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AN INNOVATIVE COMPACT HEAT EXCHANGER SOLUTION FOR ALUMINUM OFF-GAS COOLING AND HEAT RECOVERY

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Abstract

A new concept of heat exchanger has been developed to cool down exhaust gases of aluminum electrolysis pots before entering a Gas Treatment Center (GTC). It optimizes operating conditions on a GTC, by reducing gas flow rates and enabling energy recovery. A prototype of heat exchanger was installed and tested for 12 months on five pots of the Norsk Hydro aluminum plant in Øvre Årdal, Norway. This prototype consisted of a bundle of finned oval tubes. Off-gas flows cross flow on the external side of the tubes. The oval shape is beneficial in terms of high gas-side heat transfer and low pressure drop. Fins ensure a compact design while being robust to gas-side fouling. Heat transfer characteristics were monitored and are presented. Stable and safe operation has been demonstrated with an early stage heat transfer reduction of approximately 10 to 15% due to fouling, which is lower than theoretical predictions.

Introduction

In recent years, the aluminum industry has seen its production shifting from northern countries to the GCC countries where energy is abundant and affordable. Moreover, a significant number of plants boosted their production capacity by implementing pot amperage creep programs (600kA in near future). Both of these developments have generally led to an increase of gas temperatures in Gas Treatment Centers. In fact, higher ambient temperatures, higher amperage combined with lower specific pot exhaust rates have led to an increase in gas pot temperatures now approaching 200°C. At these temperatures it is necessary to cool gases to maintain good performances in terms of fluoride adsorption by alumina [1] (HF rejections increase easily to 1 mg/Nm^3 if the gas temperature exceeds 130°C) and to protect filter bags. In GTCs these bags typically are made of polyester felt, which has a temperature limitation of 140°-145°C. Alternative media are available but extremely costly – Aramid felt resists up to 200°C but is three to four times more expensive than polyester.

Several technologies are known today for gas pot cooling [2]:

- Dilution using ambient air;
- Hairpin coolers (cooling by increasing heat exchange section);
- Water spray cooling (cooling by water evaporation);
- Heat exchangers (HEX).

The use of heat exchangers technology for gas cooling presents the following advantages:

- Very effective gas cooling (40°C or more);
- Reduction of filtration area and fan power consumption (reduction of ca. 16% compared with air dilution technology);
- It is the only cooling technology with heat recovery potential.

However, using heat exchangers for cooling pot gases requires taking up some challenges and anticipating potential risks, among which are:

- Risk of fouling;
- Risk of abrasion due to alumina;
- Risk of interruption of gas exhaustion (for example during heat exchanger maintenance);
- Risk of pressure drop increase due to heat exchangers clogging.

Therefore, selecting a specific heat exchanger technology implies to study relevant design and operation parameters, in order to cope with these limitations.

In this article, we present the results of a new, innovative heat exchanger.

HEX Tests Rig Exposition

Earlier work

HEX Tube Geometry

Important aspects when developing the off-gas heat exchanger were compactness, low gas-side pressure drop characteristics and low fouling tendencies. Additionally, the design should be modular and service-friendly. Based on field tests of several basic heat exchanger tube geometries in a small-scale test unit ([3], [4]) the preferred basic configuration for the scale-up consisted in oval tubes equipped with rectangular fins (see Figure 1). In order to ensure robust operating characteristics, the fin pitch was kept moderately close. However, early small-scale experiments have shown that even denser fin packing would operate safely with respect to fouling.

The particle-laden off-gas flows in cross flow on the external side of the tubes. The oval shape of the tubes ensures a low drag profile and the fins increase the gas-side heat transfer surface per unit tube length thereby achieving a compact heat exchanger unit. The testing of the basic tube geometry showed good resistance to fouling and abrasion from particles in the gas, as demonstrated by Næss [3].

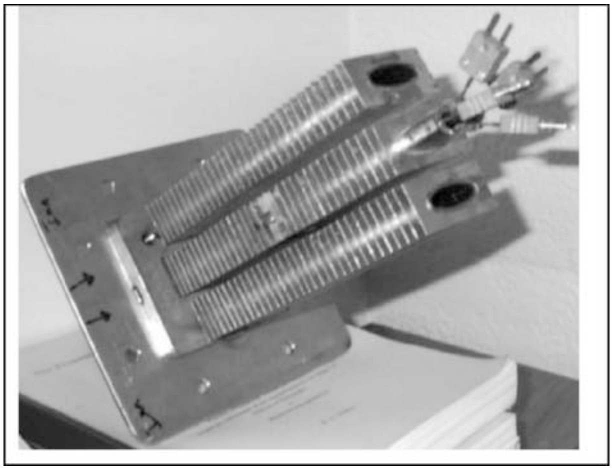

Figure 1: Oval finned tube test geometry [3]

HEX Test Facility

In order to verify the results from the small scale experiments, two heat exchangers using the same tube and fin geometry were designed and installed: The main unit (129 m^2) was to undergo an endurance test to verify long-term stability and resistance towards fouling/scaling, and a smaller unit (12 m^2) was designed to investigate the influence of flow characteristics on the heat exchanger behavior.

The main heat exchanger was installed at Hydro's test center (TOS) in Øvre Årdal, Norway, where off-gas from a series of test cells were fed through the HEX. The unit was dimensioned for a nominal gas flow rate of 68,300 m^3/h at 140°C (47,500 Nm^3/h). The main features of the heat exchanger are detailed in Table 1. The coolant inlet temperature was kept constant at 50°C in order to avoid any potential gas component condensation.

Table 1: Main heat exchanger data

Element	Value	Unit
Frontal dimension	1400x1400	mm
Number of tube rows	4	
Flow arrangement	Cross-counterflow	
Coolant	Water/glycol mixture	
Total heat transfer surface	129	m^2

The test facility was installed as detailed in Figure 2. The main off-gas duct (lower duct in Figure 2) was temporarily closed and the gas was led to the heat exchanger test facility. The off-gas flow rate through the heat exchanger was controlled by a variable-speed fan, and the surplus gas bypassed the heat exchanger through a bypass channel. The heat exchanger and coolant circuit were instrumented in order to monitor the heat duty, the gas side pressure drop and the particle concentration in gas. All data were monitored and stored at 10-minute intervals in a database.

The smaller heat exchanger, fitted with a ca. 12 m^2 heat transfer surface and a frontal dimension of 440x420 mm, was supplied with off-gas from a different line of electrolysis cells. The tube design and layout were identical to those of the main unit. The purpose of this unit was to investigate the fouling behavior at different flow rates. The instrumentation was also similar to the main unit.

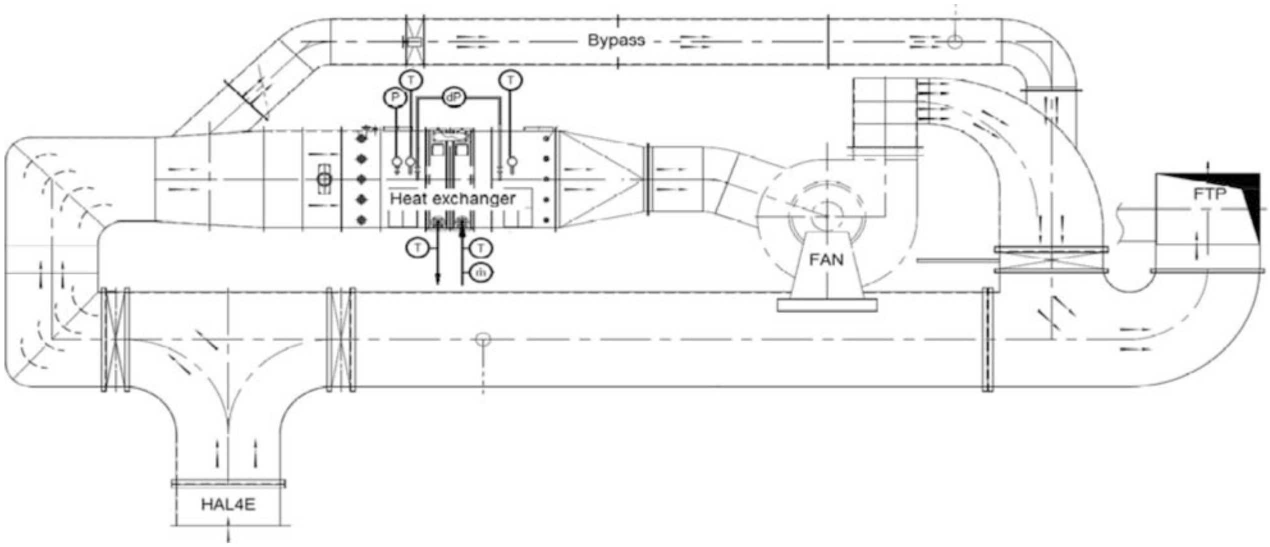

Figure 2: Heat exchanger test facility.

Test results

Main heat exchanger:

The main heat exchanger was kept at constant gas volume flow rate for a period of ca. 1 year, interrupted by a period of inspection and testing at different gas speeds lasting ca. 1000 hours. The main findings are presented in the following.

The gas and coolant temperatures at each end of the heat exchanger are shown in Figure 3. As observed, the gas inlet temperature was lower than anticipated, due to circumstances related to the electrolysis cell operation. The coolant inlet temperature was maintained at 50 ±0.5 °C, effectively avoiding any moisture condensation on the gas side.

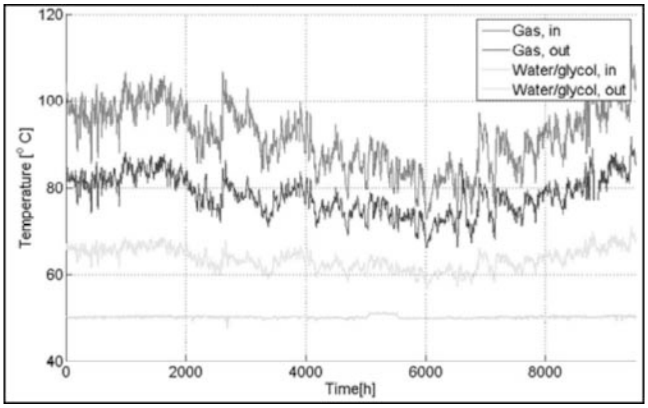

Figure 3 Process temperatures during the test run

The development of the overall heat transfer coefficient (U) is depicted in Figure 4 and defined as

$$U = \frac{Q}{A_{tot} \cdot LMTD} \qquad [W / m^2 \cdot K]$$

Where Q is the heat duty, A_{tot} is the total heat transfer surface and LMTD is the mean temperature driving force. In the figure, U_0 is a reference value. It is observed that the overall heat transfer coefficient decreases for the first period (ca. 2,000 hrs), after which it becomes constant. The reduction is associated with particles depositing on the downstream side of the tubes (in the wake region). When a stable layer is formed, there is no more net particle deposition, and the heat transfer coefficient stabilizes. As observed, the reduction in heat transfer coefficient due to particles settling is moderate, in the range of 10%. This reduction in heat transfer is in agreement with the theoretical predictions [4].The period of ca. 2,500 - 3,500 hrs in Figure 3 represents a period of heat exchanger inspection and testing, where the gas side flow rate was significantly reduced. During this period, more particle deposition was anticipated. It is of importance to notice that when the gas flow rate was increased to nominal value again at ca. 3,500 hrs, the heat transfer coefficient increased to the same value as before the reduction of flow rate, and remained roughly constant for the remaining test period. This is an indication that any additional particles that may have deposited during the lower gas flow rate period were effectively removed when the flow rate was increased again, building confidence to the robustness of the heat exchanger long-term stable operation.

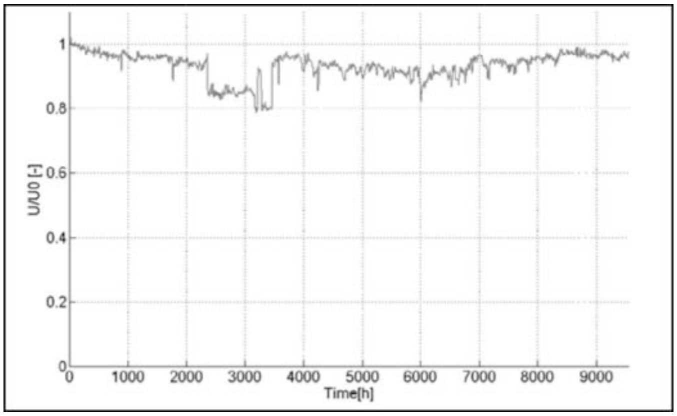

Figure 4: Development of the overall heat transfer coefficient

The corresponding development of the pressure drop across the heat exchanger is shown in Figure 5. The pressure drop seems to follow an asymptotic behavior stabilizing at approximately 33% above the initial (clean) value. This increase in pressure drop is considered acceptable. Part of the increase in pressure drop was due to debris (insulation pieces etc.) collecting at the front surface of the heat exchanger, which was easily removed.

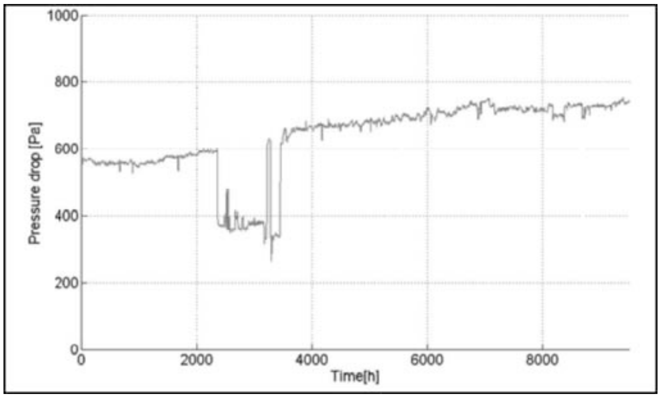

Figure 4: Development of the gas side pressure drop

At the end of the test (ca. 9,500 hrs), the heat exchanger was stopped for inspection. The visual inspection showed very little fouling of the upstream side of the heat exchanger (see Figure 6), and only moderate on the downstream side (Figure 7). On the downstream side, dust had formed a small wing-shaped profile behind the tube; otherwise the heat transfer surface was virtually clean, aside from a thin layer of scaling and small amounts of debris collecting on the upstream side of the heat exchanger.

The visual inspection revealed no signs of erosion or mechanical wear on the test unit, confirming its mechanical integrity.

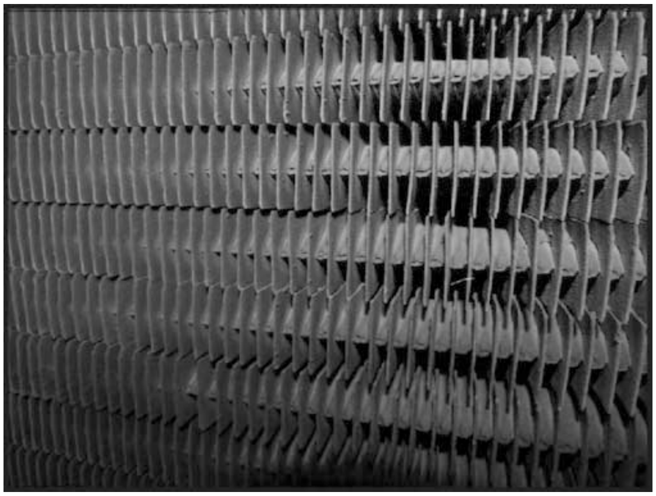

Figure 6: View of the heat exchanger after ca 9000 hrs operation, upstream side

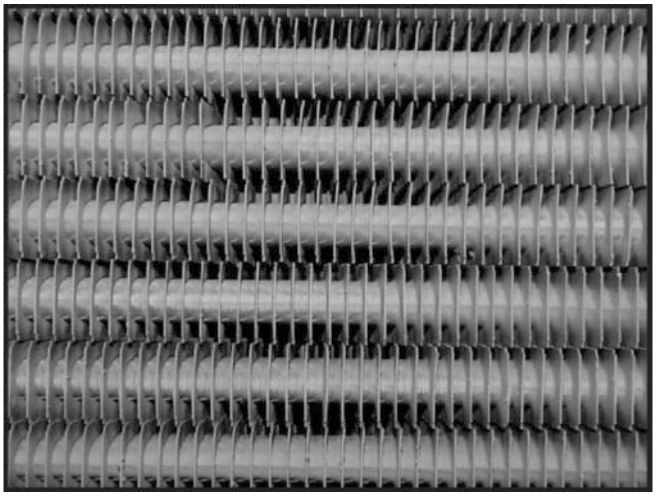

Figure 7: View of the heat exchanger after ca 9000 hrs operation, downstream side.

Since heat transfer reduction due to particle deposition is small (in the range of 10%), and the associated increase in pressure drop is also limited (ca. 33%), the need for on- or off-line cleaning seems limited as well. Based on the observation that both heat transfer coefficient and pressure drop seem to stabilize at asymptotic values, the need for cleaning, at least in the present installation, is not really an issue. However, in more severe environments, where higher fouling rates may be encountered, on- or off-line cleaning can be achieved by brushing or compressed air jet cleaning, as the observed deposits are fluffy and easily removed. Therefore, in order to maintain its performances, it is recommended to clean the exchanger in situ by compressed air every six months and outside by chemical cleaning every two years only in severe environments. This does mean a level of redundancy has to be included in the design.

Small-scale unit

The small-scale unit (12 m^2) was operated at different gas flow rates of nominal and nominal ±20%, where nominal represents the same gas velocity as in the larger unit. Basically, the test at nominal gas velocity confirmed the behavior of the larger unit, having a moderate and stabilized reduction in the apparent heat transfer coefficient (14%) at nominal operating conditions, and a negligible change in pressure drop during a 1400 hr test run.

Increasing gas velocity to nominal+20% showed similar behavior with regards to fouling as for the nominal case, but with a stabilized 14% increase in pressure drop during the ca. 1300 hr test run.

Changing the gas-side velocity to nominal-20% showed a negligible increase in fouling relative to nominal case, but a 30% increase in pressure drop over a 1200 hr test run.

Visual inspection of the unit showed no signs of mechanical wear or damage of any kind, adding trust to the long-term mechanical integrity of the unit.

Conclusion

This experimental work has demonstrated the capacity of elliptical design of tubes to ensure an optimum performance of aluminium gas pot cooling during long periods (stable heat transfer and low pressure drop). The parameters of heat exchanger operation enable an auto-cleaning of the heat exchanger with limited fouling.

The elliptical design of heat exchanger tubes with fins offers the possibility to use a very compact heat exchanger with very limited length (lower than 600mm for gas cooling with $\Delta T = 40°C$). This compact design allows integrating easily a heat exchanger in new gas treatment centers and in existing smelters, in case of an aluminium production capacity increase, with limited modification works.

In the future, additional tests will be carried out on wet and hot exhaust pot gas in Gulf countries smelters

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