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Boiler Pipes and Tubes for Higher Efficiency of Power Generation

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Abstract

The power generation efficiency of thermal power plants is being improved to reduce CO_2 emissions. As the boiler tubes and pipes Nippon Steel has developed for this purpose, here are introduced large-diameter and thick-walled pipes of high-creep strength 9Cr-1.8WNbV steel (NF616) for ultra-supercritical coal-fired power plants and tubes of highly corrosion-resistant 20-25%Cr austenitic stainless steel for refuse incineration boilers.

1. Introduction

Reducing CO_2 emissions that are feared to have an adverse effect on global warming has become an important issue in the electric power generation field. The power generation efficiency of thermal power plants and refuse-fired power plants has been improved to cut down the CO_2 emissions. Integrated gasification combined cycle (IGCC) power generation and pressurized fluidized bed combined cycle power generation are considered as highly efficient methods of utility thermal power generation in the long term. At present, LNG combined cycle power generation and ultra-supercritical coal-fired power generation are promising processes. Refuse incineration is finding increasing usage in power generation, and the efficiency of refuse-fired power generation is being enthusiastically improved by increasing the steam temperature and pressure.

As the boiler pipes and tubes developed by Nippon Steel and helpful in improving the efficiency of power generation, this report introduces large-diameter, thick-walled and high-strength ferritic heat-resistant steel pipes (NF616) for high-temperature and high-pressure thermal power plants, such as ultra-supercritical coal-fired power plants, and various highly corrosion-resistant austenitic stainless steel tubes for use in severely corrosive refuse incineration boilers.

2. High-Strength Ferritic Heat-Resistant Steel Pipes NF616

2.1 Background

The steam temperature and pressure of Japan's thermal power plants have been increased. The increasing steam temperature and pressure have highlighted the importance of developing large-diameter and thick-walled steel pipes and tubes for headers and main steam pipes, among other parts. Headers are large-diameter pipes that distribute the steam to the tubes in the boiler furnace or recollect the steam after heating in the furnace. Main steam pipes are large-diameter pipes that introduce the steam from the boiler into the turbine. The headers and main steam pipes both carry the high-temperature and high-pressure steam, and require high elevated-temperature strength.

In Japan, atomic power generation is positioned as a base power source, and thermal power generation is adjusted to meet the day and night power demand variations. The problem of failure by thermal stress resulting from the temperature change with the load variation dictates the use of ferritic heat-resistant steel of small thermal expansion coefficient and large thermal conductivity as material for large-diameter and thick-walled pipes, such as the headers and main steam pipes. Generally, ferritic heat-resistant steels were low in creep strength, and this shortcoming had to be solved.

The 9Cr-1MoNbV steel (Ka-STPA28) developed in the United States has creep strength and fabricability superior to those of the conventional steel 2¹/₄Cr-1Mo (STPA24), and came to be extensively used in thermal power plants the world over. At recent thermal power plants operating at a steam temperature of 600°C or higher, the 9Cr-1MoNbV steel must be used in larger wall thickness to suit this high steam temperature. Materials of higher creep strength are need in its place.

The 9Cr-1.8WNbV steel (NF616)¹⁾ Nippon Steel jointly developed with Professor Emeritus Fujita of the University of Tokyo

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Table 1 Chemical composition comparison of Ka-STPA29 (NF616) with other steels (mass%)

Standard	Element	C	Si	Mn	Cr	W	Mo	V	Nb	N	B
STPA24 (2¹/₄Cr-1Mo)	Specified Range	≤0.15	≤0.50	0.30 - 0.60	1.90 - 2.60	–	0.87 - 1.13	–	–	–	–
Ka-STPA28 (9Cr-1MoNbV)	Specified Range	0.08 - 0.12	0.20 - 0.50	0.30 - 0.60	8.00 - 9.50	–	0.85 - 1.05	0.18 - 0.25	0.06 - 0.10	0.030 - 0.070	–
Ka-STPA29 (NF616)	Specified Range	0.07 - 0.13	≤0.50	0.30 - 0.60	8.50 - 9.50	1.50 - 2.00	0.30 - 0.60	0.15 - 0.25	0.04 - 0.09	0.030 - 0.070	0.001 - 0.006
	Typical	0.10	0.23	0.50	9.09	1.83	0.43	0.20	0.064	0.046	0.0012

is a material that fulfils this need. The steel was standardized in the ASME and ASTM as tube (T92) and pipe (P92). In Japan, NF616 was also standardized as tube (Ka- STBA29), pipe (Ka-STPA29), and forgings (Ka-SFVAF29) in the "MITI Code for Thermal Power Plants" in June 1997, and has already been put to commercial use.

2.2 Chemical composition and physical properties

Table 1 lists the specified ranges and typical example of chemical composition of NF616 as compared with other steels. NF616 is characterized by the addition of tungsten (W) to increase its creep strength. Like the 9Cr-1MoNbV steel, it utilizes precipitation strengthening by the addition of niobium and vanadium. NF616 shows tempered martensite structure without delta ferrite, even when cooled after tempering at relatively low cooling rate. It is thus suited for thick-walled components that require high toughness.

Fig. 1 compares the thermal expansion coefficient of various steels. The thermal expansion coefficient of NF616 is practically the same as that of the 9Cr-1MoNbV steel and is about two-thirds of that of the austenitic stainless steel TP316. The thermal conductivity, Young's modulus, and other physical properties of NF616 are equivalent to those of the 9Cr-1MoNbV steel[1].

2.3 Creep strength and maximum allowable stress

Fig. 2 shows the creep rupture strength of NF616 pipes and forgings as compared with the average creep strength curves of the 9Cr-1MoNbV steel. Though these two steels do not have large differences at shorter times, NF616 shows higher strength at longer times.

The maximum allowable stress of Ka-STPA29 (NF616) determined based on its tensile strength at elevated temperatures, creep rupture, and creep strain data is compared with that of other Cr-Mo(W) steels in **Fig. 3**. The maximum allowable stress does not increase with increasing chromium content from 2¹/₄Cr-1Mo steel to 9Cr-1Mo steel. It substantially increases for the 9Cr-1MoNbV steel with Nb and V additions and rises further for the 9Cr-1.8WNbV steel with W addition. The maximum allowable stress of NF616 is higher by about 30% and 40% than that of the 9Cr-1MoNbV steel at 600°C and 625°C, respectively.

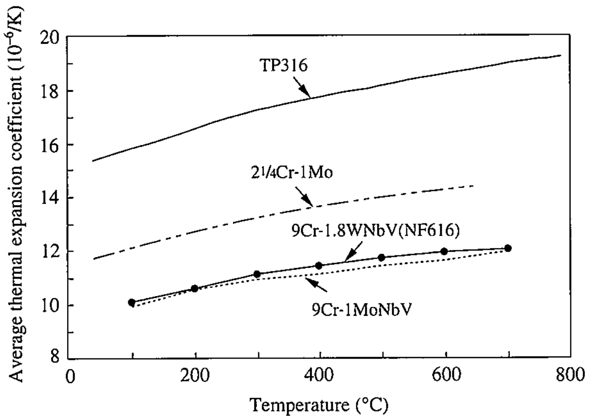


Fig. 1 Comparison of thermal expansion coefficient of steels

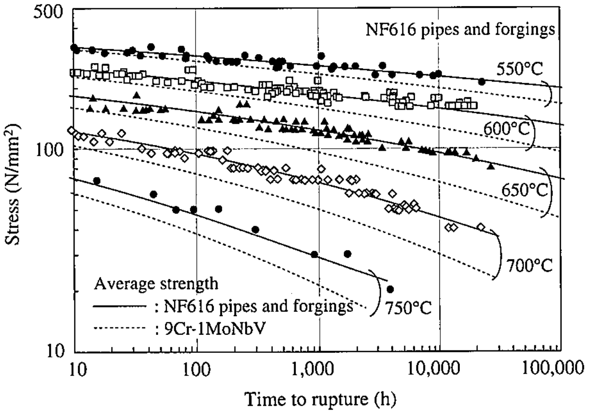


Fig. 2 Comparison of creep rupture strength of NF616 pipes and forgings, with 9Cr-1MoNbV steel

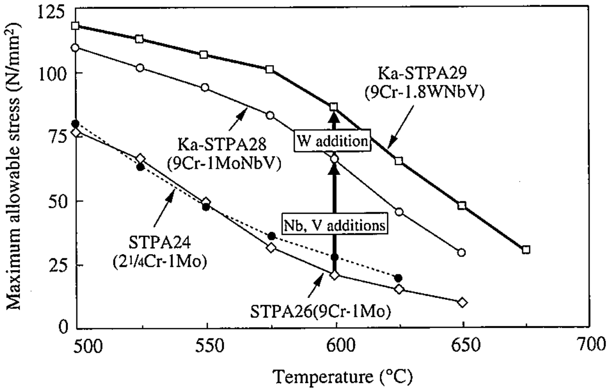


Fig. 3 Comparison of maximum allowable stress of steels

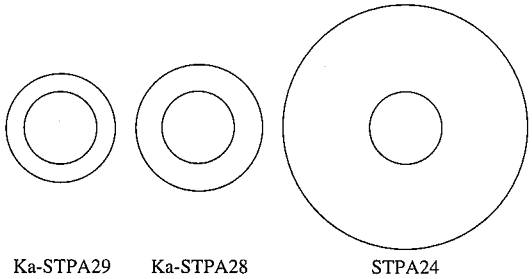
2.4 Merit of using high-strength ferritic steel

The merit of using high-strength ferritic steel, like Ka-STPA29, lies in the wall thickness reduction of large-diameter steel pipes. Examples of the wall thickness of headers with an inside diameter of 420 mm calculated under JIS B 8201 is given in **Table 2**. The required minimum wall thickness is 151 mm for Ka-STPA28 and 104 mm for Ka-STPA29. This means a wall thickness reduction of about 30% and a weight reduction of about 36%. With STPA24, the required minimum wall thickness is 490 mm, the outside diameter is 1,400 mm, and the weight is 5.17 times greater than that of Ka-STPA28. This is an unrealistic pipe. Conversely speaking, thermal power plants could not achieve the advanced steam conditions

Table 2 Example of calculation of minimum wall thickness of header

Material	Ka-STPA29	Ka-STPA28	STPA24
Minimum wall thickness t_{min} (mm)	104	151	490
Outside diameter D_o (mm)	628	722	1,400
Weight ratio	0.63	1.00	5.17

Calculation conditions: Metal temperature = 615°C, Maximum operating pressure = 25 MPa, Inside diameter = 420 mm, Ligament factor = 0.8



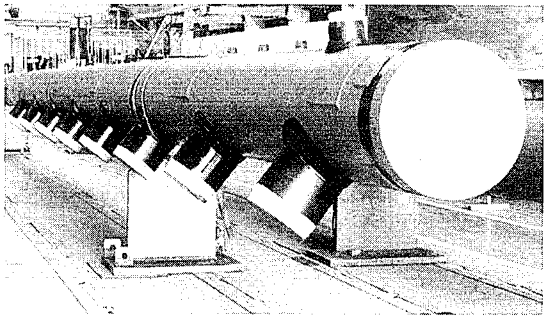


Photo 1 Header made of NF616 for a 1,000-MW coal-fired boiler (Courtesy of Babcock Hitachi K. K.)

without these 9%Cr steels. A 1,000-MW coal-fired boiler uses 500 tons or more of Ka-STPA28 in the headers and main steam pipes. Substitution of Ka-STPA29 for Ka-STPA28 can save a weight of about 200 tons or more.

If the wall thickness reduction is achieved by adopting high-strength ferritic steel in this way, the thermal stress that varies with the wall thickness during the load variation can be reduced. There are many other benefits such as the reduction in welding and transportation costs, and the reduction in boiler house weight.

2.5 Application to commercial plants

When a high-strength heat-resistant steel like NF616 is used at a commercial plant, it is indispensable to develop high-strength welding materials. The development and commercialization of GTA, SMA, and SA welding materials with matching chemical composition are already completed[2]. Peripheral forged parts, like tees and flanges, are developed and are confirmed to have the same elevated-temperature strength as the pipes. NF616 was adopted for use in two coal-fired utility boilers with steam temperatures of 600°C/610°C, as headers and other parts. NF616 parts were welded and fabricated without any problem. **Photo 1** shows a manufactured NF616 header.

3. Austenitic Stainless Steel Tubes for Refuse-Fired Power Boilers

3.1 Background

Waste recycle is one of the most important issues today. It is desirable that municipal refuse should be separated and recycled. If that is difficult, the heat produced by waste incineration may be used in the form of electricity as another method of recycling. As of June 1995, there were 181 refuse incineration plants that generate electricity in Japan. This number is expected to increase.

The steam temperature and pressure adopted for refuse-fired boilers in Japan were traditionally 300°C and 3 MPa or less, respectively, and were lower than those of fossil-fired boilers for power generation. The power generation efficiency of the refuse-fired power plants was thus low at 10 to 15%. This is because the corrosive environment in the refuse incinerator is so severe that the corrosion of heat transfer tubes is pronounced when the steam temperature exceeds 300°C. Now that electricity can be sold to electric power companies, refuse incineration plants operating at a steam temperature of over 300°C and power generation efficiency of over 20% are built in Japan.

Carbon steel tubes are sufficient for conventional refuse-fired boilers operating at a steam temperature of 300°C or lower, because their corrosion environment is not severe. Refuse-fired boilers operating at a steam temperature in excess of 300°C require austenitic stainless steel or nickel-base alloy super heater tubes. At present, type 310 (25Cr-20Ni), type 309 (23Cr-12Ni) and similar grades stainless steel tubes tend to be selected as super heater tubes up to 400°C steam temperature. Besides these conventionally standardized steels, newly developed steels for other applications are also used in many refuse incineration boilers. To achieve refuse-fired power generation with higher efficiency, it is important to make the corrosive environment milder by an ingenious boiler design and to select materials suited for the corrosive environment.

3.2 Corrosive environment of refuse incinerators

The environment of refuse incinerators varies with the location of incinerator, quality of refuse, type of incinerator and operating conditions, among other factors, and cannot be generalized. The largest difference between the refuse and the fossil fuels is that chlorine arising from polyvinyl chloride and salts in foods in the refuse is included in the incinerator flue gas and deposited on the heat transfer tubes. The chlorine exists in an amount of about 1,000 ppm as HCl gas in the incinerator flue gas and mainly as alkaline metal chloride in the deposited ash. Though the SO_x concentration is often low at 100 ppm or less, the deposited ash always contains sulfate as well. The chlorides and sulfates form low-melting eutectic compounds and extremely accelerate the molten salt corrosion of the heat transfer tubes when the metal temperature exceeds the melting temperature of the molten salts. Chlorides of heavy metals, such as lead and zinc, contained in the plastics and tires in the refuse lowers the melting point of molten salts and the temperature at which accelerated corrosion starts[3].

3.3 Effects of alloying elements on corrosion resistance

Roughly speaking, the corrosion resistance of alloys in the refuse incinerator environment improves with increasing content of chromium and nickel in combination. More specifically, the effect of alloying elements differs between a sulfate environment and a chloride environment.

Molten sulfate corrosion is frequently experienced in coal-fired boilers and gas turbines, and is reported in many research papers. Generally, high-chromium steels show better corrosion resistance. Nickel is not effective, but molybdenum addition are claimed to be harmful[4]. Silicon is sometimes harmful because it promotes the grain-boundary precipitation of $Cr_{23}C_6$, reduces the effective chromium content, and accelerates grain-boundary corrosion[5].

When various materials were tested for corrosion in chloride rich environment, alloys increased in corrosion resistance with increasing nickel and molybdenum contents, and no large difference in corrosion resistance with chromium content was observed between alloys with a chromium content of 20% or more.

Whether the actual ash mainly consists of chlorides or sulfates cannot be generalized because the ash composition varies with the incinerator or the position in the incinerator. The materials appear to be often selected by considering their corrosion resistance in the environment that is predominantly composed and causes more severe corrosion.

3.4 Corrosion test results of alloys

Table 3 lists the chemical compositions of standard steels and Nippon Steel-developed steels used as materials for corrosion test.

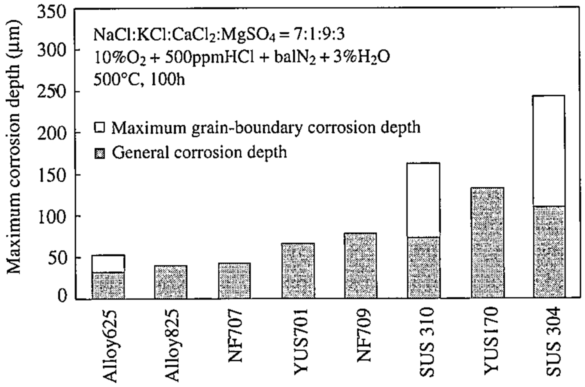


Fig. 4 Comparison of corrosion resistance of alloys in chloride rich environment at 500°C

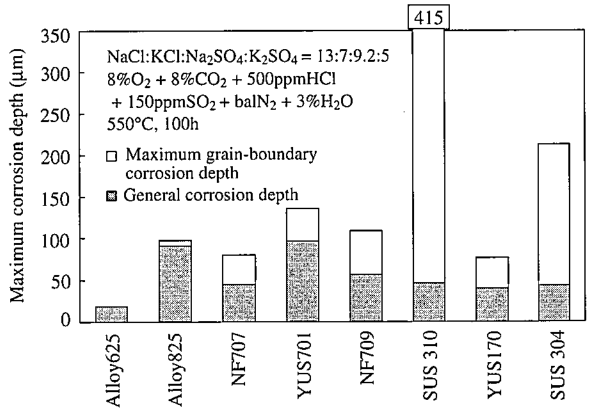


Fig. 5 Comparison of corrosion resistance of alloys in chloride-sulfate mixture environment at 550°C

Figs. 4 and **5** show the laboratory corrosion test results of the alloys in chloride rich environment and a chloride-sulfate rich environment, respectively. The general corrosion depth calculated from the corrosion weight loss and the maximum grain-boundary corrosion depth determined by the cross-sectional microscopy of specimens are shown. **Photo 2** are the cross-sectional micrographs of the specimens after the laboratory corrosion test of the specimens in the chloride rich environment.

In the chloride rich environment, the corrosion loss is largest for SUS 304 and type 309, intermediate for type 310 and high-silicon alloys, and lowest for high-nickel alloys. In the chloride-sulfate rich environment, the alloys are ordered by corrosion resistance in a somewhat different sequence. For example, YUS170, which is a type 309 alloy, exhibits corrosion resistance equivalent to that of type 310.

The new alloys developed by Nippon Steel are briefly introduced below.

YUS170 is developed as a seawater-resistant steel and is used in soda recovery boilers. It exhibits relatively good corrosion resistance in the chloride-sulfate rich environment.

NF709 is a high-strength steel developed for ultra-supercritical boilers. Among type 310 and similar alloys, NF709 contains large amounts of nickel and molybdenum that are advantageous in a chloride environment. In the laboratory corrosion test in the chloride rich environment, NF709 was superior to SUS 310 in grain-boundary corrosion resistance. NF709R (0.03C-22Cr-25Ni-Mo) with less carbon and more chromium than NF709 is also produced. YUS170 and NF709/NF709R have their standardization in the MITI Code for Thermal Power Plants completed and are usable now. Particularly, NF709R is finding many applications.

YUS701 is a steel developed for high-temperature applications like radiant tubes and is characterized by the addition of 2 to 3% silicon. Although basically a type 309, it exhibited corrosion resistance equivalent to that of NF709 in the corrosion test in the chloride rich environment.

NF707 has higher chromium and nickel contents than NF709. It demonstrated good corrosion resistance in both the chloride rich environment and the chloride-sulfate mixture environment.

Fig. 6 shows the results of corrosion test of the NF709R (Ka-SUS310J2TB) and SUS 310TB conducted in a refuse-fired boiler for the purpose of material selection. In the corrosion test, the inside surface of each tube inserted into the boiler tubes was cooled with air to control the metal temperature. After about 2,000 hours of test, NF709R had a smaller thickness loss than SUS 310TB. Based on this result, NF709R was selected as material for the super heater tubes of a new refuse-fired boiler.

Table 3 Chemical compositions of alloys used in corrosion test in refuse-fired boiler environment (mass%)

Material		C	Si	Mn	Ni	Cr	Mo	Nb	Balance	Remarks
304	SUS 304	0.05	0.5	1.2	8.64	18.4	–	–		
Type 309	YUS170*	0.02	0.4	1.1	13.6	24.0	0.8	–	N	Ka-SUS309J1TB
Type 310	SUS 310	0.04	1.0	1.8	19.9	24.4	–	–		
	NF709*	0.07	0.5	1.0	25.4	20.2	1.5	0.3	N, Ti, B	Ka-SUS310J2TB
High Si	YUS701*	0.11	2.0	1.4	12.2	23.7	0.6	–	N	
High Ni	NF707*	0.07	0.6	0.6	35.5	25.4	1.5	0.3	N, Ti, B	
	Alloy 825	0.03	0.2	0.4	40.4	22.8	2.7	–	Cu, Ti	
	Alloy 625	0.02	0.1	0.1	60.4	22.5	8.7	3.5	Ti, Fe	

*Developed by Nippon Steel

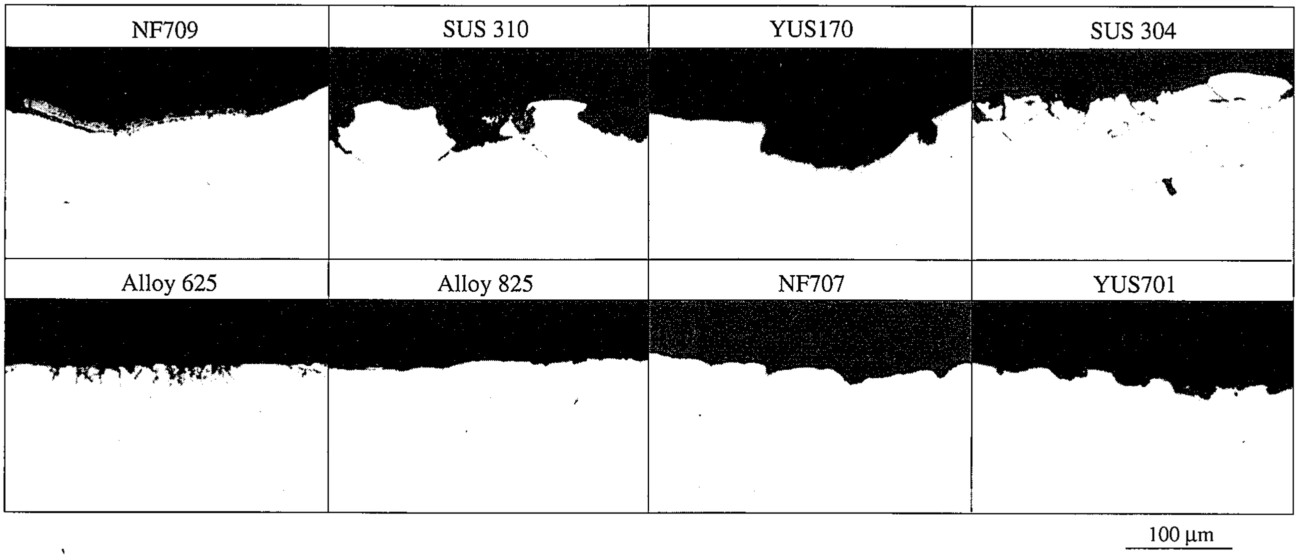


Photo 2 Cross sections of specimens after corrosion test in chloride rich environment at 550°C for 100 h

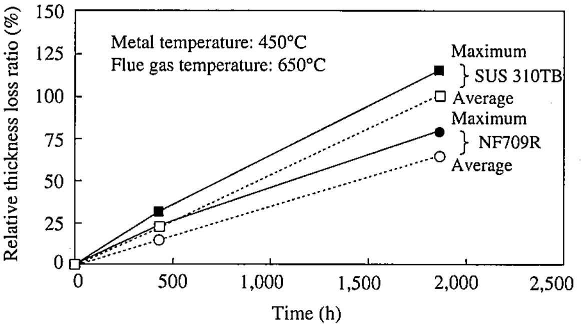


Fig. 6 Comparison of relative corrosion loss in corrosion test in a refuse-fired boiler (Average corrosion loss of SUS 310TB after 1,872 h = 100%)

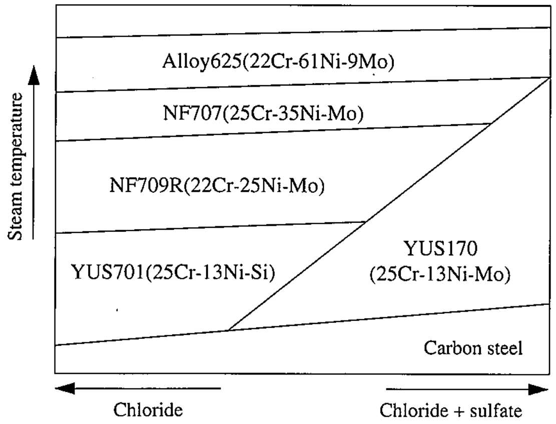


Fig. 7 Schematic diagram for selecting super heater tube materials for refuse incinerators by considering corrosion resistance and material cost

3.5 Material selection according to environment

Fig. 7 is a schematic diagram constructed from the results of various tests, including the above-mentioned corrosion test, and used to select materials to suit specific corrosion environments and temperatures. Carbon steel is sufficient at low temperatures. In a chloride rich environment, steels containing 20 to 25% chromium and increased nickel are required as the temperature rises. In an environment where chlorides coexist with sulfates, a type 309 alloy with a lower nickel content and a higher chromium content is sometimes effective.

4. Conclusions

Steel pipes and tubes intended for boilers and developed for improving the efficiency of electric power generation have been introduced above. The authors hope that they will contribute to the reduction in the CO_2 emissions.

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