Journal of Aerosol Science 104 (2017) 43–57

Contents lists available at ScienceDirect

Journal of Aerosol Science

journal homepage: www.elsevier.com/locate/jaerosci

Real-time aerosol measurements in pilot scale coal fired post-combustion CO_2 capture

Chiranjib Saha*, James H. Irvin

Southern Research, National Carbon Capture Center (NCCC), 31800 Highway 25 North, Wilsonville, AL 35186, USA

ARTICLE INFO

Keywords:
Aerosols
CO_2 capture
ELPI$^+$
Pilot plant

ABSTRACT

Coal fired plants account for nearly 40% of the world's electric power generation and are a large source of CO_2 emissions. Post-combustion CO_2 capture using amine based solvents is a relatively mature technology. Recent pilot plants test data indicate that amine and its degradation produce emissions in the form of aerosols, which must be controlled for commercial success of this technology. In this study, the aerosols from CO_2 depleted flue gas at the National Carbon Capture Center (NCCC) Pilot Solvent Test Unit (PSTU) and Slipstream Solvent Test Unit (SSTU) were measured using an isokinetic probe and a Dekati Electric Low Pressure Impactor (ELPI^{+TM}). Multiple tests were conducted to quantify the effects of different process changes. PSTU measurements demonstrated sample sensitivity to transient intercooler start-up conditions, dilution gas temperatures and absorber beds in operation. During this test, the typical concentration (expressed in number of particles per volume) ranged from E+06 to E+07 cm^{-3} and the peak occurred near 0.12 μm with an observed increase in sub 0.01 μm aerosol concentration during transient intercooler start-up conditions. The measurements also demonstrated sample sensitivity to dilution gas temperatures by showing that aerosol size and concentration peaks shifted at higher diluter operating temperatures, especially above 100 °C. Several tests were also conducted at the absorber inlet and wash tower outlet of the SSTU with varying dilution ratios and temperatures. Comparison of SSTU and PSTU results are presented in this paper. The stage cuts for different impactor stages of different ELPI$^+$ instruments are calibrated which showed minimum deviation in the range of 0.02–0.70% from original calibration. Generally, the concentrations were higher at the absorber inlet compared to the wash tower outlet. Also, a higher concentration was observed for the smallest size fraction at the wash tower outlet compared to the absorber inlet. Similar to the PSTU, the concentration measured at the SSTU was in the range of E+06 cm^{-3}. These results are promising and will enable the development of process control strategies to mitigate solvent losses and reduce operational and maintenance expenses.

1. Introduction

Coal currently accounts for the 40% of world's electric power generation because it is an abundant fossil fuel and geographically well spread. This role of coal is expected to continue in the foreseeable future. Being carbon intensive, coal results in large CO_2

Abbreviations: CPC, Condensation Particle Counter; DOE, Department of Energy; ELPI, Electrical Low Pressure Impactor; HT, High Temperature; MEA, Monoethanolamine; MW, Megawatt; NCCC, National Carbon Capture Center; PDI, Phase Doppler Interferometer; PSTU, Pilot Solvent Test Unit; SSTU, Slipstream Solvent Test Unit; WFGD, Wet Flue Gas Desulfurization; WTO, Wash Tower Outlet

* Corresponding author.
E-mail addresses: csaha@southernresearch.org, chiranjib.saha.ju@gmail.com (C. Saha).

http://dx.doi.org/10.1016/j.jaerosci.2016.11.005
Received 7 July 2016; Received in revised form 7 September 2016; Accepted 11 November 2016
Available online 16 November 2016
0021-8502/

emissions from power generations. There is a strong incentive to develop technologies that would allow more efficient CO_2 capture from coal-fired plants under the current regulatory scenario. The three major approaches currently under investigation for CO_2 capture are post-combustion, pre-combustion and oxy-combustion (World Energy Outlook, 2011). Post-combustion capture using amine scrubbing will most likely be the preferred technology because the technology is at a mature stage compared to the other two technologies (Rochelle, Freeman, Van Wagener, Xu, & Voice, 2011) and also it can be retrofitted to the existing power plants in the near-to middle-term (Figueroa, Sean Plasynski, McIlvried, & Srivastava, 2008; Romeo et al., 2008; Qi, 2011).

Amine based post-combustion CO_2 capture makes use of the reversible nature of the chemical reaction of solvent (amine) with acid gas CO_2 in an absorption-desorption process. Fig. 1 shows the process flow diagram. However, this process is associated with certain losses of amine due to thermal and oxidative degradation, vapor emission and aerosol formation. Water wash after the absorber column has shown to be effective in reducing vapor emissions. However, controlling aerosol based solvent emissions requires detailed investigation (Mertens et al., 2014a; Khakharia, Vlugt, & Goetheer, 2014) because recent pilot plant studies have shown that aerosol emissions can dominate the amine losses from the process (Mertens et al., 2014a).

The aerosols are termed as smoke, fume, mist and fog formed as suspensions of liquid droplets with upper limits of 10 μm in diameter (Schaber, 1995). The presence of sulfur in coal leads to the aerosol generation due to the reaction of water vapor and SO_3 in flue gas that forms H_2SO_4 downstream of the combustion process (Brachert, Khakharia & Schaber, 2014). SO_3 is also formed from the catalytic oxidation of SO_2 inside a Selective Catalytic Reduction (SCR) system during the reduction of the NO_X (Srivastava, Erickson. & Jambhekar, 2004). In wet flue gas desulfurization, temperature drops rapidly and super-saturation assists in converting incoming gaseous H_2SO_4 to homogeneous nucleation of aerosol droplets (Brachert et al., 2014). Therefore, designing counter-measures for aerosol emissions are crucial for cost-effective and environmentally benign commercial application of this technology.

Recently very few studies have been performed to measure the aerosol number concentration and size distribution at sub-pilot/pilot scale using ELPI$^+$, phase doppler interferometers (PDI), and condensation particle counters (CPC) (Chen, Sache, Lin, & Rochelle, 2014; Mertens et al., 2014a; Mertens, Desagher, Schallert, Khakharia, & Goetheer, 2014b; Mertens et al., 2014c; Brachert et al., 2014; Khakharia et al., 2013). Simulated flue gas with externally generated SO_2/H_2SO_4 were mostly used. Moreover, the effect of real-time process changes during measurements were not extensively quantified. The details of the isokinetic aerosol sampling were not well reported. In this study aerosols are characterized using an ELPI$^+$ from the coal combustion flue gas supplied to the PSTU and SSTU at the NCCC in Wilsonville, AL. The issues identified above in literature are addressed to develop a robust set of results that will help to design countermeasures. The results reported in this paper are for generic MEA solvent. For a specific solvent, further aerosol characterization will be needed.

2. Pilot plant description and methods

The aerosol size distributions and concentrations under different operating conditions were measured at the PSTU and the SSTU using isokinetic probes and a Dekati ELPI$^+$. In this section, a brief description of the pilot plants, operating conditions, sampling set-

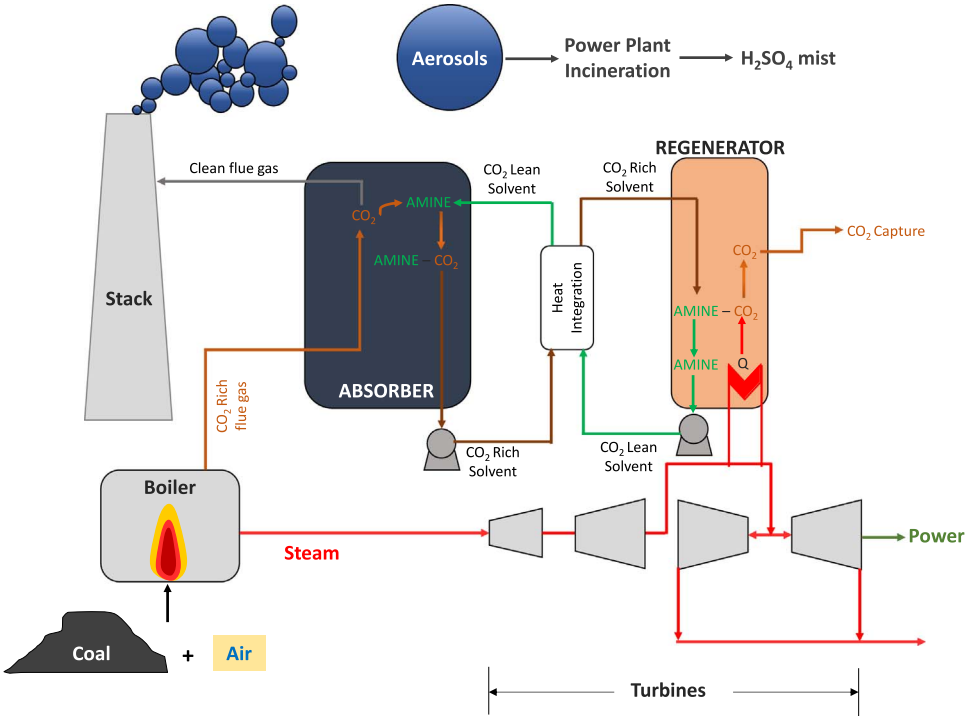


Fig. 1. Schematic of post-combustion CO_2 capture using amine.

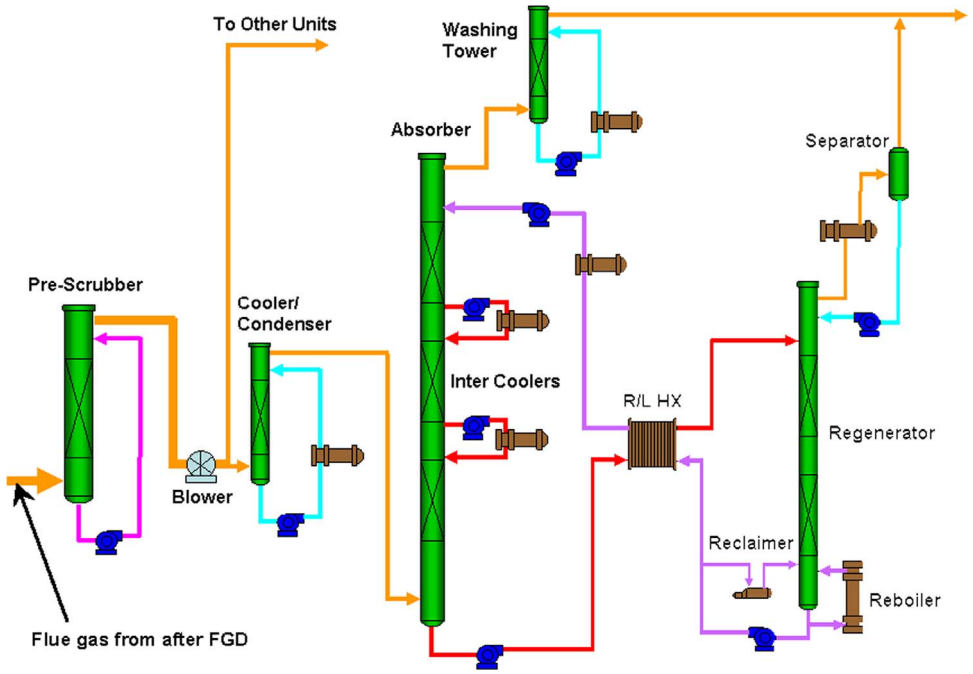


Fig. 2. Simplified process flow diagram of PSTU. FGD – Flue Gas Desulphurization, R/L HX – Rich/Lean Heat Exchanger.

up and ELPI$^+$ analyzer systems are briefly described.

2.1. Pilot Solvent Test Unit (PSTU)

The process flow diagram of the Pilot Solvent Test Unit (PSTU) at the National Carbon Capture Center (NCCC) is shown in Fig. 2 (DOE Report, 2012). The coal-fired flue gas is provided by Unit 5 of the Alabama Power E.C. Gaston Power Plant. Up to 35,000 lb/hr of flue gas is extracted downstream of the Wet Flue Gas Desulfurization (WFGD) system from Unit 5 and nominally 5000 lb/hr [~0.5 MW (MW)] of flue gas flows to the absorber of the PSTU (DOE Report, 2012). There are five major columns, or subsystems, which include (DOE Report, 2012):

- The pre-scrubber which removes the small amount of SO_2 remaining in the flue gas
- A cooler/condenser unit that cools the flue gas to appropriate reaction temperatures and removes flue gas moisture
- An absorber to promote efficient gas-liquid contacting to remove CO_2 from the flue gas
- A washing tower that cools the CO_2-depleted flue gas, removing trace amounts of entrained solvent
- A regenerator that provides heat to release the CO_2 from the solvent

.

Isokinetic samples for aerosol measurements using the ELPI$^+$ were extracted from the wash tower outlet.

2.2. Slipstream Solvent Test Unit (SSTU)

The Slipstream Solvent Test Unit (SSTU) was installed at the NCCC to increase the flexibility of the post-combustion CO_2 facilities by allowing testing of solvents less than 4000 gallons (required for the PSTU) at relatively smaller scale than PSTU. Similar to the PSTU, the SSTU comprises an absorber, regenerator, wash tower and associated equipment along with analytical instrumentation. The operation of the unit was started in 2015 (DOE Final Report, 2014). Fig. 3 provides a simplified process diagram of the SSTU.

The PSTU and the SSTU are fully integrated systems for comprehensive solvent characterization at pilot-scale and at bench-scale respectively (DOE Final Report, 2014). The SSTU is about one tenth the size of the PSTU. Nominally 500 lb/hr (~0.05 MW) of flue gas flows to the absorber of the SSTU from the PSTU cooler. Isokinetic samples for aerosol measurements using the ELPI$^+$ were extracted from the absorber inlet and wash tower outlet of the SSTU to characterize the change in real-time aerosols generated.

The details of the measurement set-up are described in the next Section 2.3. It should be noted that the tests at the PSTU were conducted in early 2015. Some of the modifications in the measurement set-up, for example, new design of the dilution probe and use of heated ELPI$^+$ stages, were incorporated prior to the test runs at the SSTU in late 2015. These changes are also discussed in the next Section 2.3.

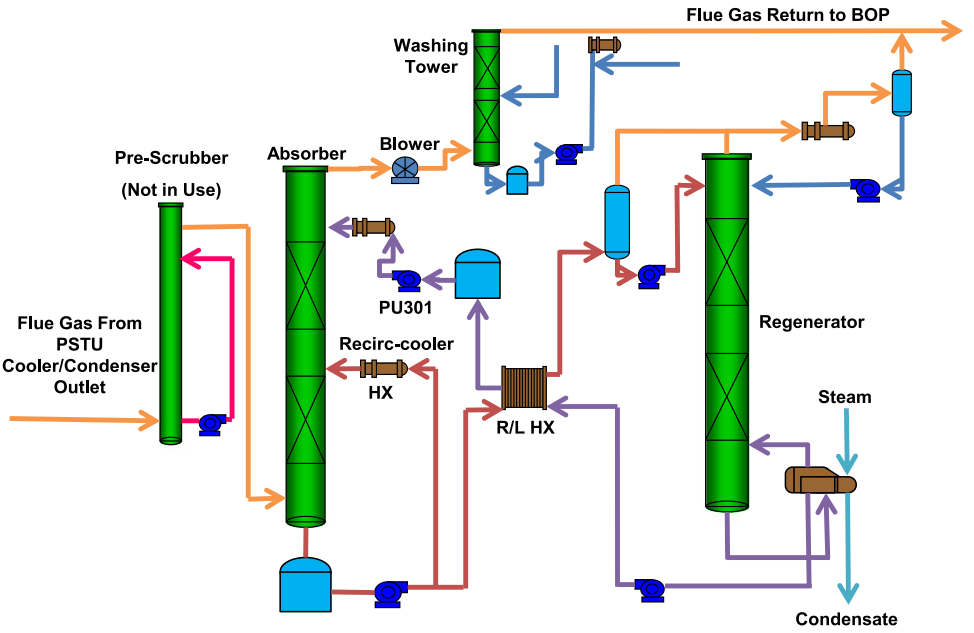


Fig. 3. Simplified process flow diagram of SSTU. PSTU – Pilot Solvent Test Unit, R/L HX – Rich/Lean Heat Exchanger, HX – Heat Exchanger, BOP – Balance of Plants, PU301 – Specific pump number from process and instrumentation diagram.

2.3. Sample extraction systems

The schematic of the ELPI$^+$ measurement set-up at the Wash Tower Outlet (WTO) of the PSTU is shown in Fig. 4. Because the sample stream at the WTO is expected to be saturated, dilution of the sample with heated air is necessary to avoid condensation on the impactor plates of the ELPI$^+$ stages. The condensation can lead to electrical short circuiting of the plates and erroneous measurements of aerosol size distribution and concentrations.

An ejector type dilutor is used. The dilution air is passed through a moisture trap and filter to dry the air and collect any particles. The dilution air is heated and the diluted samples from the outlet of the dilution chamber is drawn to an ELPI$^+$ for aerosol characterization. The dilution ratio is defined by Eq. (1) ("DEKATI® Diluter User Manual: Ver. 5.1," 2014).

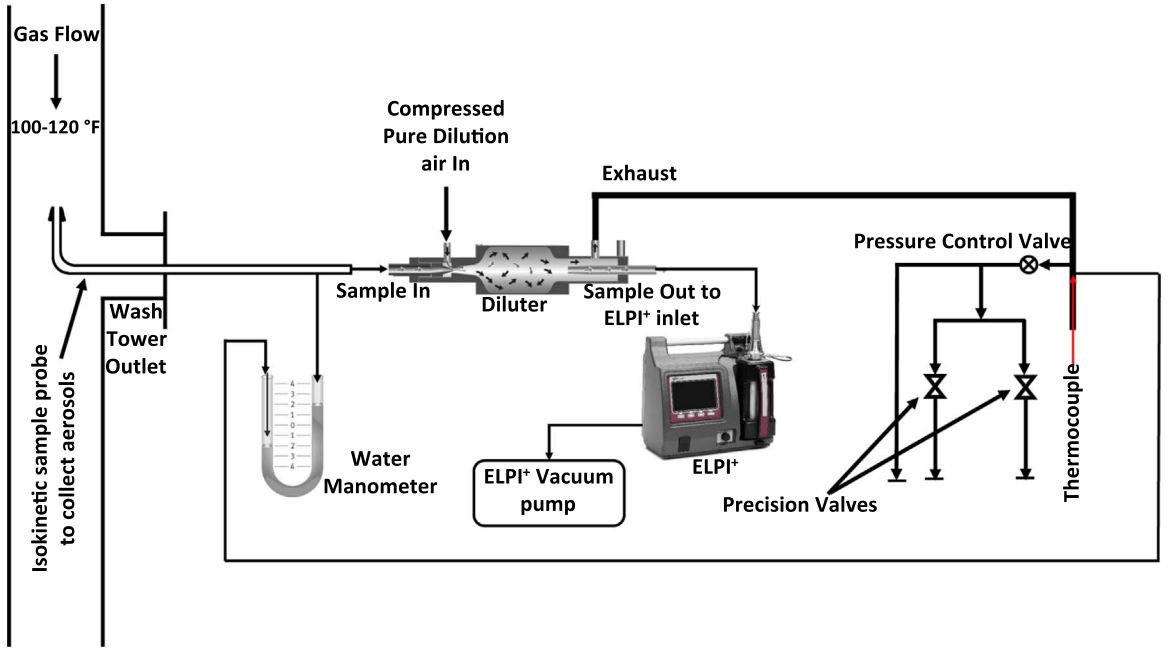


Fig. 4. Schematic of the isokinetic sample extraction system for ELPI^{+TM} measurements at wash tower outlet of PSTU.

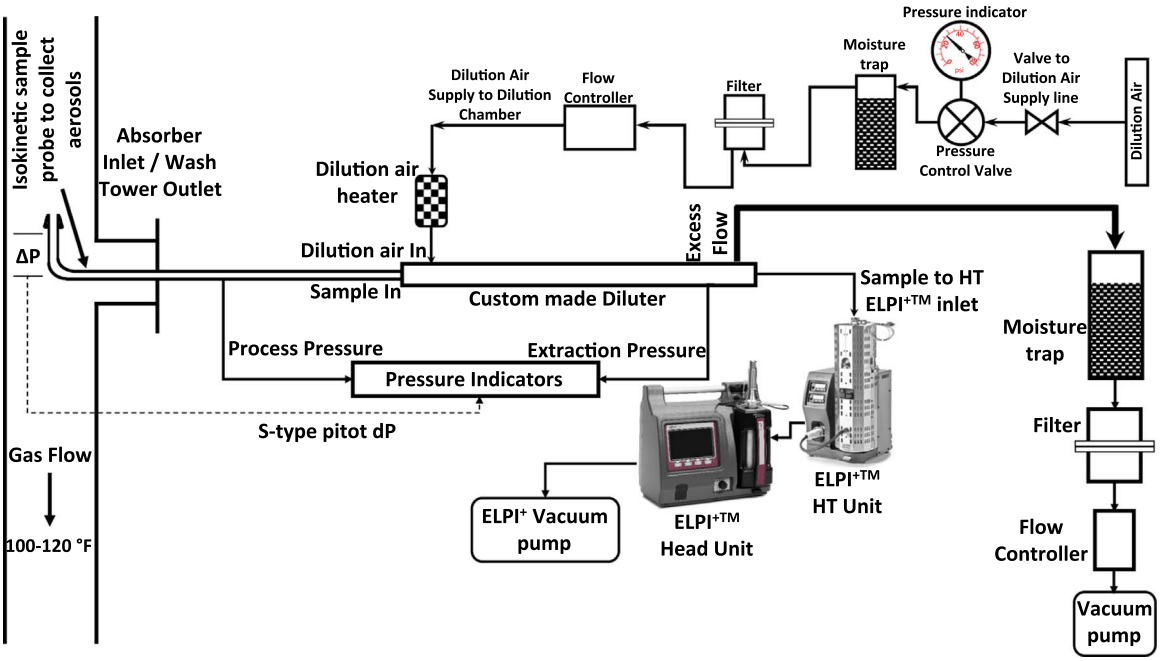


Fig. 5. Schematic of the isokinetic sample extraction system for HT ELPI$^+$ measurements at absorber inlet / wash tower outlet of SSTU.

$$N = \frac{V_{sample} + V_{air}}{V_{sample}} \quad (1)$$

where N=Dilution ratio

V_{sample}=Sample volume flow

V_{air}=Air volume flow

In an ejector type dilutor, the flow ratio (and thus the dilution ratio) is automatically kept constant over a wide operation range as long as the sample pressure is constant. The initial concentration of the sample is calculated by multiplying the diluted sample concentration with the dilution ratio N ("DEKATI® Diluter User Manual: Ver. 5.1," 2014).

The High Temperature (HT) ELPI$^+$ system was installed for aerosol characterization at the absorber inlet and wash tower outlet of the SSTU as shown in Fig. 5. It should be noted that a custom made dilutor was used instead of an ejector type dilutor. In an ejector type dilutor, a critical orifice is used to control the dilution air flow. The pressure drop through the orifice helps to draw the sample to the dilution chamber. The inlet pressure at dilutor has to be kept constant slightly more than atmospheric pressure to ensure constant pressure drop across the dilutor and prevent back flow of the sample from the dilutor to the sample nozzle. Maximum flow is fixed for a particular pump. Therefore, the outlet pressure from the ejector type dilutor is also fixed to achieve the constant pressure drop. However, there is a chance of change in process pressure drop and hence the gas stream velocity. But if ejector type dilutor is used, there is a less flexibility of choosing different sample extraction nozzles to accommodate for any change in this velocity. Moreover, due to the presence of restrictions in the form of critical orifice in ejector type dilutor, there is a chance of small amount of aerosol sample destruction on its way to ELPI sampling system. This sample destruction is although anticipated to be very small in quantity by Dekati Ltd. During PSTU tests, we have carefully calculated the pressure drops across the ejector type dilutor (critical orifice) and choose the sample extraction nozzle. To avoid these limitations, we have designed carefully the custom made dilutor that is capable of sampling aerosol emissions with different sampling nozzles to account for different process stream velocities. This dilutor also has minimum restriction points that allow for non-destruction aerosol emission as much as possible. Thus the use of the custom made dilutor and HT ELPI$^+$ ensured representative sample extraction.

2.4. PSTU and SSTU operating parameters

Typical operating parameters for the two test units during ELPI+ testing are listed below in Table 1.

2.5. Dekati Electrical Low Pressure Impactor (ELPI$^+$)

Real-time measurements of size distribution and concentration for 0.006 to 10 μm aerosols are possible using the ELPI$^+$. The operating principle of the ELPI$^+$ is based on the fact that the particles are first charged to a known level in a corona charger. According to their aerodynamic diameter, the particles are size classified in a low-pressure cascade impactor after charging. Electrometers are connected to each impactor stage which is electrically insulated. The electrometer of each impactor stage records

Table 1
Operating parameters.

Operating Parameters	PSTU	SSTU
Absorber Flue Gas Flow Rate (G), lb/h	4400	405
Solvent Flow Rate (L), lb/h	20,000	950
Re-boiler Steam Flow Rate (S), lb/h	1,434	125
Absorber Inlet Flue Gas Temperature, °F	110	123
Absorber Inlet Solvent Temperature, °F	106	104
Wash Tower Exit Temperature, °F	115	75
Regenerator Pressure, psig	14	15
Inlet Flue Gas CO_2 Content, vol%	12	11
Number of Absorber Beds	1, 2 and 3	1 and 2
Number of Intercoolers	2	1

an electrical current as produced by charged particles collected on the stage. This current is proportional to the concentration of particles on each stage. Fig. 6 describes the operating principle of the ELPI^{+TM} (ELPI^{+TM}, 2015 User Manual: Ver. 1.50," 2015).

There are 13 impactor stages and one filter stage that collect aerosol/particle samples in the range of 6 nm to 10 μm. The particle size collection range of the impactor stages is 17 nm to 10 μm, and the filter stage reduces the particle size from 17 nm to 6 nm. Nominal sample flow is 10 L/min at temperatures below 60 °C. However, the SSTU tests were performed using HT ELPI^{+TM} which has three different temperature settings (60 °C, 120 °C, and 180 °C). SSTU tests were conducted at the 60 °C setting. The ambience of the ELPI^{+TM} should be 10–35 °C with relative humidity of up to 90%. Pressure under the first stage is 40 mbar and the pump for 10 L/min ELPI+ should draw a minimum of 16 m^3/h at 40 mbara, although the recommended value is 25 m^3/h at 40 mbar.

Different impactor stages are used for particle size fractioning. Each ELPI$^+$ unit is shipped with a unique impactor serial number and is calibrated with D50% stage cut points with aerodynamic diameters by Dekati. However, the pressure and temperatures on a particular day may differ slightly from the calibration pressure and temperatures. Therefore, the stage cut points are corrected for each test day. If wrong values have been used during the measurement, the data should be recalculated with correct values using the ELPI$^+$ data file filter program. The maximum variation of new calibration values based on each test day's condition from the original calibrated values of the stage cuts was between 0.02% and 0.70%, which is considered acceptable according to the manufacturer.

3. Results and discussions

The results of aerosol measurements from the PSTU and the SSTU are reported in this section. The effect of aerosol concentrations and size distributions under different test conditions such as dilution ratio, temperature and other test parameters are discussed in this section.

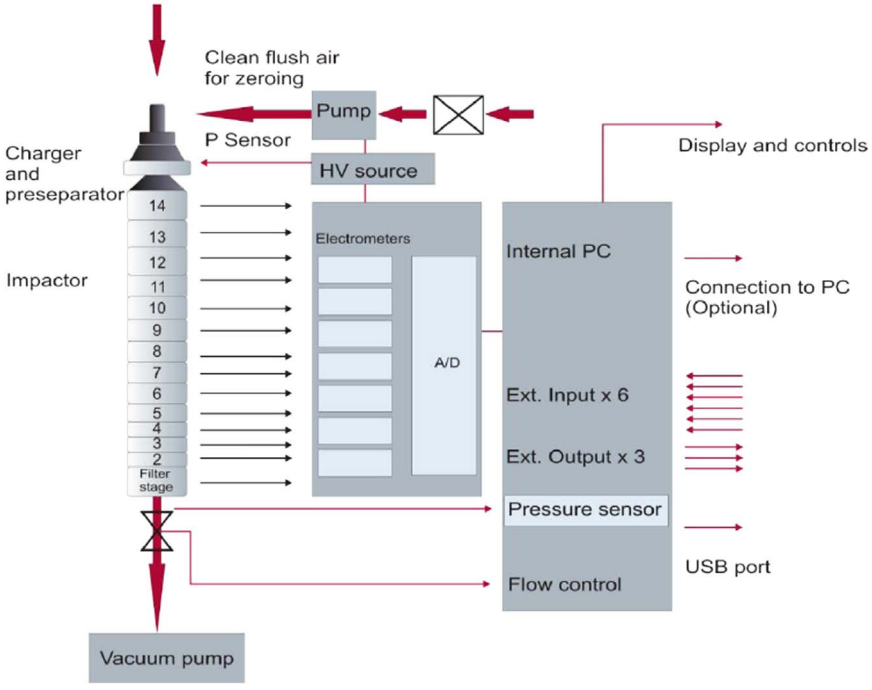


Fig. 6. Operating principle of DEKATI ELPI^{+TM}.

3.1. PSTU tests

The real-time ELPI$^+$ measurements were taken at the WTO of the PSTU. Tests were conducted on three different days to investigate the effects of different test conditions such as dilution temperature and use of intercoolers and absorber beds.

Fig. 7 represents the effect on total particle number concentration as measured real-time by EPLI$^+$ on test day 2. The X-axis represents the total test duration, primary Y-axis represent combined number concentration of all stages and secondary Y-axis represent some of the absorber process parameters. It can be seen from this figure that the CO_2 and H_2O concentration at the absorber inlet were almost constant during the test period. The aerosol number concentration was generally in the range of E+06 to E+07 cm^{-3}. These results are in agreement with literature results (Mertens et al., 2014a; Srivastava et al., 2004). As indicated by the absorber temperature profiles, both intercoolers were turned on for two different periods (from 0:30 to 2:25 and 3:50 to 4:15 h of total test time). The intercoolers strongly influenced the particle concentrations, which generally decreased with decreasing absorber temperature.

The color-coded intensity graphs in Fig. 8 display the particle size distribution as a function of time. X, Y and Z axes show the time, particle size and the concentration respectively. The bottom two graphs provide the number concentrations as functions of particle sizes. The particle sizes in these graphs are the aerodynamic sizes. A large number of aerosols with relatively higher size can be seen from the intensity and number concentration (left hand side one) plots when both the absorber intercoolers were off or not under operation. A plume of mist or aerosols was evident in the smallest size range immediately after the intercoolers were turned on as can be seen from the intensity and number concentration (right hand side one) plots. As time progressed, the aerosol concentration at smallest size (shown in figure at the right hand side) moved towards relatively higher size and the effect of turning the intercoolers on aerosol concentration settles down. The total number concentration also decreases when both intercoolers operated.

The real-time aerosol number concentrations at the highest dilution temperature of 180 °C were measured on test day 1. These results are compared with the lower dilution temperature aerosol concentration measurements on test day 2 at 90 °C in Fig. 9. A clear shift of higher number concentration towards lower sizes at the high dilution temperature can be seen. This size change is likely related to accelerated evaporation due to low relative humidity and elevated temperature of the aerosols. The larger aerosols may separate into very small aerosols and contribute to this high number concentration at the lowest size fraction. Therefore, it can be concluded that for an ejector type dilutor, the temperature above the condensation point should be high enough that the aerosols are not vaporized or burst into very small size that is hard to capture.

The effect of number of absorber beds under operation on particle number concentrations was also investigated in real-time using the ELPI$^+$. Fig. 10 shows the particle number concentration of each stage plotted over the test duration. As soon as the third bed was turned on, the number concentration of each stage reached a new, higher value and remained at around this value until the third bed was turned off.

Further, the number concentration graphs (Fig. 11) for two and three absorber beds in operation show that the aerosol number concentration for two beds ranged between 0.04–0.40 μm aerodynamic diameters and for three beds were 0.02 to 0.8 μm. The cumulative number concentration was about twice as high with three beds than with two. All three beds are similar and contain structured packing. It is possible that the third bed, when not in operation, may act as a demister due to the compact design which helps to knock out most of the smallest aerosols and perhaps half of the larger aerosols. However, detailed investigation in future test campaigns is necessary for definite conclusions.

3.2. SSTU Tests

Fig. 12 shows the real-time ELPI$^+$ measurements of aerosol number concentrations and cumulative percentages at the absorber

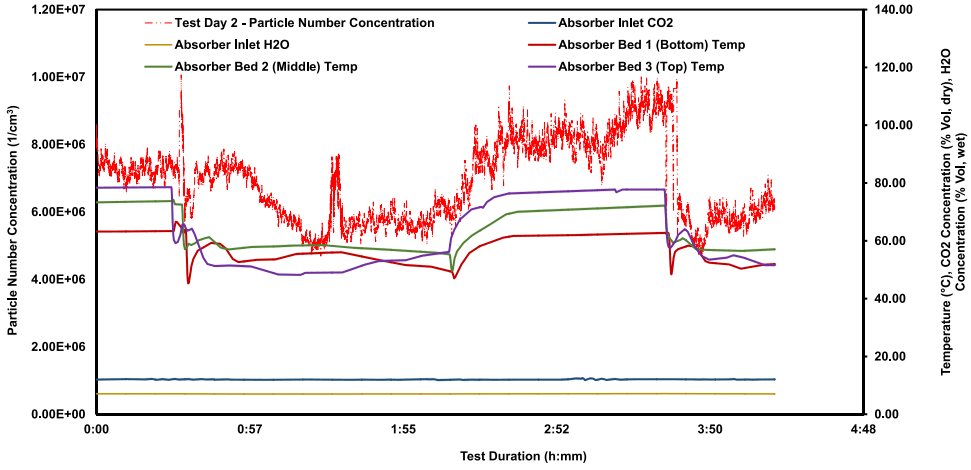
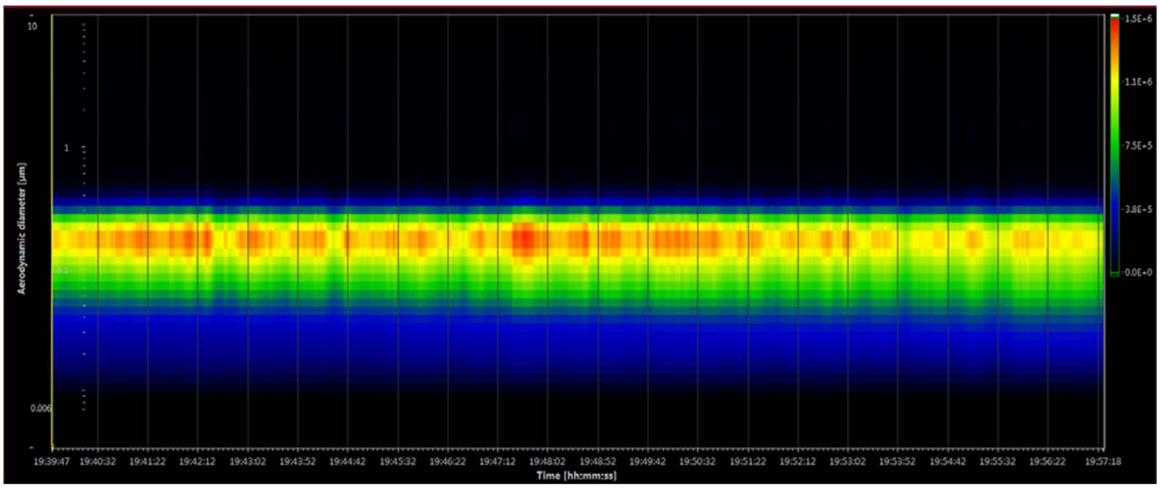
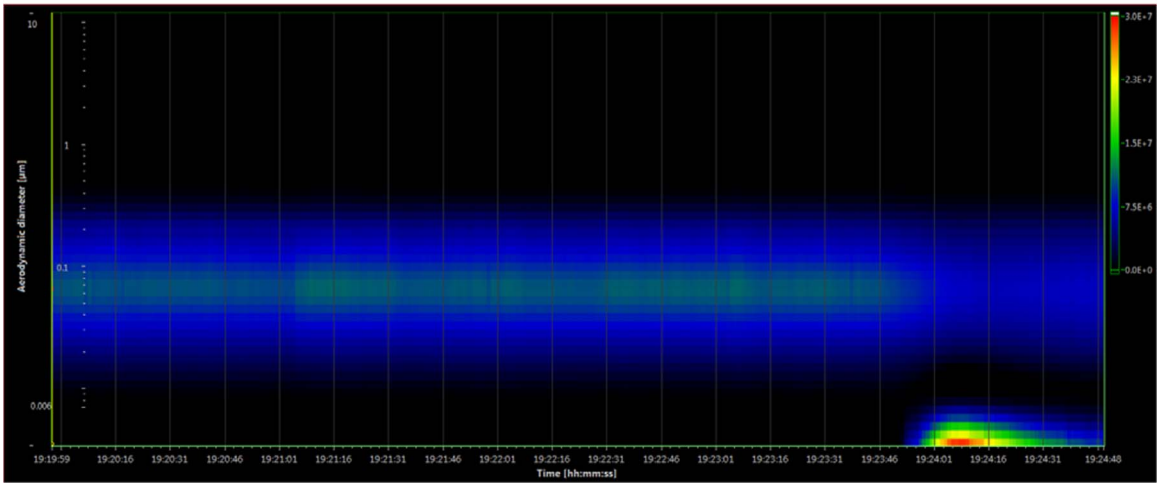


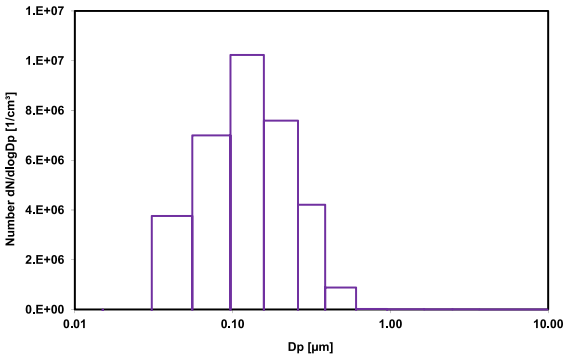
Fig. 7. Real-time ELPI$^+$ measurements of aerosol concentrations with varying absorber temperatures.



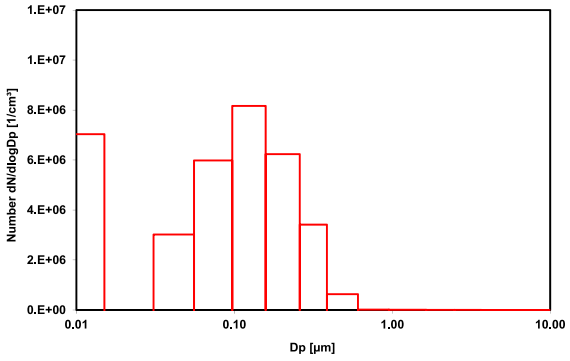
Intercoolers Off (intensity plot)



Intercoolers On (intensity plot)



Intercoolers Off (no. conc.)



Intercoolers On (no. conc.)

Fig. 8. Real-time aerosol intensity and number concentrations (no. conc.) measured by ELPI^{+TM} before and after intercoolers turned on.

inlet and wash tower outlet. The process and physical conditions (dilution ratio, dilution heating temperature, gas flow rate, isokinetic nozzle size, HT-ELPI^{+} temperature set points, etc.) were kept consistent for the two sets of measurements. As expected, the aerosol concentration was much lower at the wash tower outlet than at the absorber inlet. The aerosol cumulative percentage plots indicate that the smaller size aerosols at the absorber inlet were captured in the wash tower. It can be seen that around 10–12% of very small size aerosols can be captured at WTO compared to Absorber Inlet at SSTU.

The effect of dilution air heating temperature at the WTO of the SSTU is plotted in Fig. 13. For PSTU, the dilution temperatures

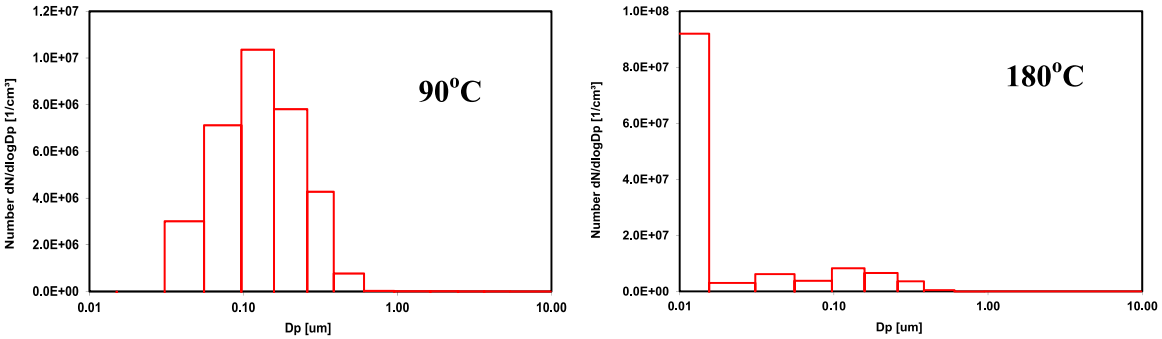


Fig. 9. Effect of dilution heating temperature on real-time ELPI⁺ measurements of aerosol number concentrations.

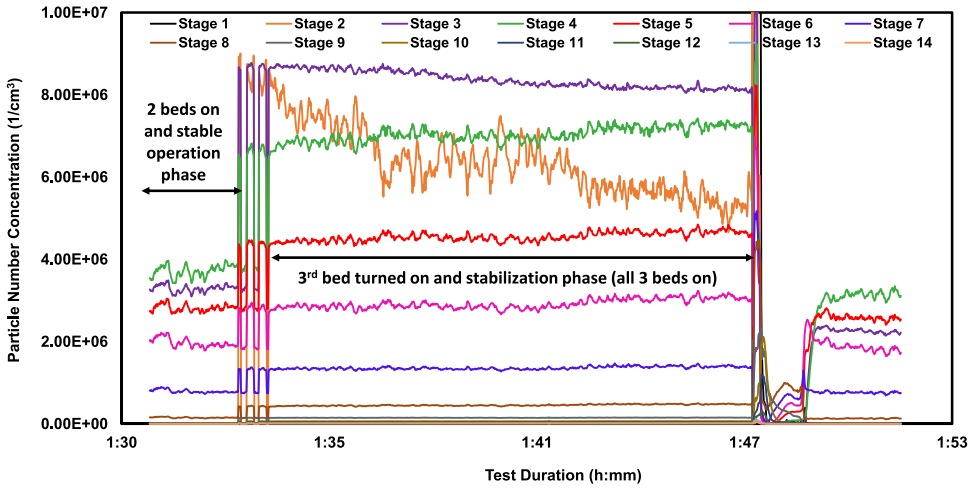


Fig. 10. Real-time ELPI⁺ measurements of absorber bed effects on aerosol number concentrations.

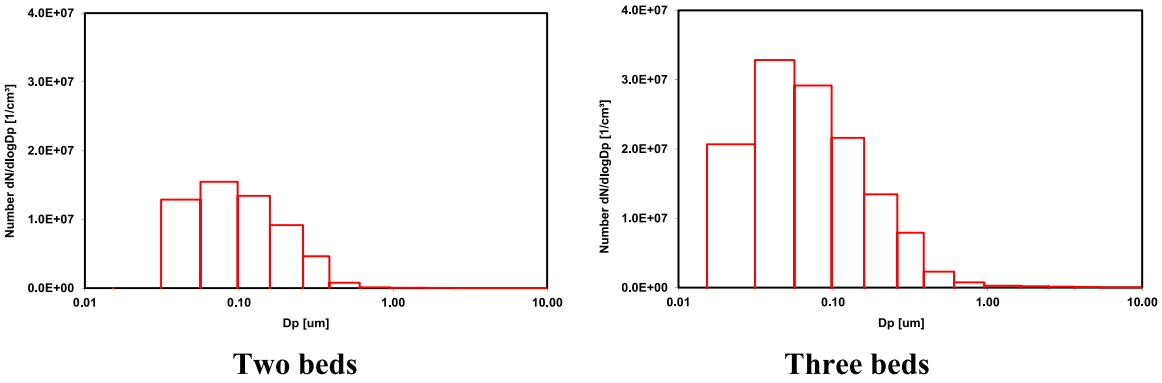


Fig. 11. Effect of number of beds under operation on real-time aerosol number concentrations.

considered for investigation were 90 °C and 180 °C. The results are explained in Fig. 9 under the previous Section 3.1. The dilution heating temperatures of 65 °C and 90 °C were chosen for the SSTU tests based on the dew point temperature of the incoming gas at the particular water vapor partial pressure. It can be seen from the figure that at higher dilution temperature there is a tendency of generation of lower size aerosols. This observation is similar to PSTU data in Fig. 9. However, there is a basic difference between the SSTU and PSTU results. The higher dilution temperature of 180 °C at PSTU led to more generation of the lowest size aerosols at the PSTU WTO. However, in the SSTU tests, only 30% of larger size aerosols at 65 °C were converted to smaller size aerosols at 90 °C. The overall characteristics of the number concentration in the size range of 0.02–0.76 μm are very similar for both cases. The cause of the lower size aerosol concentration at lower dilution temperature, whether from evaporation due to low relative humidity or from process changes or both, is to be further investigated. Nevertheless, the information obtained is very important in that it proved that dilution temperature just above dew point temperature is sufficient for characterizing aerosols without artifacts. From the

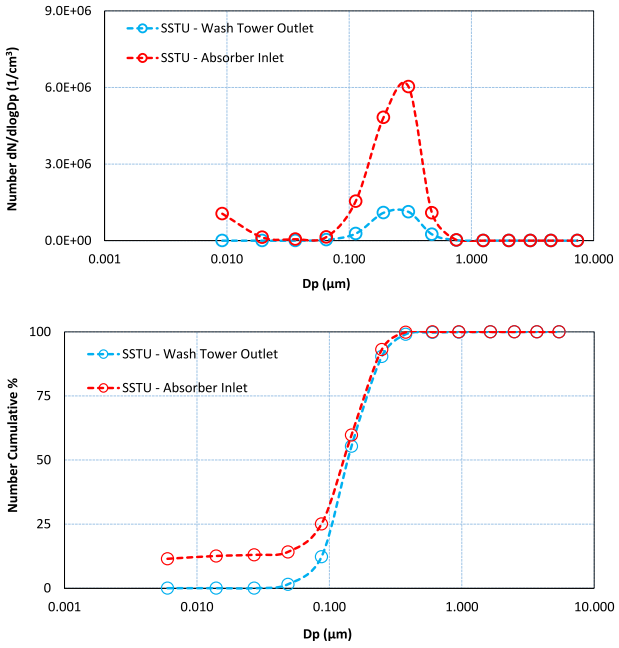


Fig. 12. Real-time ELPI⁺ measurements of aerosol number concentrations and cumulative percentage at absorber inlet and wash tower outlet.

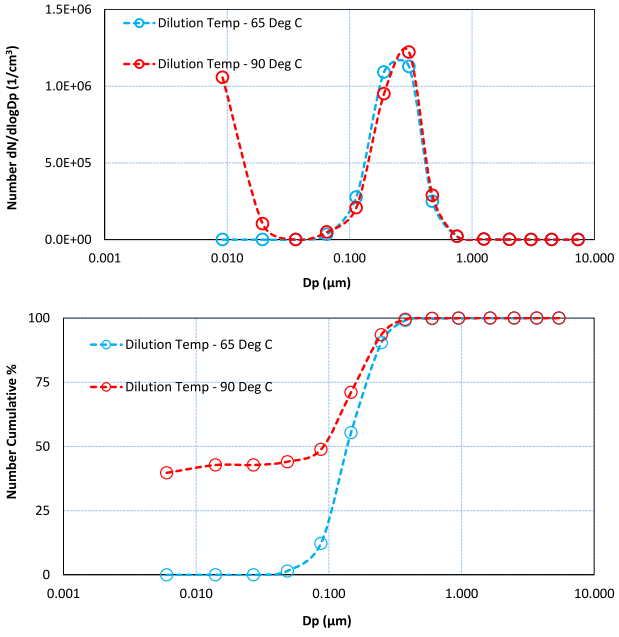


Fig. 13. Effect of dilution heating temperature on real-time aerosol number concentrations and cumulative percentage at wash tower outlet.

cumulative plot, it can be quantified that around 30% of large size aerosols evaporates to very small size aerosols due to the effect of high dilution temperature.

3.3. Comparison of PSTU and SSTU results

Fig. 14 shows the comparison of aerosol concentrations at the PSTU scrubber inlet, and the wash tower outlets of the PSTU and SSTU. It should be noted that parameters, such the dilution ratio and isokinetic sampler nozzle size, were not identical for both wash tower outlet measurements. It can be seen from the number concentration plots that the aerosol concentration is very high at PSTU scrubber inlet as compared to the wash tower outlets. This observation is expected, as the wash towers remove a substantial amount

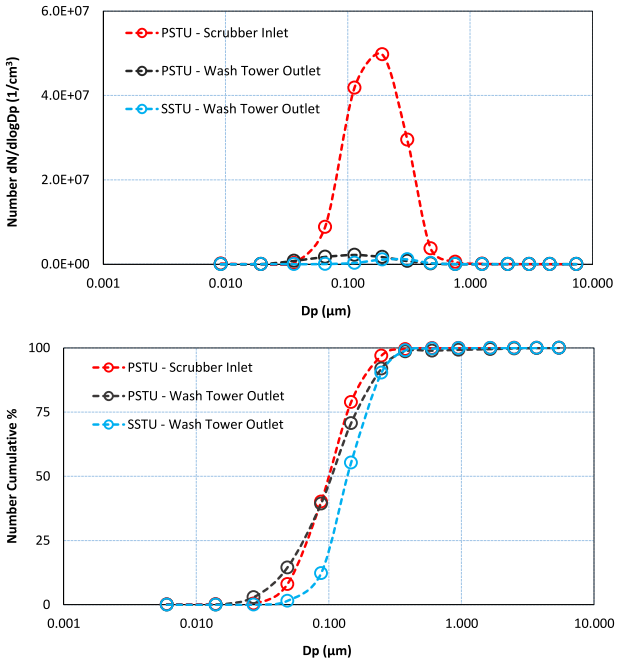


Fig. 14. Comparison of real-time aerosol number concentrations and cumulative percentage.

of aerosols. The cumulative aerosol percentages reveal that there were less small size aerosol accumulation at the wash tower outlet of the PSTU than that of the SSTU. This inconsistency is likely due to dissimilar process parameters as mentioned above, although further investigation is needed.

3.4. Optical images

Optical images of stages 3 and 4 are shown in Fig. 15. The upper two images are of substrates collected after the test, and the lower two images are of the back of the impactor jet plates. A regular pattern of collection can be observed. The pattern indicates aerosol collection with very fine solids.

However, at higher stages of aerodynamic diameters, it is believed that the aerosol droplets coalesced in flow eddies and formed larger droplets. Also light yellowish color of the droplets at higher stages indicates the presence of solvent with in the liquids. The images of higher stages 6 and 7 are presented in Fig. 16.

The physical appearance of the aerosols and their collection patterns as shown in Figs. 15 and 16 are very important because these give us clear picture about the aerodynamic diameter, stage cuts we have determined earlier, effect of coalescence of the aerosols and an estimates of amine emissions with the aerosols. The ELPI measurements only give us electrical signals but these physical information is complementary for real-time aerosol measurements as reported in this manuscript.

3.5. Test-site and measurement set-up photos (Figs. 17 and 18).

4. Summary and conclusions

Although amine based post-combustion CO_2 capture is a promising technology, studies indicate that amine emissions in the form of aerosols must be controlled for commercial success of this technology. Most of the recent studies characterizing aerosols used simulated flue gas with externally generated H_2SO_4, the main precursor for aerosol generation. However, in this study, aerosols produced from flue gas from a commercially dispatched coal-fired power plant was characterized by real-time measurements using isokinetic sampling systems and the ELPI$^+$. Measurements were taken on the NCCC's PSTU and SSTU while operating with MEA to quantify the effects of different process changes on aerosol concentration and size.

Aerosol concentration generally was in the range of E+06 to E+07 cm^{-3} at the PSTU wash tower outlet. These results are in agreement with some of the reported results in current literature. Use of intercoolers decreased the aerosol concentrations measured at the same location. Moreover, aerosol intensity and concentration showed a plume of mist or aerosols in smallest size immediately after the intercoolers were put in service.

The effect of dilution heating temperature was also investigated, which showed a clear shift of increased number concentration

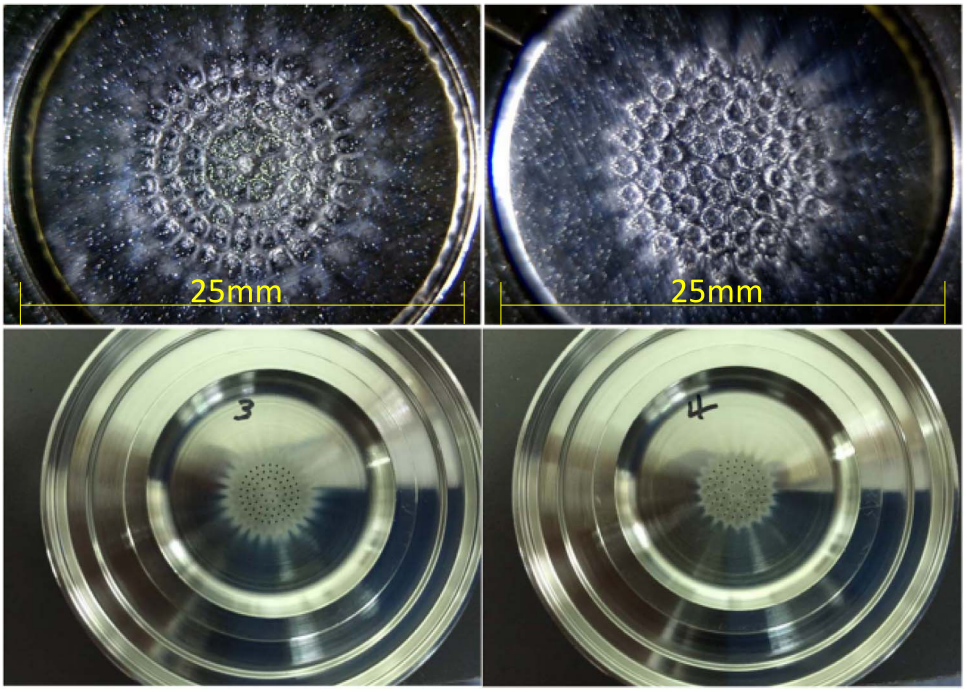


Fig. 15. Optical images of stage 3 and 4 of ELPI^{+TM}.

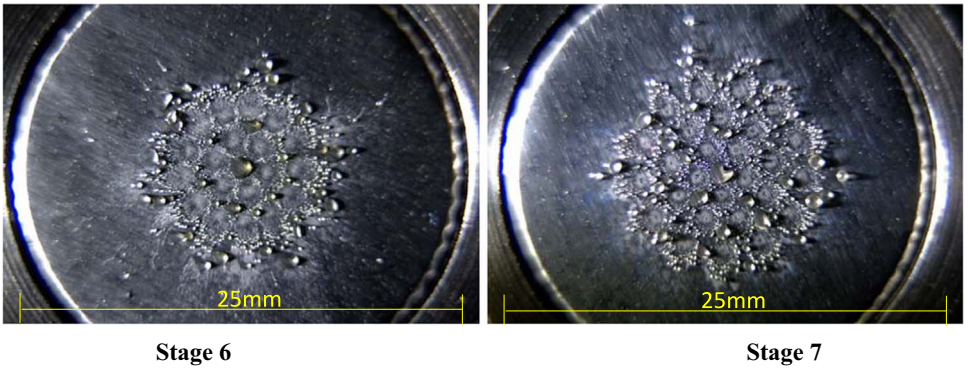


Fig. 16. Optical images of stage 6 and 7 of ELPI^{+TM}.

towards smaller sizes at high dilution temperature due to accelerated evaporation caused by low relative humidity and elevated temperature of the aerosols. The tests at the SSTU however showed that the effect can be diminished if the dilution heating temperature can be set just above the dew point temperature of the incoming gas. This result is important because some of the previous studies have used dilution temperature in the range of 80–200 °C.

The effect of absorber beds indicated an increase in aerosol number concentration when the third bed was turned on at the PSTU. This observation needs further investigation in future test campaigns. As expected, the aerosol concentration was very low at wash tower outlet compared to the absorber inlet at the SSTU. Moreover, a small amount of smaller size aerosols at SSTU absorber inlet is observed which are captured in the wash tower. As expected, the aerosol concentrations were very high at the PSTU scrubber inlet compared to the wash tower outlets of the PSTU and SSTU.

It should also be noted that the results represented in this work is based on MEA solvent. Separate detailed investigations will be required for different solvents. Also, it should be noted here that the calibration of the stage cuts of ELPI^{+TM} shows a maximum deviation of 0.02–0.70% from the original calibration by Dekati. Overall, these results are very promising and further tests using the ELIP^{+} are planned at the NCCC. These results represent a preliminary basis for developing control measures for aerosol emissions to make amine based post-combustion CO_2 capture commercially viable.

Fig. 17. Test site photo at post-combustion CO_2 capture facility.

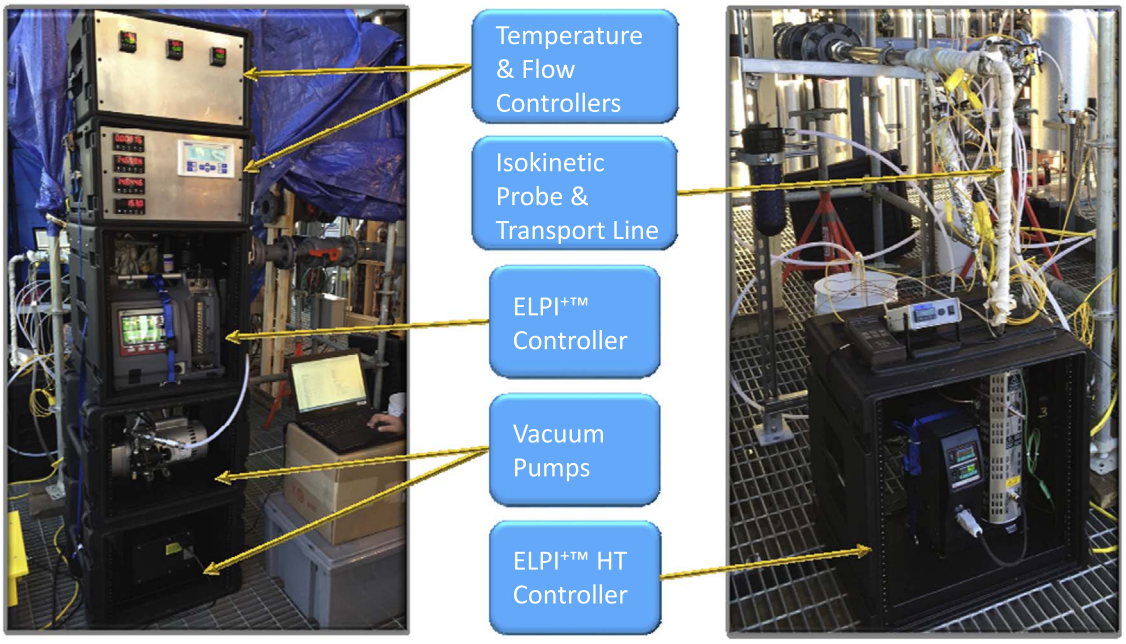


Fig. 18. ELPI^{+TM} measurement set-up; photos taken during one of the test campaigns.

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United

States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Acknowledgements

The U.S. Department of Energy (DOE) is acknowledged for this work. This material is based upon work supported by the Department of Energy under Award Number(s) DE-FE0022596. Also acknowledged are the following organizations: NETL, Southern Company, EPRI, Luminant, American Electric Power, Duke Energy and Cloud Peak Energy. Harry Nortega, Terry Hammond and Todd Snyder are acknowledged for helping in test set-ups and various measurement related activities.

References

Brachert, L., Khakharia, J. M., P., & Schaber, K. (2014). The challenge of measuring sulfuric acid aerosols: number concentration and size evaluation using a condensation particle counter (CPC) and an electrical low pressure impactor (ELPI+). *Journal of Aerosol Science*, *67*, 21–27.

Chen, E., Sache, S. M. F., D., Lin, Y., & Rochelle, G. T. (2014). Pilot plant activities with concentrated piperazine. *Energy Procedia*, *63*, 1376–1391.

DEKATI, (2014). ® Diluter User Manual: Ver. 5.1.

DOE, (2012). Report.

DOE, (2014). Final Report.

ELPI, (2015). +TM User Manual: Ver. 1.50

Figueroa, José D., Sean Plasynski, T. F., McIlvried, Howard, & Srivastava, Rameshwar D. (2008). Advances in CO_2 capture technology—the U.S. Department of Energy's Carbon Sequestration Program. *International Journal of Greenhouse Gas Control*, *2*(2), 9–20.

Khakharia, P., Vlugt, J. M., T. J. H., & Goetheer, E. (2014). Predicting aerosol based emissions in a post combustion CO_2 capture process using an Aspen Plus Model. *Energy Procedia*, *63*, 911–925.

Khakharia, P., Mertens, L. B., J., Huizinga, A., Schallert, B., Schaber, K., Vlugt, T. J. H., & Goetheer, E. (2013). Investigation of aerosol based emission of MEA due to sulphuric acid aerosol and soot in a Post Combustion CO_2 Capture process. *International Journal of Greenhouse Gas Control*, *19*, 138–144.

Mertens, J., Desagher, L. B., D., Schallert, B., Khakharia, P., & Goetheer, E. (2014). Predicting amine mist formation based on aerosol number concentration and size measurements in flue gas. *Energy Procedia*, *63*, 893–901.

Mertens, J., Rogiers, C. A., P., Brachertb, L., Khakharia, P., Goetheer, E., & Schaber, K. (2014). A wet electrostatic precipitator (WESP) as countermeasure to mistformation in amine based carbon capture. *International Journal of Greenhouse Gas Control*, *31*, 175–181.

Mertens, J., Desagher, L. B., D., Thielens, M. L., Khakharia, P., Goetheerc, E., & Schaber, K. (2014). ELPI$^+$ measurements of aerosol growth in an amine absorption column. *International Journal of Greenhouse Gas Control*, *23*, 44–50.

Qi, G. W., Yanbing, Estevez, Luis, Duan, Xiaonan, Anako, Nkechi, Park, Ah-Hyung Alissa, Li, Wen, Jones, Christopher W., & Giannelis, Emmanuel P. (2011). High efficiency nanocomposite sorbents for CO_2 capture based on amine-functionalized mesoporous capsules. *Energy Environmental Science*, *4*(2), 444–452.

Rochelle, G., Freeman, E. C., S., Wagener, D. Van, Xu, Q., & Voice, A. (2011). Aqueous piperazine as the new standard for CO_2 capture technology. *Chemical Engineering Journal*, *171*, 725–733.

Romeo, L. M., Escosa, J. C. A., J. M., Paño, J., Giménez, A., Sánchez-Biezma, A., & Ballesteros, J. C. (2008). Oxyfuel carbonation/calcination cycle for low cost CO_2 capture in existing power plants. *Energy Conversion and Management*, *49*(10), 2809–2814.

Schaber, K. (1995). Aerosol formation in absorption processes. *Chemical Engineering Science*, *50*, 1347–1360.

Srivastava, R. K., Erickson, C. A. M., C., & Jambhekar, R. (2004). Emissions of sulfur trioxide from coal-fired power plants. *Journal of the Air Waste Management Association*, *54*, 750–762.

World Energy Outlook (2011).

Chiranjib Saha holds a PhD from Monash University, Australia in Energy & Fuels research. Dr. Saha currently leads and manages research projects in the demonstration of various types of CO_2 capture technologies at NCCC. Dr. Saha has almost ten years of clean electric power generation research experience that includes combustion aerosol emissions, chemical looping, oxy-fuel, membrane technologies development, IGCC power generation, heat transfer-structure-dynamics of flames, steam turbines' sealing design-secondary flows-heat transfer analysis etc. Dr. Saha has worked in different countries like India, Australia and Canada and in organizations like General Electric (GE, Energy) and CanmetEnergy (Natural Resources of Canada).

James H. Irvin is currently serving as the Manager of Fossil Technologies group at Southern Research. Mr. Irvin has over ten years of experience in applied R & D in areas such as process development of gasification, hydrothermal carbonization and other thermochemical conversion processes, aerosol emissions characterization from post-combustion CO_2 capture, pre and post-combustion solvent testing and analytical instrument integration. Since 2011 Mr. Irvin has managed teams of applied R & D scientists and engineers and successfully developed technologies which resulted in commercial licenses.