Enabling efficient heat recovery from aluminium pot gas

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Abstract

In the present work, previous studies carried out by the Norwegian aluminium industry and research centres with the aim of recovering heat from aluminium production off-gas, are reviewed. The main challenge in improving heat recovery is the fouling phenomena, which is due to the presence of particulate matter and corrosive gases in the off-gas. Fouling can occur due to particle deposition, condensation of corrosive acids and scaling reactions, which in turn can build up hard layers, particularly, on heat exchanger surfaces.

The review focuses primarily on fundamental studies (theoretical and experimental), which address off-gas composition characterization, particle size distribution and particle deposition phenomena in laboratory and industrial environments. Moreover, it presents commercial concepts already implemented in industry applications. Upcoming activities in regards to the scaling phenomena, which include the design of a cold-finger for laboratory and industrial measurements, as well as mathematical modelling using CFD, are also discussed.

Keywords

Aluminium Industry, Heat Recovery, Fouling, Scaling, CFD

1 Introduction

The impact of human activities on the environment is ever more noticeable as new economic powers are emerging and becoming rapidly industrialized. Governmental regulations are becoming more stringent in order to avoid harmful emissions and to enforce a better use of available resources and energy. A large share of emissions and energy loss can be tailored to different types of industry, which have some things in common. On one hand, they are responsible for a huge amount of low temperature (80-150 °C) waste heat loss to the environment. Recovery of such heat for useful purposes (e.g. power production, district heating, etc.) is a challenge since highly efficient heat exchangers are required in order to keep high enough temperature levels for practical utilization. Additionally, heat recovery is usually hindered by fouling phenomena caused by the unclean nature of industrial effluents carrying the waste heat.

Fouling is a general term that refers to the unwanted deposition of solid layers on surfaces, which reduce heat transfer and may cause clogging problems amongst other issues. Such layers can develop from different mechanisms that are unique for every process but that share some characteristics. Some examples would be deposition of particulate matter, scale formation from chemical reactions, biofouling, corrosion and combinations thereof [1, 2]. Direct precipitation from supersaturated species can cause the growth of crystal layers strongly adhered to the heat exchangers walls. Such layers can cause subsequent reactions with other chemicals and increase the adhesion of particulate matter. Further aging reactions can also generate complex multi-phase structures. Fouling is very costly for industry due to units oversizing, degradation, maintenance and cleaning-induced downtime.

In order to tackle these issues and others, the Norwegian Research Council has launched an ambitious research centre (SFI metal production [3]) managed by the Norwegian University of Science and Technology (NTNU) in conjunction with relevant partners from the metal industry (ferroalloys, aluminium and titanium), academic institutions and supply industry. The centre was started on April 2015 and will go on for eight years with a total budget of 247 million NOK with the objective of developing new production processes that are more environmentally responsible and more energy and cost efficient.

The present paper, which has been produced within the SFI metal production, has the objective of analysing previous work performed within the consortium and identifying challenges ahead in the field of heat recovery from aluminium production off-gas.

2 Fundamentals

This section presents studies that focus on the description and understanding of different fouling mechanisms (i.e. particles motion, adhesion, re-suspension, bulk behaviour, chemical reactions, etc.) both using theoretical and experimental approaches.

2.1 Theoretical models

The first step required in the development of mathematical models that can reproduce complex multi-phase systems is the understanding of the relevant underlying physical principles. This is performed by defining the governing equations, which should account for the interactions between particle-fluid, particle-particle, particle-wall as well as external forces. Two main modelling frameworks exist for the description of the physical governing equations accounting for fluid and particles motion; namely Eulerian and Langrangian descriptions.

The Eulerian framework treats both phases as a continuum in a macroscopic scale. Space is discretized in fixed nodes where fluxes of mass, momentum and energy are computed to obtain the distribution of mass, velocity and energy among others in the problem domain. The Eulerian framework allows for separate description of fluid and particles flow, which can be computed in parallel. The fixed mesh shows advantages when simulating high materials deformation (i.e explosions, high velocity impacts) compared to the Lagrangian approach. However, this description gives access to limited information on particles and fails to describe transient dynamics of multilayer formation from a microscopic point of view. Moreover, it is difficult to treat irregular geometries and it requires complicated mesh generation procedures [4, 5].

Lagrangian methods on the other hand involve trajectory calculations typically for a large number of particles moving in a fluid turbulence field, which can be generated with different methods. Different subclasses exist within this frame ranging from models that can resolve interactions between all particles at a microscopic level to models where statistical averaging is used to define mean-fields affecting the different particles in a mesoscopic scale. Whereas the former models can give insight to detailed mechanisms for particle deposition and resuspension, they cannot be scaled to real inhomogeneous 3D systems. Mesoscopic models using "one point probability density functional" could however have the potential of describing complex systems with a larger level of detail than Eulerian models [6] and yet be applied to complex real size systems. Rapid increase in CPU power is making this field ever more attractive. The main issue when modelling particle deposition is the description of the complex events occurring in the near-wall region. Different methods are used to try and describe the boundary layer problem ranging from simple fully absorbing walls to models were adhesion and re-suspension mechanisms are introduced.

In an article published in 1990 by Johansen [7] an Eulerian-Eulerian one-dimensional model was presented to study particle deposition on fully absorbing vertical wall. The main objective was to study the influence of the turbulent migration and the transversal lift on the deposition rate. Results were validated against experimental data from the literature. The model represented deposition data very well and could account for the large scatter of experimental values found in the literature (3 orders of magnitude difference for particle deposition from different studies) which could be assigned to different particle relaxation times (proportional to particle size). Reynolds number, electrostatic charging of particles and Brownian motion were also found to play a significant role as well.

The model was extended to account for the effect of temperature gradients on particle deposition [8]. Re-entrainment of particles hitting the wall was also introduced by considering that deposition could not occur if the shear force (proportional to fluid velocity) acting on the projected area of the particles exceeded the thermophoretic adhesive force. Results showed that the introduction of re-entrainment produced results in excellent agreement with experimental data as can be seen in Figure 1.

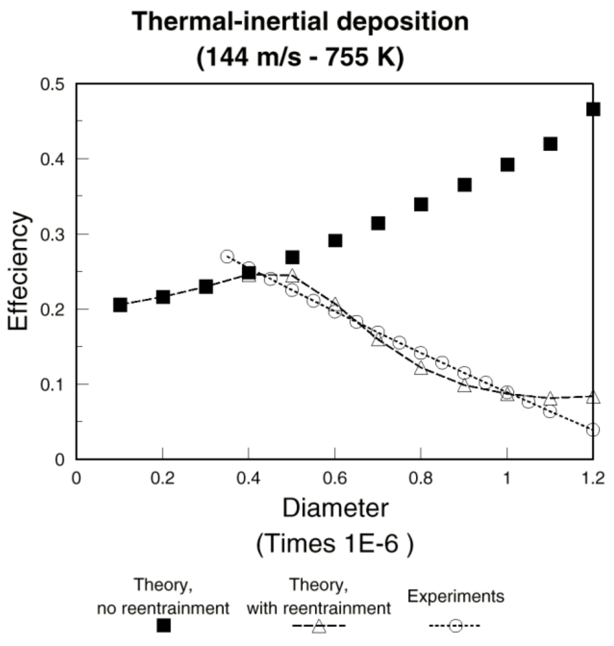

Figure 1 Thermal-inertial deposition of particles [8].

Years later the near-wall effects where specifically addressed by Johnsen and Johansen in [9] where a detailed boundary layer model was presented which could be applied as boundary condition for coarse grid computational fluid dynamic (CFD) models. The one-dimensional boundary layer was solved numerically in a fine grid capable of resolving the near-wall XDLVO force lengths scales.

The model reproduced the typical deposition rate versus particle relaxation time plot but was not further validated with experimental data. The effect of various physical phenomena like turbulence, granular pressure and XDLVO forces as function of distance from the wall were studied for different particle sizes. Results showed that dominant mechanisms varied depending on region and particle size. Close to the wall XDLVO forces were dominant suggesting that achieving surface repulsive forces (i.e. using coating) could prevent fouling.

In another paper published on the same year [10] the same authors modified the model to account for particle wall adhesion/re-entrainment by using an adhesion probability derived from a turbulent shear stress probability function. Results showed that in general deposition rate will increase for increasing fluid velocities until shear induced re-entrainment rate becomes of the same order as deposition rate. Moreover, large particles were found to be more easily re-entrained than smaller particles due to weaker adhesive forces. Finally, results were compared with two experimental studies with satisfactory results but it was concluded that further development to handle thermo-chemical behaviour was required.

The previous models described above lack the possibility to account for chemical reactions that are often involved in the fouling process phenomena. The presence of gas species that might become saturated upon cooling in heat exchangers can cause their precipitation in heat exchanger walls thereby causing corrosion problems and enhanced stickiness and reactivity of the walls. This issues were addressed by Johnsen et al. [11] by development of a generic modelling framework to investigate the diffusive mass transport through the turbulent, reactive boundary layer of multicomponent fluid mixtures precipitating in a heat exchanger wall. In the same manner as the article previously described, this framework can be used as boundary layer for coarse grid CFD models. A fully developed flow was assumed parallel to the wall and 1-dimensional equations for species and heat transport perpendicular to the wall were formulated. Fluid mixture properties required in the modelling framework were based on the pure species properties. Future work will involve implementation of the current modelling frameworks via user-defined functions, in commercially available CFD software.

2.2 Experimental studies – particle characterization and deposition

The level of complexity of theoretical models is increasing rapidly but there is still a big gap when trying to describe and predict phenomenon occurring in industrial environments. For the particular case of aluminium off-gas difficulties arise due to both the complex interaction between particulate and gaseous compounds present in the off-gas together with the composition variability that occurs during cells operation. This variability is smoothed as pipes from different sections are joined into larger ducts eventually leading to the gas treatment facilities. However, it is desirable to perform heat recovery as close as possible to the heat source in order to reduce the amount of heat loss to the environment.

This section will present experimental results obtained in the last years in collaborative projects between the Norwegian aluminium industry and research centres. The aim of those studies, besides the understanding of the deposition and clogging phenomena, is also to obtain a better knowledge of the process material and energy balances in order to improve materials recycling, product purity and emissions control among others.

2.2.1 Laboratory tests

Different laboratory studies have analysed the deposition and resuspension phenomena of a particle-laden gas into different substrates mimicking real life tubes and heat exchanger walls.

A probe to monitor gas-side fouling in cross-flow heat exchangers was developed and tested in NTNU laboratory experiments in 2002 [12]. The probe was designed to monitor both heat flux and mass accumulated on the front and rear side (with respect of the incoming gas) of a cylinder in cross-flow. Results showed that heat transfer was larger in the front side for clean air (without particles) due to the increased thermal convection given the higher gas velocities in this side. It was also found that the deposition layer and measured fouling resistance was larger in the front side of the tube.

In 2012 a wind tunnel rig was designed and built in NTNU to investigate in more detail deposition and resuspension mechanisms using both commercial (mainly of silicon oxide and aluminium oxide) and industrial particles (aluminium oxide). [13]. Velocity field inside the test section was measured by means of Pitot static probes and Laser Doppler Anemometry (LDA). Moreover, mass deposition was studied by gravimetric means using probes and by optical means using a camera to visualize deposited layer thickness. Similar kind of experiments were performed in the same rig by NTNU master students [14], [15] and [16] which were also combined with theoretical simulations. The circular probe developed by Temu et al. [12] was used for the fouling experiments. Results for the velocity field measured in the test section with the cylindrical probe by LDA compared to simulations using 2-D COMSOL software can be seen in Figure 2. Both results show the typical wake velocity profiles in the front (left) and rear (right) side of the tubes with respect of the incoming gas. Experiments were run for 45 minutes under isothermal conditions and particle deposition was only observed in the front side (incoming gas). No additional growth was observed after the first 15 minutes.

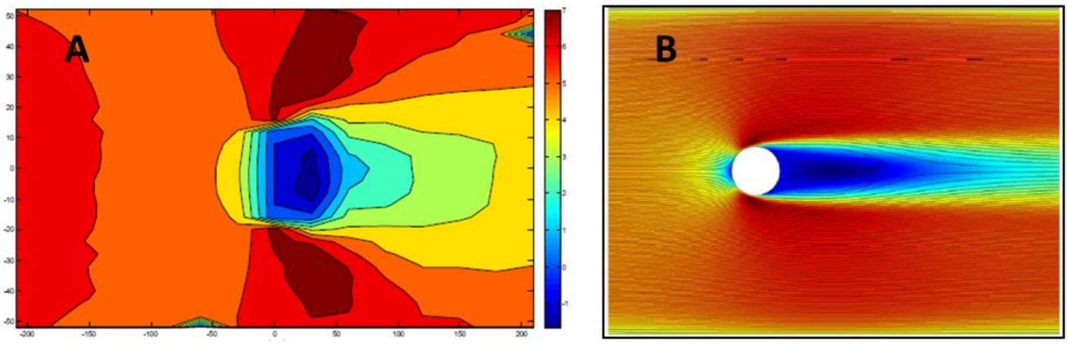

Figure 2. Flow velocities of the test section with a circular cylinder probe measured by LDA (A) and simulated using 2-D COMSOL software [13].

2.2.2 In-situ tests in industrial plants

The experiments presented in the previous section are valuable to get a better understanding of the fundamental mechanisms that govern particle deposition and resuspension but they only represent idealized systems that deviate substantially from real cases. Experiments in real plants are therefore necessary to characterize the composition of the different species present in the off-gas and to identify which ones are involved in the fouling process.

In a study by Næss et al. in 2006 [17] a test section was built where two different probes could be used to monitor fouling effect on heat transfer over time. Both probes were cylindrical, one of them having an annular fin. Off-gas from aluminium smelting process was iso-kinetically extracted from the centre of a duct leading to the bag filters, and circulated through the test section before being redirected to the duct. The transport pipe was wrapped with electric wires that could increase the temperature of the off-gas before entering the test section from 120 °C to 180 °C. Particle size distributions were measured using a cascade impactor in both the main off-gas duct and test section giving similar results, with 70% (by mass) of the particles being in the submicron range. The average particle concentration was found to be 195 mg/Nm^3 for the test section and 300 mg/Nm^3 for the main duct. The discrepancy was partly justified for the loss of larger particles in the extraction of the gas in the test section. Acid dew point was reported to be approximately 42 °C. Therefore, experiments were run keeping wall temperatures between 60-70 °C to avoid corrosion issues and increased deposition due to the enhanced particle sticking in wet conditions.

Experiments were run for over 1500 hours where heat transfer was decreased asymptotically until stable conditions were reached. For both geometries a massive deposition of particles was observed in the rear side of the tubes where the shear forces are minimum due to the tube shading effect. This effect is opposed to the ones observed in laboratory experiments were deposits in the rear side were minimal [12, 13]. The reason for this discrepancy is not clear and should be further investigated. Differences in the test section geometries and increased complexity of particle size distribution and chemistry for the industrial case might be important contributions explaining such different behaviours. Both geometries displayed very close heat transfer behaviour even though the fouling resistance was larger for the fin case. That was due to higher fin efficiencies when fouling increased, which compensated the higher resistance. Experiments at different superficial mass fluxes revealed that fouling was minimized at larger gas velocities and that stable conditions were reached more rapidly as can be seen in Figure 3.

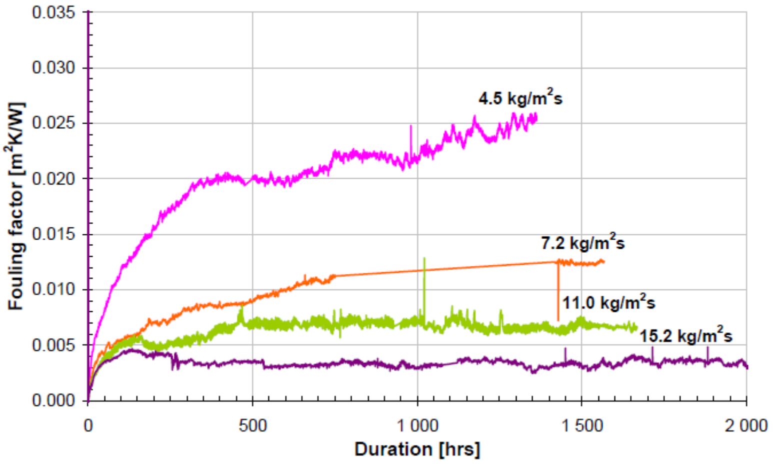

Figure 3 Fouling factor versus time for the annular-fin test tube at various superficial mass fluxes [17].

The effect of thermophoresis was also investigated by using different gas temperatures. Results determined an increase of 18% in the fouling factor due to 17% increase in the mean temperature difference between the off-gas and the pressurized air circulating inside the probe. Results from this study suggested that heat exchangers that could reach stable and acceptable fouling conditions need mass fluxes that are above 10 kg/m^{2}s. This means that local gas velocities in narrow gap regions would be in the range 20 m/s, which could cause erosion problems due to particle impaction and high gas pressure drops. This might increase fan power consumption to undesired levels.

In an NTNU master thesis from 2008 [18] an isokinetic sampling system was built and used to measure particle concentration from the pot gas of the Hydro aluminium plant in Sunndal. The particle concentration in the flue gas from 56 electrolytic cells was found to be 363 mg/Nm^3 with a standard deviation of 12%, which is in good agreement with the study by Næss et al. presented above.

In 2010 in situ measurements were performed to characterize the flue gas in the aluminium plant of Nordural during a master thesis from the university of Reykjavík [19]. Measurements were performed at the stack leading to the gas treatment centre where gas from 180 pots was gathered. A system for isokinetic sampling was built to collect particulate samples, which were analysed by several means. A pitot tube was used before each run to determine duct gas velocities, which were found to be in the range of 14-17.5 m/s.

Chemical composition analysis by an Energy Dispersive Spectrometer (EDS) coupled in a Scanning Electron Microscope (SEM) showed that the dust mainly contained carbon, oxygen, fluorine and aluminium. Notable amounts of sodium and some trace amounts of sulphur, potassium, calcium, iron and nickel were also detected X-Ray Powder Refraction (XRD) was used to identify the different crystalline phases of the particles. Results showed that the solid matter mainly consists of alumina followed by cryolite (Na_3AlF_6), chiolite ($Na_5Al_3F_{14}$) and kogarkoite ($Na_3(SO_4)F$) with trace amounts of fluorite (CaF_2) and sodium aluminium fluoride ($NaAlF_4$).

In addition, a Macro Elemental Analyzer (MEA) was used to measure the concentration of organic carbon in the samples, which was found to be 15.7% of the total particles mass. It was pointed out that this value might have been larger than usual since some cells were experiencing anode problems. Particle size and dispersion were measured by SEM and with a Laser Diffraction Meter (LDM). An average particle size by volume of 18.5 µm was found. Moreover particles with equivalent diameters between 4.5 to 61 µm represented 80% of the total mass which is a rather large discrepancy from the results reported by Næss et al. (2006) [17]who reported 70% of the mass corresponding to particles in the submicron range.

Finally, particulate deposition on a probe showed similar results for both upstream and downstream deposits compared to the samples extracted with the isokinetic sampling system.

The particle sampling methods employed in the above study give a good insight on the overall particulates composition but fail to provide with information regarding the amount, composition and size distribution of the individual particles. With this purpose in mind, an electrical low pressure impactor was used in a PhD thesis to perform experiments in the aluminium plants of Alcoa Mosjøen and Hydro Sunndal [20]. This innovative technique allows for online monitoring of the particle size distribution by charging the particles before entering the impactor section, which separates them by size. The use of suitable substrates in the impactor allows particle collection for further characterization. Different publications from that thesis are presented hereby.

In 2011 the Electrical Low Pressure Impactor was used to sample particles from aluminium raw gas extracted from two different sites [21]; on one hand from the main duct of a production line before the dry scrubber and on the other hand from the stack between the dry and wet scrubbers. This equipment allowed for real-time sampling of 12 particle classes divided in the size ranges between 7nm and 10 µm. Results showed that larger number of particles were measured with the impactor equipment in the sub-micron range than were previously reported in a study using SEM for that purpose [22]. SEM images of the size-classified particulates revealed a change in agglomerate morphology for the different particle size classes.

In another publication next year the same author investigated the effect of different operational conditions on presence of impurities of ultra-fine particles (<10 µm) using a similar methodology as described above [23]. Energy dispersive spectroscopy (EDS) and mass spectroscopy (HR ICP-MS) analysis revealed a significant increase in contaminant level for particles with diameters larger than 0.75 µm. The findings indicated that particles with diameters lower than 1.2 µm consist mainly of quenched bath fumes $NaAlF_4$, $Na_5Al_3F_{14}$ partly converted to $NaAlF_6$ and AlO_3. The effect of distributed point suction (DPS) was also investigated but although the suctions rates were drastically changed, the variation between recorded mass-concentrations of different measurements were surprisingly small.

2.3 Experimental studies – Scale formation

Scaling is the formation of hard and strongly adhered layers on surfaces due to reaction of chemicals. Usually many components and operational factors may influence the creation of such layers. The fact that the effect of scaling may go unnoticed for long periods of time makes it difficult to predict its formation and growth. Scaling in aluminium production industry appears in the form of an amorphous "hard grey scale" (HGS) which forms in high attrition areas such as dry scrubbers and some transport pipes. Its accumulation reduces gas removal efficiency, hinders alumina transport causing clogging in some extreme cases and reduces filters life among other issues.

In 2008 Dando and Lindsay [24] presented a study aimed to define the chemistry and formation mechanism of HGS. Samples of HGS were collected from numerous Alcoa smelters worldwide and some pictures were presented which can be seen in Figure 4. Chemical composition of HGS was studied by means of X-Ray diffraction whereas synthesis mechanisms were investigated by successfully synthesizing HGS from smelting materials in a laboratory. A key mechanism for HGS formation seems to be the creation of alumina high-energy surface induced by inter-particle collisions, which upon rapid and exothermic reaction with water creates local elevated temperatures that induce further reactions with alumina fines and bath superfines.

Results based on elemental composition showed that alumina, sodium and fluoride accounted for over 90% of the total mass of hard grey scale, which suggested that scrubber scale is formed principally from alumina and bath fines together with minor contributions from adsorbed fluoride and bath fumes ($NaAlF_4$).

Figure 4. Samples of hard grey scale

Another study from 2013 [25] which investigated trace element concentration from pot exhaust and from depositions in fume treatment facilities agreed in the following result reported by the work on hard grey scale presented by Dando and Lindsay [24]. Both studies pointed out that the composition of particulate solids collected at the inlet of an injector scrubber shows similar chemical composition than the hard grey scale which deposits in scrubbers, despite the higher degree of crystallinity and higher carbon and sulphur content.

In this study, a cyclone was used to sample particles that were analyzed by mass spectroscopy (HD ICP-MS). It was observed that impurities concentration increased in the coarse fraction of the samples (>1 µm). It was also concluded that soluble glass forming elements in the raw gas such as Na, K, Si and loosely bound surface water of the alumina are key ingredients for the formation of an amorphous binder matrix as scale forming elements settle and moisture condensates at designated areas in the fume treatment facilities.

A follow-up study presented by the same authors in 2014 [26] further compared chemical composition and crystalline structure of pot exhaust particles and scale samples collected from the gas treatment centre of the same aluminium smelter. Samples were analysed by means of different X-ray and mass spectroscopy techniques (XRF, XPS, XRD, ICP-MS) as well as IR spectroscopy. A new mechanism for recrystallization of sodium fluoro-aluminates due to HF adsorption reactions in combination with moisture was suggested.

3 Available commercial solutions

This section presents commercial concepts that have been already built with the aim of actively cooling down the aluminium pot gas by the use of fouling-resistance enhanced heat exchangers.

3.1 Alstom funnel heat exchanger design

A patent was developed by Alstom in 2011 [27] with the objective of reducing fan power requirement to drive flue gas through the cleaning system. It is based in a branched system of ducts drawing pot gas from individual electrolytic cells that merges in a common duct. The system was designed to accelerate the gas flow right before the merging so gas velocity from individual branches is larger than the gas velocity from the main duct.

The idea is that individual regulatory flaps placed at the end of each individual branch may replace dampers that are used to regulate pressure drop across duct transporting gas from all cells. Thus, a distributed and more efficient control of flow conditions in each individual electrolytic cell may be achieved.

Moreover, individual heat exchangers are placed at every individual branch right before the merging with the main duct. Funnel shaped inlet channels will cause gas acceleration which besides aiding pressure drop regulation as mentioned before, will enhance heat recovery due to larger heat transfer caused by higher turbulent regime and lower particle deposition rate.

3.2 Advanced fume treatment with waste heat recovery: Alstom

Alstom also developed a fume treatment method [28] with heat recovery by circulating cooling water during the scrubbing with alumina. The company claimed higher efficiency in pollutant capture with lower emissions of HF and tars including PAHs. The system does not increase humidity, which significantly reduces corrosion, tar deposits and filter bag hydrolysis.

3.3 A method and equipment for heat recovery: Patent Hydro-NTNU

A prototype for heat recovery from flue gas was presented in a patent in 2013 [29]. Flue gas from aluminium industry was used in experiments conducted to find optimum gas velocities to minimize particle deposition and pressure. Heat exchanger design consisted of circular or elliptical tubes and rectangular fins.

Gas and tube wall temperatures in the experiments were set around 130 °C and 70 °C respectively. Results showed that stabilization of heat transfer due to fouling was achieved between 50-500 hours of operation. Gas velocities at acceptable output conditions were found to be 12 m/s or higher.

Results with such prototypes were also presented in a conference in 2013 [30]. A large (129 m^2) and small (12 m^2) were installed and tested in a Hydro test facility in Årdal. Heat duty, gas side pressure drop and particle concentration in the gas were monitored during 9500 hours tests. Results showed little fouling at the upstream side of the heat exchanger and only moderate on the downstream side where dust had formed a small wing-shaped profile behind the tube. A thin layer of scale and small amounts of debris were also found in the upstream side of the heat exchanger.

3.4 Fives Solios heat exchanger prototypes installed in Årdal (Hydro)

Two Heat exchanger prototypes following the lab-scale concepts described above were installed in the Norsk Hydro aluminium plant in Øvre Årdal with operational results presented in 2014 [31]. Decrease of heat transfer coefficient over time due to fouling was around 10%, lower than the theoretical predictions. Pressure drop increased by 33% in an asymptotic manner and the authors recommend occasional cleaning of the heat exchanger with compressed air. The heat exchanger has a segmented configuration that allows switching of the different parts by clean ones while cleaning procedures are applied. Future work was planned to test the heat exchangers in more severe conditions, i.e. on wet and hot exhaust pot gas in Gulf countries smelters.

4 Cold finger design and planned PhD activities

The present review has shown that quite some effort has been spent in characterizing the complex mixture of gas and particulate matter generated by the electrochemical aluminium production cells. There are still many uncertainties regarding mechanisms for scale formation and growth. The influence of different operational conditions on scaling is not well understood and that makes this phenomenon difficult to predict. Future process modifications such as the distributed pot suction (DPS) will offer increased potential for heat recovery from aluminium pot gas at higher temperatures but at the same will present challenges when dealing with higher dust and hazardous gas concentrations.

In order to advance in the understanding of the scaling phenomenon under the current and future conditions a cold-finger will be built with the following objectives in mind:

- Reproduce heat exchanger conditions in terms of tube size and geometry, gas velocity and temperature
- Equipped with sensors in order to monitor heat transfer, gas velocity and dew point among others
- Collect scale deposits for further analysis
- Obtain relevant experimental data for CFD models validation

As mentioned in section 2.1 an Eulerian-Eulerian approach will be initially used for the modelling of the test section. Upgrading of the current boundary models from 1 to 2 dimensions will be necessary to assess deposition rates for flow directed towards the wall as opposed to the parallel flow described so far. This model will then be coupled with a CFD coarse grid model of the test section by using function calls. In this manner, different particle sizes will be computed in parallel calls producing an overall deposition rate that will be compared with the experimental results.

Particle size distributions from previous studies will be used as inputs for the model although new measurements in the same experimental site would be desirable and hence will be pursued during the planning phase of the project. Lagrangian methods for particle transport and deposition might be considered in a later stage of the PhD in order to locally predict the formation of scale deposits with a mechanistic model. Characterization of scale samples at different timeframes will be carried out to get a better understanding of the composition of the primary scale layers and their evolution over time. Laboratory experiments using "lab-smelters" which can reproduce industrial off-gas conditions under controlled and known particle/gas compositions will be used to investigate under which conditions scale forms and to correlate those results with those obtained from industrial sample analysis.

Velocity profiles in the test section are also an important input required for the models. Measurement of duct velocities by means of a Pitot tube will be performed in the same hatch for gas extraction prior to the measurements. This is important in order to choose a suitable nozzle diameter for isokinetic extraction of the off-gas [20]. A fan or an ejector will be placed downstream of the test section in order to regulate the volumetric flow and thus assess the effect of different gas velocities in the deposition profile and composition.

The cold-finger will be designed in a tube in tube configuration with two tubes staggered in two discs at both ends of the tubes, which can be clamped at the walls of the test section. Tubes clearance between themselves and the walls will be fixed around 1 cm making the flow conditions relevant for flow across a tube row. There are currently two possible working fluids under consideration. On one hand the use of pressurized air offers a safe and cheap choice which has been used in previous industrial tests [17, 19]. On the other hand the possibility of using pressurized CO_2 will also be assessed as this fluid could be potentially used in a supercritical power cycle system for power production in the future. The use of water is strictly forbidden in the potroom but could be considered as well if the experiments were to be performed in the large joining ducts in front of the dry scrubber in the outer courtyard zone.

Measurement campaigns will be designed in order to study short-term and long-term exposure effects on surface fouling. The effect of distribution pot suction (DPS) will also be investigated by performing experiments in the DPS test cells available in the Hydro aluminium plant in Årdal.

5 Conclusions

Mitigation of fouling is desired in many industrial processes as it supposes a great cost in terms of units degradation and maintenance-induced downtimes. Research efforts on the topic from the Norwegian aluminium companies, providers and research centres have been reviewed with the purpose of designing future work ahead.

In aluminium industry, fouling is caused by particle deposition in low velocity regions and by scale formation in high attrition areas. Both phenomena have been observed in previous experimental studies trying to emulate heat exchanger conditions. The mechanisms behind scale formation are still not well understood, however fouling mitigation is key in designing novel efficient heat exchangers.

Some commercial heat exchangers exist with the aim of cooling down the gas before the filters. However, those concepts are not efficient enough from the perspective of further heat utilization (especially for power production). In conclusion, future efficient heat exchanger designs will require better understanding of fouling and scaling formation in order to find geometrical and operational conditions that can minimize its detrimental effects. In this regard, the plans for a future PhD candidate within the SFI metal production project have been described which include the design of a cold-finger rig for industrial measurements and theoretical modelling of the fouling effect using computational fluid dynamics based models.

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