Materials for elevated temperature heat exchangers in reactors


Several materials have been introduced for heat exchangers in 4th generation extremely high temperature reactor (EHTR) also called as next generation nuclear plant (NGNP). These materials are subjected to the extremely high temperatures and helium coolant that results in vigorous corrosion. It increases complications in choosing materials that can provide efficient functionality in these conditions and at temperatures and creep cracking that cause variations to the load bearing potential. The materials chosen should be cost-effective and firm to meet the reactors life expectancy minimum 60 years.

Introduction

Nuclear power is considered as a way to develop a competent energy source. There are several advanced factors under evaluations that will be implemented in the nuclear plants and produce more protective design to develop more cost effective and green energy. Using nuclear power also reduces the consumption of limited natural resources while delivering the long lasting product that will develop energy for a long term before refueling becomes necessary.

The advanced design concepts in nuclear power are 4th generation reactors. It is assumed that these designs will not exist for manufacturing before 2030 excluding for the extremely high temperature reactor (EHTR) that is assumed to be accomplished in 2021.

With outlet temperatures of almost 1000oC, the material choice has become the major challenges in producing competitive products specifically with a desired life of 60 years. Although, the life cycle is one of the main complications in material choice, the materials are required that can offer great creeping resistance, corrosion resistance and prolong elevated temperature structure consistency and cold and hot working and welding ease.

Various parts in the nuclear reactor such as control rods, steam generator and heat exchanger are subjected to various temperature limits and hence every part will have exclusive material requirements. This post focuses on materials for heat exchangers in EHTR that can be exposed up to 1000oC or above. The coolant used, helium gas has a crucial role in the material selection due to the reactions between material and gas which will be of attacking nature to the material. The contaminants like nitrogen, carbon monoxide, carbon dioxide, hydrogen, methane and water result in reactions like oxidation, carburization and decarburization.

Modern nuclear reactors are 2nd and 3rd generation reactors. 3rd generation reactors include enhanced fuel technology, thermal efficiency, oxide protection systems and typical design for low maintenance and investment capital.

Issues in Modern reactors

With enhanced technology and materials, processes and productions, it was observed that modern reactors would require to be constructed to maintain the energy and safety criteria. However some reactors have received five to ten year life enhancements, their lives will be ended while the 4th generation units are planned to be accomplished. Depending on 4th generation designs, the prime issues seen in the current reactors are considerable increase in temperature that permits for process applications or hydrogen generation and an alteration in coolant helium. Due to large increase in temperature, creeping and environmental failure become problems.

Needs of Proposed Reactor:

Due to the differences in EHTR design, new materials factors should be met to make this design possible. The main criteria are:

1. Melting points: Due to extremely high outlet temperature at 1000oC, a material should have a high melting point to this limit
2. Creeping resistance: A material in this condition will be exposed to the elevated temperatures and stresses that will make it more prone to elastic deformation to failure. Therefore it must have very high creeping resistance to perform in this application.
3. Environmental resistance: The pits or cracking in the material will make it more prone to attack. Oxidation or other attack of alloys generally depends on the contaminants in helium and closeness to carbon.
4. Oxidation and corrosion resistance: Material should withstand oxidation resulted by contaminants in helium at the above stated elevated temperatures.

A chosen material should meet the above factors to make the design successful. Following table evaluates modern reactor factors and proposed reactor conditions. It is called as Gas cooled reactors using Magnox and Fe – 9Cr at the elevated temperature conditions. There are considerable differences in the system needs from modern system to the proposed generation of reactors and the materials selected for the new applications will also require to meet these needs.

Factors	Modern system (AGR), Coolant : carbon dioxide	Under design system, Coolant : helium
Melting point	Outlet temperature 648oC	Above 1000oC
Oxidation resistance	At 100,000 hours weight gain of 25 mg/cm2	Material must prevent corrosion due to contaminants in helium
Creep resistance (T/ temp)	921/973 = 0.946 Melting point of Fe-9Cr – materials utilized in gas cooled reactor	1273 / 1650 = 0.77 Following melting point of Inconel 617
Temp refers to melting point in K		

Material Selection

There are several materials that tend to be suitable for the purposed reactors such as ferritic or martensitic steels, monolithic ceramic materials, ceramic composite and nickel based alloys. Depending on the position of material in reactor and the kind of reactor only a few materials can withstand the temperatures at which they would be subjected for a prolong period. Tests were conducted to find their creeping resistance, tensile strength and corrosion resistance up to the application temperatures. Depending on the requirements and basic research, Nickel based alloys are found to be suitable for the EHTR.

Nickel based alloys

Nickel based alloys are the ideal candidate for applications in nuclear reactors and few of them have been employed in the earlier nuclear models as well. The heat and corrosion resistance properties of nickel based superalloys have been already widely accepted. Through broad research of nickel based alloys, some were found to meet the needs of EHTR generation. The super alloys that are found suitable are Inconel 617, Hastelloy X and Incoloy 800. These have been examined as the candidates, and the material properties have been evaluated for the complete research. The mechanical properties of the alloys are shown in the following table to help evaluating how they will be suitable for EHTR.

Property	Inconel 617	Hastelloy X	Incoloy 800
Melting point (oC)	1332 to 1377	1260 to 1355	1350 to 1400
Thermal conductivity , W/moC	At 1000oC – 28.7	At 1000oC – 27.9	At 1000oC - 31.9
Tensile strength, MPa	At 760oC – 893	At 1093oC - 90	170
Oxidation resistance at 1095oC with 1008 hours (micro-m)	At 980oC – 0.19	0.038	0.137

Chemical compositions of chosen nickel based alloys are specified as following

Alloy	C	Fe	Ni	Cr	Co	Ti	Al	Mo	Othera

Incoloy 800H	.08	Bal	32	21	-	.4	.4	-	-
Hastelloy X	.07	18	Bal	22	1.5	-	-	9	W 0.6
Inconel 617	.07	-	Bal	22	12.5	0.4	1	9	-
Nimonic80A	.08	-	Bal.	19.5	-	2.2	1.4	-	-
Alloy 713 LC	.05	-	Bal.	12	-	0.6	6	4.5	Nb 2
T2M	.02	-	-	-	-	-	-	Bal.	Ti 0.5, Zr 0.08

Every element has an individual contribution to strength and corrosion resistance properties of an alloy. Some of the above alloys have been modified to meet the specific purpose. For instance, higher magnitude of aluminum enhances oxidation resistance which ultimately increases corrosion resistance.

Inconel 617

Nickel alloy 617 is a NiCrCoMo alloy providing outstanding high temperature strength and oxidation resistance. It has been tested for applications at temperatures about 982oC according to ASME VIII div. 1. Besides of high temperature strength, it also offers great resistance to extensive range of corrosive conditions and is readily produced and welded by traditional methods. It is also commonly known that Inconel 617 attains outstanding creeping strength properties at the elevated temperatures.

Thermal Properties

Temp.	Electrical Resistivity ohm-circ mil/f	Thermal Conductivity Btu-in./ft in./in./°F	Coeff. Of Expansion 10 -6 in./in./°F	Specific Heat Btu/lb-°F
78 °F	736	94	-	0.100
200 °F	748	101	7.0	0.104
400 °F	757	113	7.2	0.111

Mechanical properties

Type	Yield Strength	Tensile Strength	Expansion	Reduction	Hardness
Plate	46.7 Ksi	106.5	62 %	56	172
Bar	46.1 Ksi	111.5	56 %	50	181
Tubing	55.6 Ksi	110.0	56 %	-	193
Sheet/strip	50.9 Ksi	109.5	58 %	-	173

High temperature creeping resistance is the main challenge in choosing a material. Creep causes unending deformation in materials under stress at temperature above half of melting point in oK. More crucial to this usage, creeping is more intense in materials that are exposed to elevated temperature for prolong periods, making creeping resistance crucial to material choice for a EHTR. Inconel 617 attains the highest extents of creeping strength while comparing with other alloys like Incoloy 800H, Hastelloy X etc. There is no significance of simulated helium coolant on 1% creep strain limit or creep rupture strength for the material about 20,000 hours of application time. Because of larger application periods essential for material in the EHTR, extrapolation was followed to find creep data for using up to 100,000 hours.

The high creep strength of Inconel 617 makes it a prominent choice for employ in nuclear applications. It has lower strain rates and higher stress rupture strength than Hastelloy X.

Fatigue conduct is also essential while evaluating the materials for use in nuclear applications. Due to the elevated temperature use, high cycle stress controlled fatigue (HCF) tests are not performed above 750oC to analyze the effect of vibrations on the materials.

Any chosen material has to go through the prolong annealing that is considered because of exposure to this high limit. The annealing causes alternations in the microstructure of materials that may cause fatigue cracks. Inconel 617 has great pair of thermal conductivity and thermal expansion coefficient at 1000oC. It also offers good ductility, subsequent to prolong thermal exposure to the elevated temperatures.

Creep stresses for temperatures from 800oC to 1000oC and periods to 100,000 hours offer indication of operation period needed for the material. A component at the elevated temperatures easily deforms at low stress levels. Inconel 617 shows a striking reduction in the maximum allowable stresses with increase in temperature. It reaches the maximum temperature capability at a similar highest permitted stress to other selected alloys.

Corrosion is a critical factor in the selection of a material. Few instances of possibility of change in properties of a material and effect on the corrosion resistance are carburization, decarburization and internal oxidation. These are resulted by contaminants in helium that is utilized as a coolant. Although, at 950oC, Inconel 617 in water depleted simulate HTR helium develops an alumina layer that fully covers the surface hence avoids further internal oxidation and carburization.

Hastelloy X (Hastelloy XR)

Hastelloy X is known for providing extraordinarily high strength and oxidation resistance. It is commonly employed in furnace applications and has also been employed in jet engine tailpipes and other components of aircrafts. Essential for nuclear operations, it is known to keep its characteristics sufficientl for the prolong time at the extremely high temperature limits. It is also easily formable and weldable by traditional techniques. Initially it was chosen for heat exchanger in Japan for heat distribution tubes and hot header. Basically Hastelloy XR was produced to enhance compatibility with helium. The variations in their chemistry are described in the following table:

Alloy	C	Mn	Si	P	S	Cr	Co	Mo	W	Fe	B	Ni	Al	Ti
Hastelloy X	.07	.61	.39	.012	<.001	21.26	1.71	8.89	.57	18.98	<.001	Bal	-	-
Hastelloy XR	.07	.83	.32	<.005	.006	21.84	.19	9.06	.53	18.26	<.001	Bal	<.05	<.05

At the elevated temperatures, these alloys can withstand slight to no plastic deformation. Hence a material is needed with excellent creeping resistance to prevent damage. Strain hardening is noticed at 750oC. However subsequent to reaching the highest stress at 950oC, the materials show creep without hardening. The tensile characteristics for Hastelloy X/XR were found by exposing at sample at 1200oC for 60 minutes then water cooling. The ultimate tensile strength at strain rate of 0.25% was 145 Mpa compared to UTS of 688 – 697 MPA at room temperature. The vigorous reduction in tensile properties is noticed from 800oC to 1000oC. The time spans also much shorter while preserving similar tensile strengths.

The corrosion in EHTR is a complicated trouble primarily because of use of Helium. At the elevated temperatures, helium may comprise of hydrogen, water, carbon dioxide, carbon dioxide and methane. These contaminants interact with the alloys resulting into attack. Corrosion is a major trouble for any material resulting in reduction in its creeping resistance and ductility that are the essential factors for a material selection. As stated, the extent of corrosion can be based on contaminants of helium that alters. Hastelloy X has many defects under the surface however lower than Incoloy 800.

Incoloy 800

Incoloy 800H is also a favorable alloy for application in EHTR. It is a FeNiCr alloy with basic chemistry similar to Incoloy 800. Although it has better creeping strength. The composition balance of alloy offers resistance to carburization and oxidation. It is well featured and available for application however made for lower service temperatures than Inconel 617 or Hastelloy X.

Among three alloys Incoloy 800H has the minimum creeping strength at the elevated temperatures. A test was conducted to find the period of failure for a moderate heat exchanger at 950oC. The heat exchanger tubes were kept in the tensile loading and internal pressure with and without cyclic tensile stress.

Tensile Properties

Temperature		Tensile Strength		Yield Strength		Elongation	Reduced Area
oF	oC	Ksi	Mpa	Ksi	Mpa	%	%
85	30	76.0	524	26.6	183	60	-
1200	650	52.5	362	18	124	47	59

1400	760	30.3	209	15.7	108	85	73
1500	815	23.6	163	17.3	119	98	79.5
1600	870	16.0	110	13.5	93	109.5	92.5
1700	925	11.8	81	9.2	63	111.5	93

It is essential to analyze the material strength data introduced for alloy 800H as was performed for others. Following the design factors for material choice, the stress rupture strength at a given temperature and period are essential to evaluate. The stress rupture strength is evaluated at the various time periods.

The stress for rupture for Incoloy 800H are identical to Inconel 617 at 1000oC and at periods of 100,000 hours however Incoloy 800H stress seem slightly smaller than rupture periods compared to the stress to rupture for Inconel 617.

Other mechanical characteristics are determined for the alloy specifically the permitted stresses, ultimate stress, tensile strength and highest allowable stress. Permissible stresses are also enhanced that compare impact strength and ultimate tensile strength to Inconel 617 at 1000oC and at a period of 100,000 hours, however Incoloy 800H stresses seem to be quite smaller at rupture times as compare to stress rupture for Inconel 617. The stresses, impact strength and ultimate tensile strength are also compared to Inconel 617.

However Incoloy 800H is stated to offer excellent oxidation resistance at the elevated temperatures and because of the reaction with the coolant, carbides and oxides are still produced at 850oC. Presence of chromium in 800H alloy enhances the production of a security oxide layer particularly while cyclic exposure to the elevated temperature.

Preferences

All the materials researched are not suitable for applications in EHTR. There are many modifications that can be performed to them to enhance strength and corrosion resistance. It is overall accepted that modifying the chemistry of alloys will change the mechanical characteristics of the alloy. The research shown here is determined to the application of the alloys.

Changing the chemistry of Incoloy 800 produces the alloy Incoloy 800H that is already suitable for the necessary application and could be changed somehow to be superior oxidation resistant. Hastelloy X has been enhanced to produce Hastelloy XR. Modifications have also been made to Inconel 617 to fit it in the applications. However materials such as Incoloy 800H may not provide the specific properties to be chosen for EHTR, it is accepted that these alloys are considered for the purposed nuclear reactors that do not need such elevated temperatures. The creep and oxidation resistance increase only at the low temperatures and hence they may be suitable for use in the under design nuclear reactors.

As the oxidation resistance has been stated to be the limited need, there are feasibilities of producing a specific coating to be employed in the elevated temperature applications that may not decrease the environmental resistance but enhance the mechanical characteristics to offer higher strength by the surface enhancement. For instance, in Incoloy 800H, aluminum oxide is produced below the surface as it does not produce the security layer that is observed in Inconel 617. The security layer may enhance the environmental resistance by providing a stronger material.

Outline

Nickel based alloys are one of the best materials for use in the nuclear reactors. Among the three alloys, **Inconel 617** is the most suitable material for use in this purpose. It meets the criteria of purposed nuclear reactors. It is also described that various other alloys may further be modified to be stronger at the elevated temperature with improved features that are required to meet the design needs of proposed conditions. As it is acknowledged which elements in alloys chemistry provide them greater strength, it is feasible to continue research and change compositions to produce a better product.

An evaluation of Inconel 617, Hastelloy X and Incoloy 800 has been made describing design stresses at 900oC. Inconel 617 has the maximum strength, almost double of Incoloy 800H that is the minimum. Inconel 617 has the maximum rupture strength with Hastelloy X as the moderate and Incoloy 800H has the minimum strength. It seems that Incoloy 800H has the maximum creeping strength and oxidation resistance for the moderate temperature limits than those needed in EHTR.

The alloys stated have been earlier extensively researched for employ in other 4tth generation nuclear systems and may be suitable. Hastelloy XR has been researched for application in the elevated temperature gas cooled reactors and Incoloy 800H for the super critical water quench nuclear plant setup. The permissible stresses are up to 1000oC.

These alloys are again evaluated to describe Inconel 617 approaching the maximum temperature potential. Hence Inconel 617 however with the research presently going through, is the best material and more compatible for use in the elevated temperature conditions.

Heanjia Super-Metals produces superalloys for nuclear engineering such as Inconel, Incoloy and Hastelloy alloys.