

WHITE PAPER



COMPARISON OF ALUMINUM AND STAINLESS STEEL FOR CONDENSING BOILER HEAT EXCHANGERS

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1.0 ABSTRACT

This paper compares two materials that are commonly used for heat exchangers in a condensing boiler. The paper begins with a brief historical overview of the heat exchanger market and its development over the years. It discusses the operational parameters, with regard to heat transfer, flue gas condensate and water chemistry. Following, it presents the advantages of aluminum and stainless steel as the material for the manufacture of a condensing boiler heat exchanger, showing a comparison between the two materials. The paper concludes with a summary of the points covered and supplies a table for easy comparison.

2.0 INTRODUCTION

Hydronic heating systems, also referred to as boilers, and their components historically originated and were developed in Europe. Later, they were adopted and modified in other regions of the world, including North America. In a conventional boiler, fuel is burned and the hot gases produced are passed through a heat exchanger (HE) where much of their heat is transferred to water, thus raising the water's temperature. Water vapor is formed as a result of combustion of hydrocarbon fuels such as natural gas, which is primarily methane. A condensing boiler extracts additional heat from the exhaust gases by condensing its hot water vapor (steam) to liquid water, thus recovering its latent heat of vaporization. By capturing some of the waste heat, the condensing boiler heat exchanger has the potential to be 10-15% more efficient than a conventional boiler operating in the proper conditions.

Condensing boilers have been largely replacing earlier, conventional designs in Europe and, to a lesser degree, in North America. The Netherlands was the first country to adopt them broadly. In Europe, their installation is strongly advocated by various influencing groups and government bodies concerned with reducing energy use. In the United Kingdom, since 2005, all new gas central-heating boilers must be high-efficiency condensing boilers. In the United States, the Federal tax credit for the installation of condensing boilers and additional rebates from power companies generated an increase in sales of condensing boilers. In Western Canada, energy suppliers offer energy rebates when these systems are installed in multi-unit dwellings.

Aluminum heat exchangers for condensing boilers have been in development in Europe for more than 30 years with significant progress made during the last decade. Currently, the European condensing boiler market is equally divided between aluminum and stainless steel heat exchangers. In North America, the availability of stainless steel heat exchangers for condensing boilers along with the perception that stainless steel is a better material has resulted in its higher market share. The following sections closely examine the differences between heat exchanger materials, their design, important operating parameters, installation and cost differences.



3.0 OPERATING ENVIRONMENT

3.1 COMBUSTION PARAMETERS

The heat exchanger uses the heat of combustion from fuel, typically natural gas or liquid petroleum gas (LPG) to raise the temperature of the central heating water from the point of entry to the heat exchanger (return) to the point of leaving the heat exchanger (supply). Except during start up, a temperature differential (ΔT) is usually maintained between supply and return temperatures of the boiler in a range of 20°F and 35°F.

A condensing boiler extracts heat from the combustion flue gases. The dew point of the flue products from the combustion of natural gas is approximately 135°F (57.2°C) depending upon the excess air level. Therefore, in order to achieve maximum efficiency by recovering the latent heat of condensation, it is necessary to cool the flue products below this temperature.

The basic chemistry for the combustion of natural gas and LP gas suggests that only CO₂, NO_x, H₂O, and N₂O are present in the combustion products. In practice, however, there are impurities or contaminants in the fuel and intake air resulting in impurities and contaminants in the flue gas and the condensate formed. These additional components produce an acidic solution that is prevalent in the flue gas condensate. While the condensate chemistry is affected by the combustion process, contaminants and impurities in the entire heating system directly affect the water chemistry of the boiler.

3.2 CONDENSATE AND WATER CHEMISTRY

The important parameters to manage in the heating system make-up water and the flue gas condensate are the chloride concentration and the pH levels.

3.2.1 Flue Gas Condensate (Liquid)

One of the variables that significantly impact the chloride concentration of the flue gas condensate is the venting system. If the heating system's intake air for the combustion process is from the outside (direct vent), the chloride concentration will typically be less than 3.0 ppm. If the air for combustion is coming from inside the building (direct exhaust), the chloride concentration tends to be much higher due to contaminants and impurities in the air. Inside air intake should be managed to keep chloride levels as low as possible. Some potential chemicals to avoid are (but are not limited to) chlorinated waxes/cleaners, swimming pool chemicals, paints, fabric softeners, adhesives and refrigerants.

3.2.2 Make-up (Heating System) Water

Every boiler manufacturer should specify the water chemistry best suited for its boiler. This should be available whether the heat exchanger is made of aluminum or stainless steel. The typical boiler heat exchanger made of aluminum requires water with a pH range between 7.0 and 8.5. A heat exchanger constructed from stainless steel requires a pH to be in the same range from 7.0 to 8.5. It is important to measure and maintain the pH level because both aluminum and stainless steel will corrode if pH levels are not within specifications. Further, improper pH levels can induce scale.

In both aluminum and stainless steel heat exchanger boiler systems, the chloride concentration of the make-up water must also be kept well below 250ppm. The EPA primary drinking water regulations do not address chloride concentration. Secondary drinking water regulations are sometimes controlled at the local and state level following federal guidelines of less than 250ppm chloride concentration. Ground water may have a wide range of chloride concentration depending on the geographic location. Though primary drinking water has lowest level of



chloride concentration, the introduction of other chemicals for safe drinking may have adverse effects on the boiler systems. It is therefore best practice, regardless of the heat exchanger material, to use boiler manufacturer recommended inhibitors with the make-up water. This protects the entire heating system and helps to keep it optimized for peak efficiency.

4.0 MATERIAL SELECTION

4.1 BACKGROUND

Traditional materials used to manufacture boiler heat exchangers were copper and cast iron. Both were readily available and relatively low cost. Cast iron was predominant in Europe until the early 1980s when copper boilers began to take over the European market. In the U.S., cast iron boilers have been in use for many decades. In recent years, both aluminum and stainless steel heat exchangers have been successfully used as main components of high efficiency condensing boilers.

4.2 ALUMINUM

The unique combinations of properties make aluminum and its alloys a most versatile and economical material for heat exchanger applications. Aluminum can be cast into very complex shapes, is light weight, and has excellent heat transfer characteristics. This makes it a very good choice for compact high efficiency heat exchangers. Also, in general, most wrought alloys, as well as silicon-containing casting alloys and magnesium-containing casting alloys, have good resistance to corrosion in freshwater and can be used in many applications without protection. One of the first applications of aluminum alloy in consumer products was kitchen utensils at the end of the 19th century. Aluminum has demonstrated its water resistance in a wide range of applications: roofing in buildings, street furniture, locks on rivers, irrigation tubes, heat exchangers, heaters for central heating, boats, aircraft, engine blocks and other automotive components.

The heat exchanger's surface is exposed to several possible forms of corrosion: uniform corrosion (due to the very acidic pH of the condensates), pitting corrosion, and crevice corrosion. After filling a heating system, the corrosion rate in the first few weeks is relatively high, but the corrosion rate soon settles at a level that is insignificant in practical terms. For this reason, aluminum heat exchangers are designed with corrosion allowance in mind.

The following table suggests which alloys have been proven to be most suitable over recent years. This information is for guidance only and material specialist insight should be sought prior to commencing a design project.

Specification	Best material	Comments
Suitability for sand casting	AlSi10Mg	Used where good resistance to corrosion combined with high strength is required.
Suitability for die casting	AlSi12	Used for large, intricate and thin walled castings in all types of molds. Also used where corrosion resistance or ductility is required.
Suitability for extrusion	H9-6060	Used for finned tubes among other uses

Some engineering design advantages inherent in the aluminum heat exchanger casting process include:

- It can be used to manufacture high efficiency heat exchangers with complex geometrical features such as internal cavities, hollow sections with fair dimensional accuracy.



- Heat exchanger construction can be simplified. Objects may be cast in a single piece which would otherwise require assembly of several pieces if constructed by other methods.
- Offers more uniform properties from a directional standpoint; i.e., cast heat exchangers exhibit the same properties regardless of which direction is selected for the test piece relative to the original casting. This is not generally true for wrought/rolled metals.

4.2.1 Advantages of Aluminum

Aluminum alloys offer several advantages for the heat exchanger of a condensing boiler.

- The possibility to manufacture cast heat exchanger - Heat exchangers with extended heating surfaces such as pins and fins (offering the specific advantage of a large surface within a limited volume), or plate heat exchangers for unit heaters that provide better heat transfer rates.
- High thermal conductivity - The thermal conductivity of the aluminum varies from that of stainless steel; stainless steel 16 [W/mK], cast iron 60 [W/mK], and aluminum 205 [W/mK]
- Lighter condensers - It has a high strength to weight ratio. This offers heat exchanger designers the potential for compact low-cost heat exchangers.
- High resistance - Aluminum clad products protect pitting corrosion of the core alloys. Aluminum has high resistance to atmospheric corrosion and environments like fresh water, saltwater, and many chemicals and their solutions.
- Manufacturing flexibility - Ability to be joined by welding, brazing, and soldering - depending on temperature, it can be hot or cold formed. It has the ability to be formed into various shapes, tubes, fin patterns, etc.

4.3 STAINLESS STEEL

Stainless steel is not a single alloy, but a part of a large family of alloys with different properties for each member. There are five classes of stainless steel: austenitic, ferritic, martensitic, duplex, and precipitation hardening. They are named according to how their microstructure resembles a similar microstructure in steel. The properties of these classes differ but are essentially the same within the same class. Ferritic and austenitic stainless steels are used primarily because of the corrosion resistance, and good mechanical properties over a broad temperature range from cryogenics to high temperature. Stainless steel has been applied successfully in a large variety of environments including acids, fresh water, and seawater.

For fuel oil and natural gas applications, different stainless steel alloys with varying amounts of chromium, nickel, molybdenum and titanium are available, and have been matched to the characteristics of condensate.

Specific alloys of stainless steel are formed by varying the amounts of specific elements. Chromium is the key element that makes the stainless steel corrosion resistant. However, both chromium and chloride ion can have negative impact on stainless steel. This is because in the passive chromium oxide layer, the chloride ion combines with chromium forming a soluble chromium chloride. As the chromium dissolves, free iron is exposed on the surface and reacts with the environment forming rust. However, alloying elements like molybdenum will minimize this reaction. Other elements may be added for specialized purposes. For example, high chromium content imparts oxidation resistance. Therefore, look for high chromium for use with nitric acid, the higher the better. High chromium is useful for high temperature oxidation resistance; therefore, any stainless steel is better than carbon steel in elevated temperature applications. High copper content in stainless steel imparts resistance to sulfuric acid. High nickel content gives resistance to reducing acids and produces a tightly adhering oxide film in high temperature oxidation.

The simplest stainless steels contain a minimum of approximately 11% chromium, in addition to iron. They are generally known as the AISI 400 series of stainless steels. Depending on the chromium and carbon contents, they may be martensitic or ferritic. The martensitic alloys, typically containing more than 0.08% carbon, can be



hardened by heat treatment. Type 410 stainless is a typical grade. Increasing chromium or reducing carbon results in a ferritic stainless steel, which is non-hardenable by heat treatment. Increasing chromium also improves corrosion resistance. Therefore, Type 441 stainless (19% chromium) and 430 stainless (18% chromium) in this family are more corrosion resistant than Type 410 stainless (12% chromium).

Type 304 or 304L is the most common grade austenitic stainless steel, which makes up over 60% of all the stainless steel made in the United States today. The other austenitic grades are developed from the 18–8 base by adding alloying elements to provide special corrosion resistant properties or better welding ability. For example, adding 2% of molybdenum to type 304L makes type 316L, which has better chloride corrosion resistance. Adding more chromium with type 310 creates the basis for high temperature applications. The major weakness of the austenitic stainless steels is their susceptibility to chloride stress corrosion cracking. High alloy grade stainless steel means high cost.

Just like aluminum, these materials are able to withstand the corrosive attack of the flue gas condensate and should have the pH levels of the heating system water maintained by using proper chemical treatment.

4.3.1 Advantages of Stainless Steel

Factors that favor stainless steels selection as heat exchanger material include the following:

- High resistance to uniform corrosion
- Resistance to oxidation
- Suitability for intended fabrication techniques such as forming and welding
- Toughness at cryogenic temperature and strength at elevated temperatures
- Resistance to galling and seizing
- Dimensional stability under thermal load

4.4 COMPARISON

Key design parameters for optimizing the heat-exchange process in a condensing boiler are as follows:

- Thermal conductivity of the material used
- Wall thicknesses
- Surface area (the larger the better)
- Flow characteristics (on both sides of the heat exchanger)
- Burner/Heat Exchanger – configuration
- Heat exchanger weight
- Heat exchanger size
- Heat exchanger reaction time to changing heat loads
- Corrosion / foul-up / maintenance

Aluminum has up to 12 times better heat transfer rate than stainless steel.

Stainless steel as a material is stronger than aluminum and as such has an advantage over aluminum in regards to wall thickness. Stainless steel can be reduced to far below 1 mm, while with cast-aluminum approximately 2.5 mm is the minimum. However, aluminum has a better "strength to weight" ratio than stainless steel. In other words, while it is not as strong as steel, the fact that it weighs less than half as much makes up for its lower strength.

Compared with the smooth stainless steel surface, the combustion chamber/water path of a cast aluminum heat exchanger may be cast with extended heat transfer surfaces. Furthermore, the condensing area for cast aluminum can also include extra pins increasing the heat transfer area, which optimizes the heat transfer, increases the unit



heat load, and reduce the heat exchanger size. A further advantage of cast aluminum is that the casing, heat exchanger and all necessary connections can be integrated into the casting; reducing the number of components and assembly times.

The corrosion resistance of both aluminum and stainless steel depends on the type of water to which it is exposed. It differs significantly in freshwater, seawater, brackish water, etc. Many parameters come into play:

- Type of water
- Alloy composition and microstructure
- Temperature
- Flow of water

Both materials of appropriate alloy/grade type, as previously discussed in this paper, are very effective at resisting corrosion. Stainless steel holds up better to extreme temperatures whereas aluminum alloy begins to show a reduction in strength at temperatures above 212°F (100°C), which are well above the maximum boiler temperature limits. However, at temperatures below 212°F, the aluminum alloy tends to outperform stainless steel, which can show signs of tension and cracking.

The 316L type stainless steel used in heat exchangers for condensing boilers is a high-alloyed steel with more than 18% chromium (Cr). When chromium is oxidized, it will form a thin oxide layer on the metal surface, protecting the underlying metal from corrosion. With a thin passive film that completely covers the metal surface, the metal is passivated and corrosion is greatly reduced. Although 316L stainless steel has a good resistance to most corrosive environments, it has relatively high susceptibility for chloride-induced stress corrosion cracking (SCC).

AlSi10Mg aluminum alloy used in heat exchangers for condensing boilers also gets its corrosion protection, just as 316L type stainless steel, from an oxide film. Unlike the oxidation process on the stainless steel, the aluminum oxide film is relatively thick. Corrosion resistance of aluminum is dependent on its ability to form Al_2O_3 Aluminum Oxide. An alloying element within Al_2O_3 , magnesium, strengthens the protective properties of the oxide film by forming mixed oxides. Another alloying element, silicon, has no negative impacts on the corrosion properties, but significantly improves the casting ability. The broad application of AlSi10Mg on heat exchangers in Europe has proved its strong corrosion resistance. Picture #1 and #2 below show a typical AlSi10Mg aluminum heat exchanger after service in a foundry environment for 4 years; the fire side is very clean without any blockage issue or obvious corrosion area in both combustion chamber and condensing heat exchanger areas. Pictures #3 through #6 show a cross section of typical cast aluminum heat exchanger on the water side in different water conditions (soft water and hard water) after 6 months testing. Examination of the heat exchanger showed no discernible thinning and minimal pitting corrosion. A few isolated pits were found in the bottom water way in the heat exchangers however, measurements of the pits after cleaning showed them to be extremely shallow. Therefore, any risk to the boilers from long-term corrosion would have been insignificant.





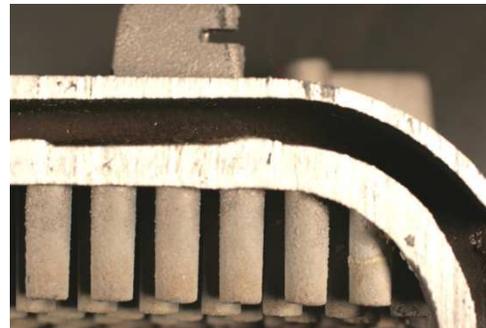
#1 Aluminum HE combustion area



#2 Aluminum HE condensing area



#3 Cross section of an Aluminum HE water way from a soft water system



#4 Cross section of an Aluminum HE water way from a hard water system



#5 Corrosion checking after cleaning of the aluminum HE water way in a soft water system



#6 Corrosion checking after cleaning of the aluminum HE water way in a hard water system



Stainless steel tubes of a typical condensing heat exchanger may be of two types: seam-welded or seamless. Seamless are often considered as more reliable. Their metallurgical homogeneity is not to be questioned. However, seamless tube manufacturing process is long and complex. This leads to a higher manufacturing cost, which may be reflected in the product price, especially in heat exchanger thin-wall tubes. For this reason alone, welded tube becomes a commonly used material for stainless steel heat exchangers. To achieve an expected heat transfer performance, these welded tubes have been involved into many cold works and welding processes, therefore, the manufacturing process stands as a major parameter. The composition and microstructure changes in the welding area and high residual stress in the cold work tremendously degrade the corrosion resistance of 316L stainless steel.

5.0 SUMMARY

When comparing heat exchangers for a condensing boiler system, there are a number of points to consider. The design differences of the heat exchanger, depending on the use of aluminum or stainless steel, is not a significant factor as the efficiency ratings equalize and provide a comparable cost structure for day-to-day operations of a boiler system. Boiler operation and quality of water, air and fuel will all impact lifetime and maintenance requirements for each similarly. This includes water chemistry requirements such as pH level as well as chloride content for make-up water, fuel, and combustion air. Heat transfer is faster for aluminum as a material and tensile strength is better for stainless steel as a material, but these advantages are offset with the aluminum heat exchanger walls being thicker. Ease of installation and service has its advantages with aluminum heat exchangers (can be disassembled), but it is dependent on the application layout.

In conclusion, aluminum and stainless steel are both good material choices for heat exchangers. There is not a clear advantage for choosing one material over the other when purchasing a condensing boiler. For this reason, most boiler OEMs (original equipment manufacturers) offer comparable heat exchanger warranties.



The following table further summarizes the key points made in this paper.

Characteristic	Aluminum Heat Exchangers	Stainless Steel Heat Exchangers
Make up water treatment	Water treatment required, recommended pH levels are between 7.0 and 8.5 and chloride content well below 250ppm	Water treatment required, recommended pH levels are between 7.0 and 8.5, and chloride content well below 250ppm
Flue gas condensate	Air in-take considerations needed to minimize chloride concentration. All contaminants should be avoided.	Air in-take considerations needed to minimize chloride concentration. All contaminants should be avoided.
Corrosion resistance	Long life of aluminum is assured by its self-forming, microscopically thin surface layer of aluminum oxide in response to corrosion	Stainless steel has good resistance to corrosion, depending on Chromium content in the SS alloy
Heat transfer efficiency (thermal conductivity)	205 W/m°C, AL has up to 12 times better heat transfer rate than SS, thicker walls than SS	16 W/m°C, SS HE has typically thinner walls than aluminum HE
Thermal expansion flexibility	Aluminum is slightly more flexible than stainless steel when exposed to thermal stress	Stainless steel is less flexible than aluminum when subjected to changing heat loads
Material strength	50 ksi or less, thicker walls, more material required to maintain strength	70 - 90 ksi, SS tensile strength is greater AL allowing for thinner walls, less material required
Weight	Aluminum is approx. 30% of the stainless steel weight - equal volume and size	Stainless steel is almost 3 times heavier than aluminum but it requires less material than aluminum
Material cost	Aluminum is significantly less expensive than stainless steel but requires more material to provide similar strength	Boilers with stainless steel heat exchangers are typically more expensive than boilers with aluminum heat exchangers
Ease of installation	Heat exchangers can be split into smaller sections for easy access in tight retrofit applications	Heat exchangers are typical one large unit with welded tubes and are more suitable for new installations
Maintenance	Annual maintenance includes checking water pH, adding inhibitors as required and if needed, cleaning heat exchanger (performance based)	Annual maintenance includes checking water pH, adding inhibitors as required and if needed, cleaning heat exchanger (performance based)
Durability	Aluminum has relatively lower strength than stainless steel but thicker walls greatly improve heat exchanger longevity	Stainless steel has high tensile strength and provides high corrosion resistance
Heating system pump size	Wider waterways result in less friction and lower pump hp	Narrower waterways are difficult to clean and result in higher pump hp
Typical heat exchanger warranty	10 yrs. (full or on prorated basis)	10 yrs. (full or on prorated basis)



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