Contents

[Aerosol studies 2](#_Toc67989709)

[Aerosol emissions from air capture devices 2](#_Toc67989710)

[Methodology 3](#_Toc67989711)

[Results and discussion 3](#_Toc67989712)

[RLS 3](#_Toc67989713)

[Cooling tower 7](#_Toc67989714)

[Packed column 13](#_Toc67989715)

[Discussion 17](#_Toc67989716)

[Nomenclature 22](#_Toc67989717)

# Aerosol studies

Gas/liquid contactors are being used in a variety of industries for decades. The simplicity, versatility and effectiveness of these contactors have made them very popular in corresponding industries. Gas-liquid contactors are being used to transfer mass and/or heat between a gas and a liquid. They are widely used in separation processes as strippers when components are removed from a liquid stream by a vapour stream, or scrubbers when removing solids or gases from a gas stream using the liquid phase. The working principle and efficiency of gas-liquid contactors have been studied quite extensively in the literature. One of the important aspects of the gas-liquid contactors that affect its efficiency and economy is the solvent drift. Drift is defined as the liquid water entrained in the air stream which is carried out of the tower through the induced draft fan stack. Drift in gas-liquid contactors is the main cause of solvent loss and thus contributes to the overall efficacy of the contactor and imposes extra maintenance costs.

As mentioned above, drift is entrained solvent droplets in the tower discharge vapours. Drift loss varies between 0.1 and 0.2 % of Circulation flow. It can be as low as 0.01 % of circulation flow if the cooling tower has windage drift eliminators. To minimise the drift, usually, a self-draining filter or a demister is implemented that removes solvent droplets from the stream and re-introduce the collected solvent to the solvent reservoir. No matter how high the efficiency of the demister/filter is, some of the solvents will be lost. On the other hand, there might be some particles within the nano/micrometre range that are small enough to be able to escape the filters and demisters. The loss due to the latter phenomenon is believed to be negligible and not contribute to significant economical outcome; however, it is of high significance in terms of adverse health and environmental effects.

Because the drift droplets contain the same chemical composition as the solvent circulating through the contactor, these droplets eventually can be converted to airborne particles. Large drift droplets settle out of the exhaust air stream and deposit near the exhaust vent. This process can lead to wetting, icing, salt deposition, and related problems such as damage to equipment or vegetation. The water content of droplets may evaporate before being deposited in the area surrounding the exhaust falling within micro or even nanometer particle diameter range. Coarse and fine particles are emitted either directly from the gas-liquid contactors or when the drift droplets evaporate and leave fine particulate matter formed by crystallization of dissolved solids. Thus, the diameter of the particulate matter in the aerosol out of such contactors can vary over a few orders of magnitude ranging from a few nanometres for freshly generated particles to a few hundred microns for larger coarse droplets and agglomerated particles. The mechanical, physical and chemical properties of the particulate matter change over this wide range and thus it is of high importance to first review the characteristics of different sized particles, formation, classification, growth and deposition mechanisms.

# Aerosol emissions from air capture devices

All air capture devices investigated in this study can be classified as a form of gas-liquid contactors. The emissions from gas-liquid contactors can occur via vapours, gases, and aerosols. Emission in the gaseous state is abundantly studied and regulated. Conversely, understanding the problems linked to aerosols in gas-liquid contactors plants is less understood since it has not been investigated as profoundly.

Based on the literature the chemical composition of the solvent and the vapour pressure of the solvent are the two key factors determining new particle generation rates in the contactor.

# Methodology

Three different instruments were used to measure number concentration, size distribution and mass concentration of aerosols that are being emitted from the air capture devices.

The instruments can measure three characteristic attributes of the particulate matter within an aerosol:

* Particle size (diameter)
* Particle number concentration
* Particle mass concentration

A TSI Scanning Mobility Particle Sizer (SMPS), consisting of a condensation particle counter (CPC TSI 2022) and an electrostatic classifier (EC TSI 3071), is used to measure the number concentration and size distribution of particulate matter in the aerosol. Also using SMPS data, the particle mass concentration can be estimated by making a few simplifying assumptions.

A TSI Dusttrak 8530 is used to measure particulate matter mass concentration. The device uses different impactors enabling the user to measure PM1, PM2.5 and PM10. For the present study, only the PM2.5 and PM10 impactors are used; for smaller particles, SMPS can yield more accurate and more precise data.

A TSI Aero Trak 9306 is used to collect data on particulate matter mass and size distribution and number concentration.

# Results and discussion

In this section, the results of the experiments carried out on the three different gas-liquid contactors are presented and discussed.

## RLS

The first air capture device to investigate is the innovative Rotating Liquid Sheet (RLS). The device uses a rotating slotted tube to project sheets of liquid in a spiral form, and thus RLS does not use any type of packing; the air gets into contact with very thin rotating sheets of the solvent and because the sheets are spiral and spinning, they also result in a pumping effect which lowers the pressure drop across the whole system.

The first plot shows a correlation graph of the variable and parameters recorded during the RLS operation. The plot is a network of a correlation data frame in which variables that are more highly correlated appear closer together and are joined by thicker paths. Paths are also coloured, blue for negative and red for positive. The proximity of the variable points is determined using multidimensional clustering methods.

The plot uses the Pearson Product-Moment Correlation Coefficient (PPMCC) to work out the correlations between variables. For the sake of simplicity, Figure 1 shows only correlations that are greater than 0.5.

There are correlations in the figure that are obvious and won’t be discussed; as such is the positive correlation between the inlet air velocity and pressure drop across the contactor. It can be seen that PM10 emissions have a negative correlation with that intake air velocity while solvent drift and air velocity have a positive correlation. The data points for RLS were not many and so some of the correlations that can be seen in the figure may represent a real relationship.

Diagram

Description automatically generated

Figure , Correlation network diagram for RLS

Having studied the correlation diagram, some of the correlations need a more profound investigation.

Figure 2 shows the effect of intake air velocity on the solvent drift. The vertical axis shows the percentage mass of solvent that escapes the contactor per unit mass of solvent in the contactor. The grey area shows the 95% confidence interval. The graph shows that the velocity of air has a slight positive effect on the drift; however, the limited number of experiments carried out on RLS makes it difficult to decide whether or not the effect is statistically significant. The RLS was equipped with a cyclone scrubber to remove large droplets in the outlet, which may be the key reason why the drift does not change considerably with increasing intake air velocity.

Chart, line chart

Description automatically generated

Figure , Effect of intake air velocity on the solvent drift in RLS

Figure 3 shows PM10 emissions in the outlet of RLS. As air velocity increases more volume of air passes through the device and also noting the centripetal force is proportional to the square of the velocity, implying that a doubling of speed will require four times the centripetal force to keep the motion in a circle. So when the velocity of air going through the cyclone increases the larger and heavier particles are removed more effetely in the cyclone.

Chart

Description automatically generated

Figure , effect of intake air velocity on PM10 emissions

Other correlations that can be observed in figure 1 are not worth a deeper study as they are either not within the scope of this study or they are not statistically important or they are not meaningful.

## Cooling tower

As mentioned before, a cooling tower is modified to be able to use as a gas-liquid contactor. A mixture of taurate and caustic is used in the cooling instead of water.

Figure 4 illustrated the more significant correlations between recorded variables and parameters. The drift has a positive correlation with PM10 and also particulate matter emissions have a direct correlation with the median diameter of the particles.

Map

Description automatically generated

Figure , Significant correlations between variables

It can be seen in the figure that the type of packing and distributor affect the particle count, so they may as well affect the PM10 emission.

Figure 5 shows the effect of distributor type, x-axis, on the PM10 emissions of the cooling tower, on the y-axis. Three types of distributors were tested for the aerosol experiments:

* a full cone random single nozzle (fc),
* a distributor made of four hollow-cone nozzles, (hc, the original design)
* and a spinning three-arm sprinkler (sp\_3arm).

The boxplot shows that the full cone nozzle caused more PM10 followed by the hollow cone and the sprinkler. The full cone system caused almost four times higher PM10 than the sprinkler although the operating flowrate of both was almost identical at around 5 lit/min.

Chart, box and whisker chart

Description automatically generated

Figure , Effect of distributor type on PM10 emissions from the cooling tower

Figure 6 shows the percentage of solvent drift against intake air velocity and categorized by the two different fill-blocks used in the cooling tower. As expected the drift increases with the increasing intake air velocity. The fill-block-n shows a more pronounced correlation with air velocity that the original fill-block.

Chart, scatter chart

Description automatically generated

Figure , Effect of intake air velocity on solvent drift for two fill-blocks in the cooling tower

Figure 7 shows the PM10 emissions for the cooling tower for the used fill-blocks and distributors. Interestingly, the slope of the stat-smooth line is almost the same in all four cases. The three distributor types tested in the experiments were quite different in terms of droplet size. The full cone random single nozzle system (fc) caused the smallest droplets and the three-arm rotating sprinkler (sp\_sarm) caused the largest solvent droplets, yet all distributors acted quite similar in terms of PM10 emissions. One possible explanation would be the fact that the cooling tower was equipped with a demister being able to effectively remove the larger droplets.

Chart, scatter chart

Description automatically generated

Figure , Effect of intake air velocity on PM10 emissions for two fill-blocks in the cooling tower

Figure 8 shows the effect of flowrate on PM10 and PM2.5 emissions from the cooling tower. It seems that flowrate does not correlate with the PM10 emissions. Again the efficacy of the demister in removing larger droplets is probably the reason why particulate matter emissions stayed steady across the wide range of solvent flowrates. Figure 9 presents the drift percentage as a function of solvent flowrate, and here again, a drift stayed almost the same while the solvent flow rate is changing from 3 (lit/min) to 55 (lit/min)

Chart, box and whisker chart

Description automatically generated

Figure , Effect of solvent flowrate on the particulate matter emissions

Chart, box and whisker chart

Description automatically generated

Figure , Effect of solvent flowrate of the drift

## Packed column

Figure 10 depicts the correlation network for recorded variables in the packed column. Two solvents were used, hence the strong correlation between medium and ph. Solvent flow rate (fliq) shows a positive correlation with the amount of carbon dioxide absorbed (co2diff). Three different packings were used and it is shown in the network that the type of packing has a statistically significant effect on the carbon dioxide absorption, drift and pressure drop across the packing (dp). The variations in the abovementioned can be attributed to the type of packings and the fact that they provided different effective surface areas for the solvent and gas to contact.

For this part of the experiments, stainless packings (ss304), high-flow plastic packings (pp) and a prototype structured packing (cp) made by Curtin University are compared.

Diagram

Description automatically generated

Figure , Correlations between variables in the packed column

Figure 11 shows the pressure drop across the packing with respect to the air velocity. Stainless steel packing (ss304) has the most effective surface area and thus caused the highest pressure drop, followed by the plastic packings and Cutin University structured packing.

Chart

Description automatically generated

Figure , effect of air velocity on pressure drop across the packings

Figure 12 shows solvent drift against solvent flowrate and for different tested packings. It can be seen from the figures that although the Curtin University packing has the lowest pressure drop, it causes the highest solvent drift comparing to stainless steel packing and plastic packing. The reason behind this observation is yet to discuss and needs a more profound investigation.

Chart, box and whisker chart

Description automatically generated

Figure , effect of solvent flowrate on solvent drift for different packings

Figure 13 shows the effect of air velocity and type of packing on the solvent drift. Much like the previous figure, while stainless packing and plastic packing were virtually in the same order in terms of solvent drift, the Curtin University structured packing caused almost twice as much drift for the same air velocity.

Chart

Description automatically generated

Figure , effect of air velocity and type of packing on solvent drift from the packed column

# Discussion

Now that all three types of gas to liquid contactors are studied one by one, this section tries to compare some of the performance characteristics of the contactors.

An interesting correction was observed between the number concentration of particles in the outlet of contactors and ambient CO2 (nc and CO2in). The correlation is real and statistically significant. But a more profound investigation showed that the correlation is due to the traffic in the surrounding area. When there is more traffic the concentrating of CO2 goes up and also the number concentration of nanoparticles increases.

Chart, scatter chart

Description automatically generated

Figure , correlation between ambient carbon dioxide on particle count

Figure 16 shows the total particle number concentration of the three contractors. It shows that the packed column caused considerably more particles followed by the cooling tower and RLS. One reason for this observation is the fact that the packed column with random packing provided the largest surface area and caused the highest pressure drop. On the contrary in RLS, where packings or fill-blocks are non-existent, caused the lowest pressure-drop, and smallest surface area and the least number of particles.

Chart, box and whisker chart

Description automatically generated

Figure , the effect of using different air capture devices on nanoparticle count

Figure 17 compares the contactors in terms of solvent drift. Although the cooling tower resulted in a fewer number of particles, the drift out of the cooling tower was more than the packed column and RLS. Here it is important to point out that 90 per cent of the particle count comes from the particles that are smaller than 100 nm and interestingly they contribute to 10 per cent of the total mass of the particulate matter emitted. it seems that because both RLS and packed column were equipped with a cyclone, the larger droplets were effectively removed from the out-going stream while smaller particles escaped the cyclone. Whereas in the cooling tower, the demister was not able to remove larger particles as effectively. Perhaps if the height of the demister is increased it can perform better.

Chart, box and whisker chart

Description automatically generated

Figure , the effect of using different air capture devices on solvent drift

Figure 18 confirms the findings of the previous figure. The median diameter of particles emitted from the cooling tower is more than RLS and packed column which corroborates why drift from the cooling tower was more.

Chart, box and whisker chart

Description automatically generated

Figure , the effect of using different air capture devices on the particulate matter median diameter

Chart, scatter chart

Description automatically generatedTo sum up, figure 18 shows the effect of intake air on solvent drift categorised by the contactor, colour-coded by packing type and sized by the flow rate. It is seen that intake air velocity plays a key role in the drift. The flow rate of the solvent did not show a statistically significant effect on the drift. From the figure, it can be deduced that the cooling tower with the original fill-block and packed column with high flow plastic packing might be preferable over the other packings and contactors. The RLS flowrate was almost five times the highest flow rate in the packed column and almost ten times higher than that of the cooling tower. Stainless still packing showed that they will cause the smallest solvent drift, but they also caused the highest pressure-drop which limits the maximum achievable flow rate.

Figure , effect of intake air velocity on the drift for the three contactors

# Nomenclature

tgin: Temperature of air at inlet

hgin: Relative humidity of air at inlet

tgout: Temperature of air at outlet

hgout: Relative humidity of air at outlet

ph: PH of the solvent

tliq: Temperature of the solvent

co2in: Carbon dioxide at the inlet (ambient CO2)

co2out: Carbon dioxide concentration in air at the outlet

dp: Pressure drop across the contactor (mm.wc)

vg: Air velocity (m/s)

dustrak: PM10 measured by TSI Dusttrak (mg/m3)

cmd: Particle median diameter (nm)

nc: Partocle number concentration (#/cm3)

mass: PM10 measured by TSI Aerotrak

ambpm: Ambient PM10 (mg/m3)

driftmgkg: Solvent drift (%)

loading: Solvent loading (fraction)

co2diff: Difference between inlet and outlet CO2 concentration

fliq: Solvent flowrate (lit/min)

packing: type of packing

medium: medium, either taurate or caustic

disb: Distributor type

device: Air capture device

# Codebook

Codebook for air capture project:

This document explains the variables in the “all\_for\_R.xlsx”

The dataset is a collection of data collected manually and or automatically from the air capture rig in CSIRO Energy site, Mayfield West. The Experimental campaign started from mid-2019 and finished in January 2021.

Below all the variables that are used in the dataset for data analysis phase is described:

Time: The time at which the observation is carried out

Run#: Observation unique ID; every observation has a unique ID to be able to identify any specific run at any time. The Run# is composed of a strig of characters “CT” for cooling tower, PC for packed column and RLS for rotating liquid sheet and a number. Also, ambient measurements are identified by “amb” in the same column.

Tgin: Inlet air temperature (C)

Hgin: Inlet air relative humidity (%)

Tgout: Outlet air temperature (C)

Hgout: Outlet air relative humidity (%)

PH: pH of the solvent

Tliq: Solvent temperature (C)

Fliq: Solvent flowrate (lit/min)

CO2in: Carbon dioxide concentration at inlet, or ambient (ppm)

CO2out: CO2 concentration at outlet (ppm)

dp: Pressure drop across the contactor (mm.H2Oc)

vg: Gas velocity (m/s)

Tliqo: Solvent temperature at outlet

Comment: Comments, type of distributor is mentioned here

dustrak: PM10 measurements by TSI Dusttrak (mg/m3)

SMPS: particulate matter median diameter from TSI SMPS (nm)

Total.no: Total number concentration of particle (#/mc3)

mass: Particulate matter mass concentration estimated by TSI SMPS from size distribution histogram (µgr/m3)

PC: Type of packed column, ss for stainless steel, pp for plastic, csp for Curtin Uni structured packing.

ambpm: Ambient PM10 (mg/m3)

flowrate1: Air flowrate (m3/s)

pmmghour: PM10 emitted per hour (mg/hr)

fliqkghr: Solvent mass flowrate (kg/hr)

driftmgkg: Drift from the contactor, mg per kg of solvent going through the contactor (fraction)

type: packing type

medium: Taurate or caustic soda

loading: Solvent loading at start of the experiment