperatures of less than 650 ℃ and attain about 30 percent efficiency [8]. Efficiency target of greater than 40 percent is possible for low compression ratios such as 5, with the increase in turbine inlet temperature to 1230 ℃, and consequently recuperator inlet to 843 ℃. At this elevated temperature level, the steel foils are susceptible to creep failure due to the fine grain size, accelerated oxidation due to moisture in the hot exhaust gas and loss of ductility due to the thermal aging. Severe creep deformation able to restrict gas flow, increase recuperator back-pressure and decrease overall efficiency.

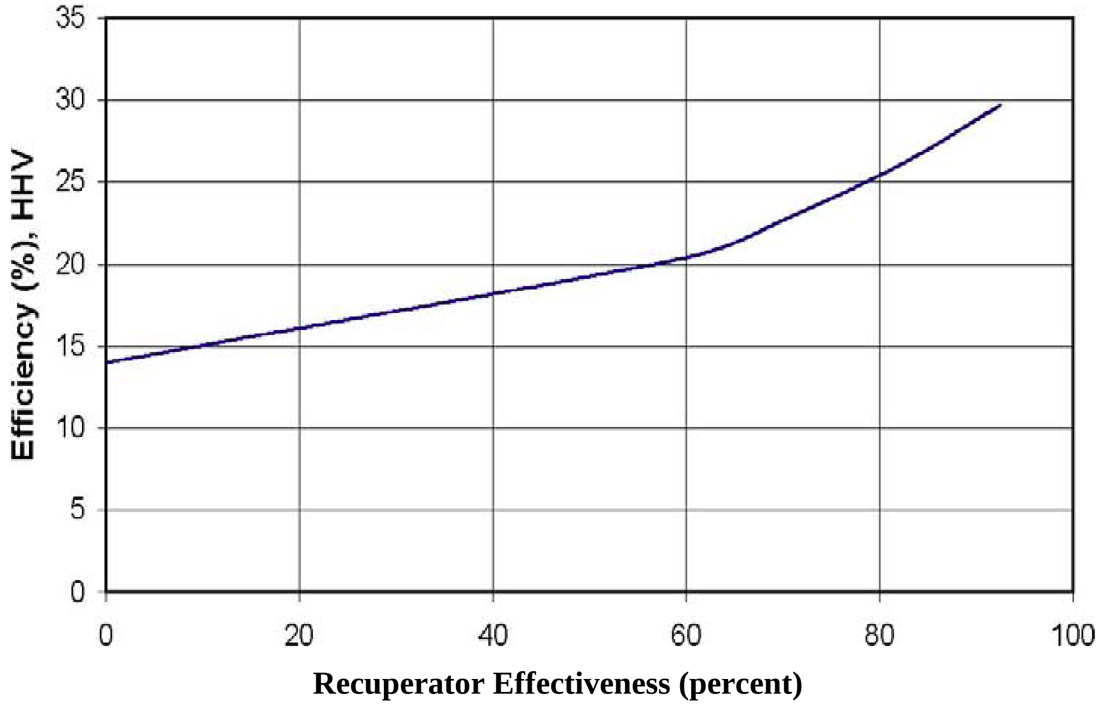

Figure 1.5 Microturbine Efficiency as a Function of Recuperator Effectiveness

Creep deformation is mutually accommodated by a combination of elastic deformation, localized plastic deformation, non-uniform creep, grain boundary sliding and diffusion flow through the grains, along grain and free surfaces [8]. The second phase particles are also responsible for cavity production which leads to intergranular failures [9]. The most important and major step in developing recuperators with upgraded performance is to characterize the current technology. combination of oxidation and corrosion behaviour, and tensile and creep strengths determine the upper temperature and useful lifetime limits. In this respect, creep tests on commercial AISI Type 347 steel recuperator stock has been conducted [6]. Aging effects on the steel up to 30,000 hours above 700 °C has been established in terms of detrimental sigma phase formation [7].

Properties and behavior of AISI 347 steel is generally known for processing and fabrication into high-temperature components such as heat-exchanger piping and gas turbine parts. However, information on these alloys fabricated into thin foils (0.1 – 0.25 mm-thick) for use in primary surface recuperators is limited or nonexistent.

Austenitic stainless steels are among the most widely used alloys for components operating in high temperature environment, in heat exchanger or recuperator and nuclear reactors. It is characterized by a minimum of 10.5 wt % Cr in order to form a passive Cr_2O_3 layer which protects the metal from further corrosion. Austenitic stainless steels also have additions of Ni to stabilize the austenite phase with a face centered cubic (FCC) crystal structure.

The combination of high temperature air and significant water vapor is common in energy generation devices such as, for example, gas turbines, steam turbines, and fuel cells, and in heat exchangers and recuperators handling the gas streams used or generated by such energy generation devices, as well as in equipment for treating, processing, or extracting chemicals or minerals at high temperatures. Accordingly, parts of such devices subjected to these conditions have been fabricated from a variety of austenitic stainless steels.

1.2 Research Objectives

The main objective of this study is to establish baseline creep characteristic and deformation mechanisms of AISI 347 austenitic stainless steel foils in air and in inert gas (Argon gas) at elevated stress (150,182 and 221 MPa) and 700^{o}C through the following tasks:

a) To establish tensile stress-strain diagram of the foil at room temperature.
b) To establish creep curve of foil at 700^{o}C and (150,182 and 221 MPa).
c) To determine creep model for the foil based on Theta projection concept and power-law model.
d) To identify creep mechanism of the foil.

1.3 Scope of Study

The study covers for AISI 347 austenitic stainless steel foils with thickness of 0.25 mm. Microstructure and chemical composition analysis are performed on the as-received foil. Tension tests of the foil are conducted at room temperature. Creep tests are performed in laboratory air environment at isothermal temperature of 700 ℃ and non-oxidation environment (inert gas) at isothermal temperature of 700 ℃. The applied stress are (150,182 and 221) MPa. Fractographic study is carried out on the fractured foil specimen. Theta projection concept model and power law creep model are executed for describing the long-term creep deformation behaviour of the foils.

1.4 Results

(Creep curves and models) set the baseline creep response of austenitic stainless steel foils at elevated temperatures and stresses can be used to advance the alloy for higher temperature applied with new composition metallurgy.

High efficiency heat exchangers are being developed for new distributed power technology systems particularly microturbines system. Recuperator is the part of microturbines that is responsible for a significant fraction of overall efficiency. Recuperators often require thin-section of austenitic stainless steels operating at elevated temperature ranges up to 800 ℃. Most of the recuperators used austenitic stainless steel of Type 347 because of its oxidation resistance properties and competitive cost. At high temperatures which above 650 ℃ with the presence of moisture environment of the turbine exhaust gas, the material is susceptible to creep and oxidation. These will cause fouling and structural deterioration and leaks, rapidly reducing the effectiveness and life of the recuperator. Therefore the study is to establish creep characteristics and deformation mechanisms of AISI Type 347 austenitic stainless steel foils at 700 ℃ and (150,182 and 221) MPa in air and inert gas.

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