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**Dominic Davis**

# Particle Residence Time Distributions in a Solar Vortex Receiver

Dominic Davis[1], Alfonso Chinnici[1], Woei L. Saw[2], Timothy Lau[1] and Graham J. Nathan[1]

[1]*School of Mechanical Engineering, Centre for Energy Technology, The University of Adelaide, South Australia 5005, Australia*

[2]*School of Chemical Engineering, Centre for Energy Technology, The University of Adelaide, South Australia 5005, Australia*

*E-mail: dominic.davis@adelaide.edu.au*

## Abstract

There is a growing interest in the use of solid particles as the absorber of concentrated solar thermal radiation, due to their high surface area per unit mass and compatibility with direct irradiation. A solar particle receiver technology that has received recent attention features direct irradiation of particles that are transported by a carrier gas and suspended in a vortex within a cylindrical cavity, termed the solar vortex receiver, SVR. To support the development of vortex-based particle receiver systems, new understanding of the particle residence time distributions within the receiver and their influencing factors is required. In the present paper, a method has been developed for measuring particle-phase residence time distributions in a laboratory-scale vortex-based solar particle receiver using a modified tracer pulse method. The measurements quantify the influence of both air volumetric flow rate and particle size on the particle residence time distribution, with trends that are consistent with expectation. Both an increase in the air flow rate and a decrease in particle size result in a shorter, narrower distribution of residence times.

## 1. Introduction

It is well known that the residence time of particles within a particulate system is a crucial parameter affecting the thermal performance of the system. Particularly in swirling systems, where the mixing of gases is intensive, events such as sensible heating, combustion and other thermochemical reactions are heavily influenced by residence time within the system (Li et al., 2008). One such swirling particulate system is a vortex-based solar particle receiver-reactor, in which particles are conveyed by a vortex flow of gas through the irradiation zone from a solar concentrator. This two-phase gas-particle flow configuration is confined to a cylindrical cavity, and has been used to demonstrate several solar thermochemical applications at laboratory-scale (Steinfeld et al., 1992; Z'Graggen et al., 2006; Davis et al., 2017). Calculation of the thermal performance of such a particulate system requires accurate information about the flow pattern within the system (Lede et al., 1987; Allal et al., 1998) and this aerodynamic behaviour is generally characterised by the particle residence time distribution (RTD); the probability distribution of how long a particle will be retained within a vessel for a given set of operational conditions. Without comprehensive understanding of the particle RTD within a vessel, calculation of the thermal performance relies on one of two assumptions (Danckwerts, 1995):

- that the fluid and particles within the vessel are well mixed and thus, all properties are uniform through the vessel, or
- that the fluid and particles follow a plug flow, where all fluid and particles that enter the vessel at the same time have the same velocity along parallel paths and will leave at the same time. Each fluid element and particle thereby has the same residence time, termed the nominal residence time, $\tau_{nom}$.

In practice, however, many systems do not conform to these assumptions. Furthermore, the hydrodynamic behaviour of particles is likely to be different to that of the transporting gas (Lede et al., 1987), particularly for cases where the Stokes number of the gas-particle flow is greater than unity (Chinnici et al., 2015). Consequently, performance calculations made with these assumptions may be inaccurate. The overall objective of the present paper, therefore, is to support the development of vortex-based solar particle receiver-reactors by providing new understanding of the particle RTD within the vessel and its influencing factors.

The vortex-based solar particle receiver-reactor concept (hereafter named the solar vortex receiver, SVR) has been demonstrated experimentally for solar thermochemistry applications by Hirsch & Steinfeld (2004), Z'Graggen et al. (2006) and Davis et al. (2017) for the thermal decomposition of natural gas, the steam-gasification of carbonaceous feedstocks and the calcination of alumina respectively. Each of these investigations conducted at laboratory-scale used concentrated solar radiation entering through a transparent quartz window, followed by the aperture of a cylindrical cavity to directly irradiate a suspension of reacting particles in a vortex flow of gas. The vortex particle-gas flow proceeds through the receiver cavity with residence times in the order of seconds and exits with elevated temperature reported at over 1000°C. A SVR has the advantage of highly efficient heat transfer to the particle phase due to direct irradiation, as demonstrated by the high extents of chemical conversion reported with residence times in the order of seconds. However, direct measurements of particle residence time within such entrained flow solar particle receivers have not previously been made. Rather, a nominal particle residence time has been calculated in previous investigations from experimental conditions as the ratio of receiver internal volume to gas volumetric flow rate ($\tau_{nom} = V_r/\dot{V}_{gas}$). This value is generally corrected for gas expansion with temperature, and evolution with extent of chemical reaction. In reality, both gas and particle residence times in a vortex flow configuration will differ from this nominal residence time, as has been shown by Shilapuram et al. (2011) in their assessments of a solar cyclone reactor with a CFD model of the reactor at laboratory-scale. They assessed the closeness of the residence time of gases and 1µm sized particles to the nominal residence time and found that the mean residence times of both phases were longer for all of the of conditions assessed. It is further important to note that not all particles are likely to have the same residence time within a vessel, rather their residence time will follow a certain distribution function for a given set of operational conditions. There is thus a need to develop methods of directly measuring particle residence time distributions within vortex-based receiver-reactors for a given set of operational conditions.

Although the energy conversion efficiency of the SVR has been found to be among the highest of directly irradiated solar reactors, it has also been found that it has a particle residence time distribution that is approximately independent of particle size (Chinnici et al., 2015). This is an adverse finding because the possible extent of sensible heating of an inert particle or chemical conversion of a reacting particle in a solar reactor depends on the ratio of the particle residence time within it to the time required for sensible heating or reaction. This is a disadvantage for industrial application because most practical systems operate with a range of particle sizes, in which case it is desirable that the larger particles have longer residence times relative to smaller particles, so that efficient processing of the poly-disperse particles is achieved. To address this issue, Chinnici et al. (2015) proposed a modified SVR configuration, termed the Solar Expanding-Vortex Particle Receiver-Reactor (SEVR), which also features a cylindrical cavity, but in contrast to the SVR, has a conical inlet section at the opposite end of the cavity to the aperture. The modified configuration also has a radially-oriented outlet. Their initial analysis by CFD indicated that the SEVR has strong potential to preferentially increase the residence time of larger particles relative to smaller particles within the receiver. It was apparent that this effect is characterised by the Stokes number, *Sk* – defined as the ratio of the response time of a particle suspended in a fluid flow to a time characteristic of the flow. For $Sk > 1$, the particle motion is only weakly influenced by fluid motion and it was found that the greater the Stokes number the longer the mean residence time of particles in the SEVR. For $Sk < 1$, the particles follow the gas streamlines more closely and have mean residence time closer to the nominal gas residence time. The mechanisms by which this preferential increase in residence time occurs were also proposed, where the radially-oriented outlet means that large particles that do not follow gas streamlines as closely due to their greater inertia are less likely to leave through the exit and are thus retained within the reactor for longer. Additionally the conical base section funnels recirculated large particles into the most intense part of the vortex for recirculation (Chinnici et al., 2015). These proposed mechanisms have been partially validated by an experimental investigation into the flow field. However, only one receiver geometry and flow rate were considered (Chinnici et al., 2016). Therefore, the aerodynamic mechanisms by which the particle residence time distribution in the SEVR are ameliorated have been proposed, but their physical effect has not been experimentally measured. There is thus a need for direct measurements of RTDs of various particle sizes within the SEVR of various geometrical configurations and with various flow rates and a consequential comparison to RTDs in the SVR configuration.

Methods of measuring particle residence times within a vessel range from relatively simple measurements of a mean residence time value, to more complicated tracking of many individual particles to obtain a distribution of residence times. The particle hold up in a vessel – the total mass, $m$, of particles within the vessel at a given instant – gives an indication of mean particle residence time, which is calculated with the mass flow rate, $\dot{m}$, by $\overline{\tau_p} = m/\dot{m}$. Both Szekely & Carr (1966) and Li et al., (2008) measured particle hold up in cyclone particle separators and found that hold up, $m$, increased linearly with solids flow rate, $\dot{m}$, indicating no influence of particle flow rate on mean particle residence time. Variation in particle residence time in such a swirl system is rather caused by changes in geometry, particle size and gas flow rate. Another method of determining mean particle residence time in a cyclone is based on the photographic measurement of the axial component of velocity at all points along the length of the cyclone (Lede et al., 1987). The mean particle residence time is then calculated by integrating the reciprocal of the particle velocity over the length of the cyclone. These methods of mean particle residence time determination operate with steady-state gas-particle flow, and are therefore more representative of particulate system operation than methods that employ a pulse particle input. However, they do not allow for the calculation of the distribution of particle residence times in the particulate system, as is manifest in vortex-based solar particle receivers. To measure the distribution of residence times in the riser of a circulating fluidised bed, Harris et al. (2002)

developed a non-disruptive optical method, which used phosphorescent pigment coated particles as a tracer located within the bulk particle phase. The tracer particles were activated at the inlet of the riser with a high intensity pulse of light, rather than a physical pulse injection of tracer. The tracer particles were then detected using a photomultiplier at the riser exit. This is a fast-response method that avoids possible measurement bias associated with physical pulse injection techniques, but requires correction for the time-decay of phosphorescence. Lede et al. (1987) and Allal et al. (1998) developed methods based on the well-established pulse response RTD measurement technique, where a pulse of particles was injected into a cyclone reactor and a vertical tube reactor, respectively. Detection of the particles at the inlet and outlet was performed with the use of a light emitting diode and phototransistor combination. The pulse response of particles measured at the outlet of the vessels approaches the RTD within the vessel as the inlet pulse approaches a perfect Dirac delta function. Measurements of the mean particle residence time with this method were found to have good agreement with the mean residence time calculated from the particle hold up for the cyclone operation, but additionally allowed assessment of the distribution of residence times. The pulse response method for particle RTD measurement however requires that the particles are a dilute phase within the vessel to ensure that the injection of particles has negligible impact on the steady-state gas flow. To measure particle RTDs in the vortex-based solar particle receiver at laboratory-scale a technique is required with short response time, due to the short residence times in the order of seconds. It is also important that the method is able to determine the distribution of residence times for a given set of operational conditions including different particle size, and can be adapted to particle receivers of various geometries and configurations.

The overall objective of this work is to support development of vortex-based particle receiver systems by providing new understanding of the particle residence time distributions and their influencing factors. Specifically, this paper develops a method of determining particle residence time distributions in a laboratory-scale vortex-based solar receiver for a range of operational conditions and receiver geometries. It is the aim of this paper to assess the influence of gas phase flow rate and particle size on particle residence time distributions in a Solar Expanding Vortex Receiver (SEVR) of a single geometry.

## 2. Methodology

The particle residence time distribution is determined in the present investigation with a modified tracer pulse method. Levenspiel (1999) and Fogler (2006) describe the tracer pulse method of RTD determination for a continuous flow vessel. In this method, a tracer with similar physical properties to the main fluid in the vessel is injected into the feed stream of the vessel in as short a time as possible. The recorded concentration of tracer at the outlet (normalised by the total amount of tracer injected) then approaches the RTD of fluid in the vessel. For the present case of a two-phase gas-particle flow, the particle phase – rather than a tracer – is injected as a pulse into the SEVR vessel, the concentration of which is directly measured at the inlet and outlet of the vessel. The concentration of particles is measured with time-resolved laser extinction measurements at both the inlet and outlet of the SEVR cavity. This method is considered valid because the particle phase is dilute within the receiver. That is, in previous assessments of the SVR the particle to air volume fraction has been < $10^{-4}$. This means that the particle phase has negligible effect on the flow-field of the gas phase, and thus the RTD determined for a pulse of particles is representative of the RTD for particles fed with constant mass flow rate. To isolate the influence of particle size on the RTD, spherical polymer particles of density $\rho_p$ = 1200 kg/m$^3$ were used. These particles have a narrow size distribution, such that it can be assumed that the two-phase particle-laden flow is truly monodisperse (Lau & Nathan, 2016).

### *2.1. Experimental arrangement*

Figure 1 presents the experimental arrangement used to determine the residence time distribution of particles within the SEVR cavity. The pulse feeding subsystem consists of two air lines connected in parallel. Prior to each measurement repetition 0.35 g of particles are loaded into the particle basket connected to the secondary feeder air line, with the valve closed. Steady state vortex flow conditions are then established within the cavity by injecting equal amounts of compressed air to the two tangential inlets, the primary feeder air line and the second tangential inlet. The receiver cavity is oriented vertically with inlet and conical section located at the bottom, such that the vortex flow proceeds upwards. To inject a pulse of particles, the valve connected to the particle basket is opened such that air flows through both feeder air lines without disrupting the total amount of air injected into the receiver cavity. It can therefore be assumed that steady state air flow conditions are maintained during particle pulse feeding. Extinction measurements are carried out with the use of a 4.5 mW, 635 nm collimated laser diode (*Thorlabs* CPS635S) and a photodetector (*Thorlabs* DET36A/M). The laser and photodetector are mounted perpendicular to the centre axis of the inlet and outlet tubes, as shown in Figure 1. As particles pass through the inlet/outlet tubes the laser light is attenuated. Laser light levels are recorded with the photodetector with a sampling frequency of 10 kHz and for a total time of 60 seconds for each measurement repetition.

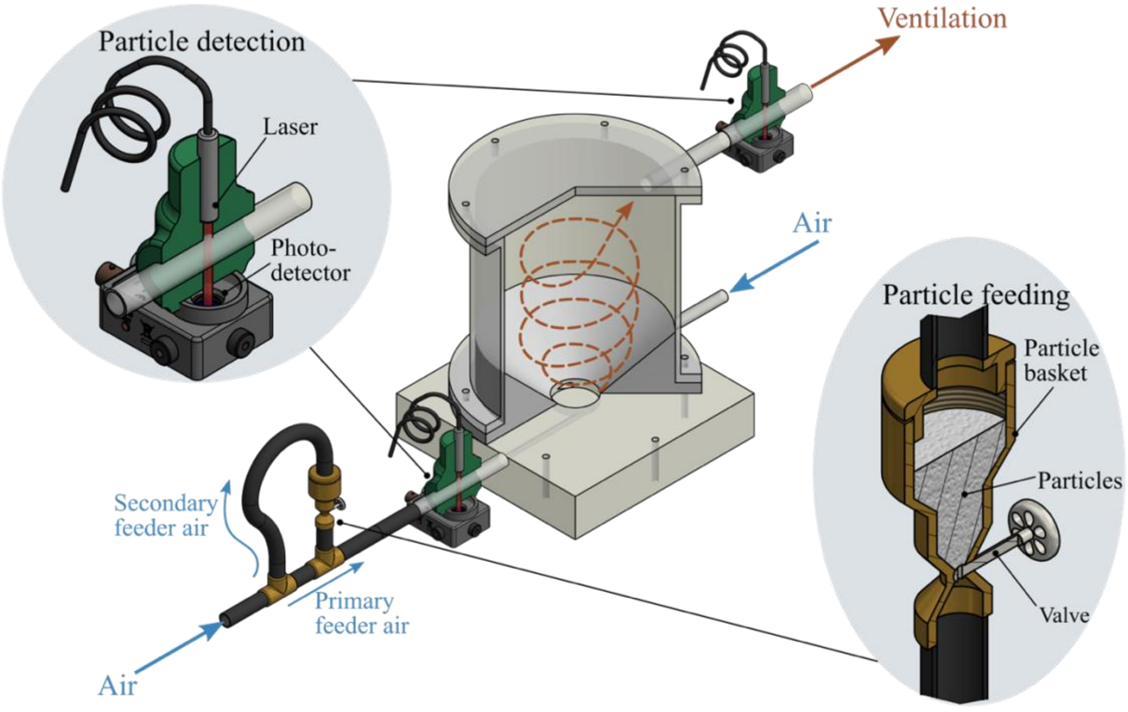


**Figure 1. Experimental arrangement used to determine the residence time distribution of particles within a solar vortex receiver. The schematic shows particle feeding and detection subsystems, as well as the receiver rig which features two tangentially-oriented inlets and a single radially-oriented outlet (the SEVR configuration).**

## 2.2. Measurement cases

The present work investigates the influence of air flow rate and particle size on the particle RTD for a single SEVR configuration. Figure 2 and Table 1 present the specific geometry of this receiver configuration. The present investigation considers operation in the fully turbulent regime, where air flow rates are chosen such that the inlet jet (with constant inlet jet diameter) is fully turbulent ($Re_{in}$ > 5000), to ensure relevance to industrial scale operation of the device.

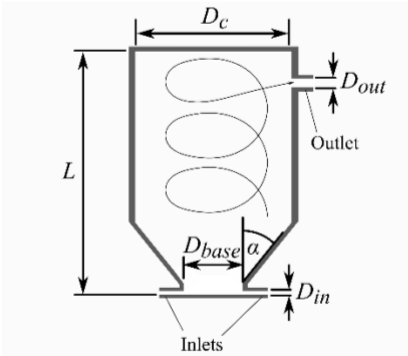


**Figure 2. Schematic diagram of the SEVR showing the key geometric dimensions, two inlets and one outlet.**

**Table 1. Values of the key geometric parameters for SEVR configuration assessed.**

| | |
|---|---|
| $D_c$ | 190 mm |
| $L$ | 237.5 mm |
| $D_{base}$ | 47.5 mm |
| $\alpha$ | 50° |
| $D_{in}$ | 6 mm |
| $D_{out}$ | 11 mm |

The particle RTD is assessed in Stokes regimes both greater and less than unity, which means that a range of particle sizes is required. The Stokes number for a swirling particulate system is calculated following previous work (Derksen et al., 2006):

$$Sk = \frac{\rho_p d_p^2 U_{in}}{18 \mu D_c}, \quad (1)$$

where $\rho_p$ is the particle density, $d_p$ is the particle diameter, $U_{in}$ is velocity of air injected into the receiver, $\mu$ is the air dynamic viscosity and $D_c$ is the receiver chamber's internal diameter. This definition of Stokes number gives an indication of the likelihood that particles will follow the gas streamlines through the receiver, and thus how similar the particle residence time is to the air residence time. Here, particle sizes $d_p$ = 40 µm and 80 µm are used, and air volumetric flow rates (in standard litres per minute, *SLPM*) $\dot{V}_{air}$ = 70, 90 110, 130 and 150 *SLPM*, which result in the inlet flow having Reynolds numbers in the range ~ 8500 – 18200, and the flow within the receiver chamber having Stokes numbers in the range 0.84 – 5.57. Because the inlet diameter is fixed at $D_{in}$ = 6 mm, $U_{in}$ varies with varying air flow rate, and therefore higher Stokes numbers result from higher air flow rates. The air volumetric flow rates used here result in nominal air residence times, $\tau_{air} = V_{receiver}/\dot{V}_{air}$ = 2.21 – 4.73 s.

## 2.3. Measurement of the residence time distribution

For a particulate system operating at steady state, the outlet concentration of particles is said to be the convolution of the inlet concentration with the residence time distribution (RTD). The convolution integral is:

$$o(t) = i(t) * E(t) = \int_0^t i(t - t')E(t')dt', \tag{2}$$

where $i(t)$ and $o(t)$ are the inlet and outlet particle concentration measurements with time, and $E(t)$ is the residence time distribution of particles within the receiver (or the exit age distribution, following Danckwerts, 1995). For the pulse injection method the recorded outlet concentration of particles approaches the particle RTD, $E(t)$, as the pulse injection approaches a perfect Dirac delta function. However, the deconvolution of Equation 2 is required to correct for imperfect or inconsistent pulses. Calculation of the particle RTD in the present investigation therefore requires the deconvolution of the inlet and outlet signals, $i(t)$ and $o(t)$, respectively. This is accomplished here by converting the recorded signals to the Fourier domain with a fast Fourier transform ($\mathcal{F}\{i(t)\}$ and $\mathcal{F}\{o(t)\}$). The deconvolution integral in Equation 2 then becomes:

$$O(s) = \mathcal{F}\{i(t)\}\mathcal{F}\{E(t)\} = I(s)E(s), \tag{3}$$

$$E(s) = \frac{O(s)}{I(s)}. \tag{4}$$

Despite filtering the recorded signals with a low-pass filter, $I(s)$ contains zeros or small magnitudes at many frequencies, which brings noise into the inverse of $E(s)$. To counter this a Tikhonov regularisation is used, where $\lambda = 10^{10}$ is the regularisation factor, and:

$$E(s) = \frac{O(s)}{I(s) + \lambda}. \tag{5}$$

The inverse fast Fourier transform is then taken to calculate the RTD with:

$$E(t) = \mathcal{F}^{-1}\{E(s)\}. \tag{6}$$

The solution of $E(t)$ is made insensitive to the size of the regularisation parameter by normalising $E(t)$ by the area bounded by the distribution.

Because particles are a discrete medium in a two-phase gas-particle flow, their measurement by extinction results in a fluctuating signal whose filtered profile follows the RTD for a given case. Fluctuations in the signal can also arise from turbulent instabilities in the flow, whose influence also needs to be filtered to derive the RTD (Danckwerts, 1995). For these reasons, the RTDs presented here are averaged from 10 repeated measurements.

Also presented here is the mean particle residence time, $\bar{\tau}_p$, of a residence time distribution, $E(t)$, the peak residence time, $\tau_{peak}$, and 60th and 90th percentile residence times, $\tau_{60}$ and $\tau_{90}$. The mean and percentile residence times are calculated according to:

$$\bar{\tau}_p = \int_0^\infty tE(t)dt, \text{ and} \tag{7}$$

$$\int_0^{\tau_{60}} E(t)dt = 0.60 \text{ and } \int_0^{\tau_{90}} E(t)dt = 0.90. \tag{8}$$

To reduce the effect of measurement noise at large $t$ on these calculated parameters, a log-normal distribution is fitted to the measured particle RTD. That is, a Gaussian curve is fitted to the RTD data, by taking the logarithm of residence time as is shown in Figure 3. The equation of the Gaussian curve is then used as $E(t)$ in equations 7 and 8. The peak residence time, $\tau_{peak}$, is the time at which the maximum in the fitted Gaussian curve occurs. This method is considered valid because the Gaussian curves fitted to the RTD data each have coefficient of determination value, $R^2 > 0.95$.

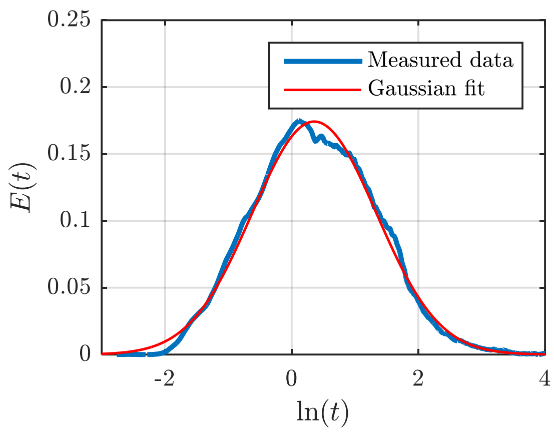


**Figure 3. Representative particle RTD measurement in comparison with a log-normal distribution, measured for particle size $d_p$ = 80 µm and $\dot{V}_{air}$ = 110 *SLPM*.**

## 3. Results & Discussion

Figure 4 presents a representative particle RTD measured for particle size $d_p$ = 80 µm and $\dot{V}_{air}$ = 90 *SLPM*, averaged from 10 repeated measurements. It can be seen that the distribution exhibits fluctuations. These are attributable to the discrete nature of particle distributions, together with the role of turbulent fluctuations, as described above. These discrete fluctuations are present despite the RTD being the average of 10 measurement repetitions. While additional repetitions could reduce this variability, there is a constraint of experimental time required to do so. Furthermore, for a particular measurement case, 40 repeated measurements were taken, from which it was found that the mean particle residence time calculated became independent of the number of averaged repetitions with 10 and more repetitions.

It can be seen from the data presented in Figure 4 that the particle RTD in the SEVR rises to a maximum within a few seconds of residence time, with $\tau_{peak}$ = 1.34 s. After this peak occurrence of residence time the distribution decreases at a slower rate than the initial increase to maximum, such that a significant proportion of particles has residence time much longer than the peak value. The log-normal curve of best fit is shown with its function, and is used to calculate the mean residence time, $\overline{\tau_p}$ = 5.88 s, and the residence time parameters, $\tau_{60}$ = 4.72 s and $\tau_{90}$ = 13.12 s. These values indicate that for this case a majority of particles have residence time within the vessel of less than 5 s. However, the distribution of the residence time extends significantly past 5 s, where 10% of the particles have residence time greater than 13.12 s.

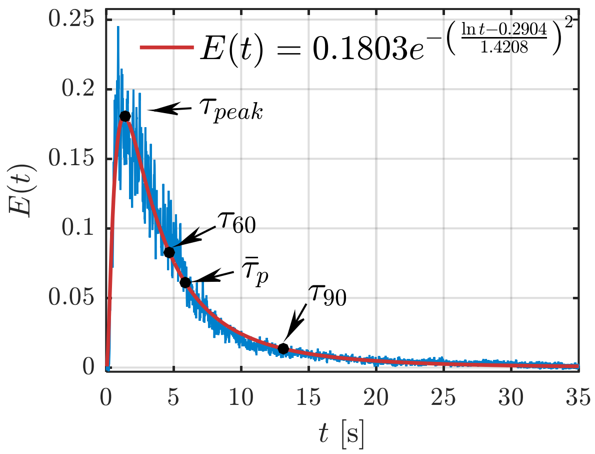


**Figure 4. Representative particle RTD measurement for particle size $d_p$ = 80 µm and $\dot{V}_{air}$ = 110 *SLPM*, in comparison with the log-normal distribution of best fit. Also shown is the function for the log-normal distribution and the location of key residence time parameters.**

### *3.1. Influence of air flow rate*

Figure 5a presents the particle RTD curves for particle size $d_p$ = 80 µm and 5 different air volumetric flow rates and constant geometry. These distributions have been smoothed for clarity, obtained from a moving point average spanning 0.125 s of measured data. The residence time parameters calculated from the curve fitted to a given RTD measurement were found to be independent of the amount of smoothing up to a moving point average span of 0.125 s of measured data. It can be seen that the RTD is shifted to a shorter and narrower distribution range by an increase in air volumetric flow rate. It should be noted that this change in flow rate was conducted at constant inlet diameter meaning that while it is expected that higher volumetric flow rates of air result in shorter residence times, the present effect on residence time may be influenced also by the inlet velocity of the flow.

Further insight into the RTDs can be gained by assessing their residence time parameters, $\bar{\tau}_p$, $\tau_{peak}$, $\tau_{60}$ and $\tau_{90}$. Figure 5b presents these parameters as a function of air volumetric flow rate for the five particle RTDs presented in Figure 5a. It can be seen that each of the residence time parameters decreases with increasing air volumetric flow rate, however these parameters decrease by different extent. The mean residence time, $\bar{\tau}_p$, decreases monotonically with increasing air flow rate, from 14.23 s for $\dot{V}_{air}$ = 70 *SLPM*, to 2.10 s for $\dot{V}_{air}$ = 150 *SLPM*. This corroborates the previous observations that with increasing air flow rate the RTD curve shifts to shorter residence times. It should be noted that, while there is significant difference between the mean residence times of the distributions presented here, there is only a small difference between the peak residence times, $\tau_{peak}$, which reduce from 2.59 s for $\dot{V}_{air}$ = 70 *SLPM*, to 0.85 s for $\dot{V}_{air}$ = 150 *SLPM*. On the other hand, the significant difference in the RTDs in Figure 5a is visible in the tail of the distribution, where for lower air flow rates the tail of the distribution increases. That is, a value of $\tau_{90}$ = 30.82 s for $\dot{V}_{air}$ = 150 *SLPM* means that there is a greater likelihood that particles recirculate in the receiver and have residence times up to and in excess of 30 s. This contrasts the cases of $\dot{V}_{air}$ = 130 *SLPM* and 150 *SLPM*, which have $\tau_{90}$ = 4.74 and 6.75 s, respectively and relatively negligible probability that of particle residence times longer than 10 s.

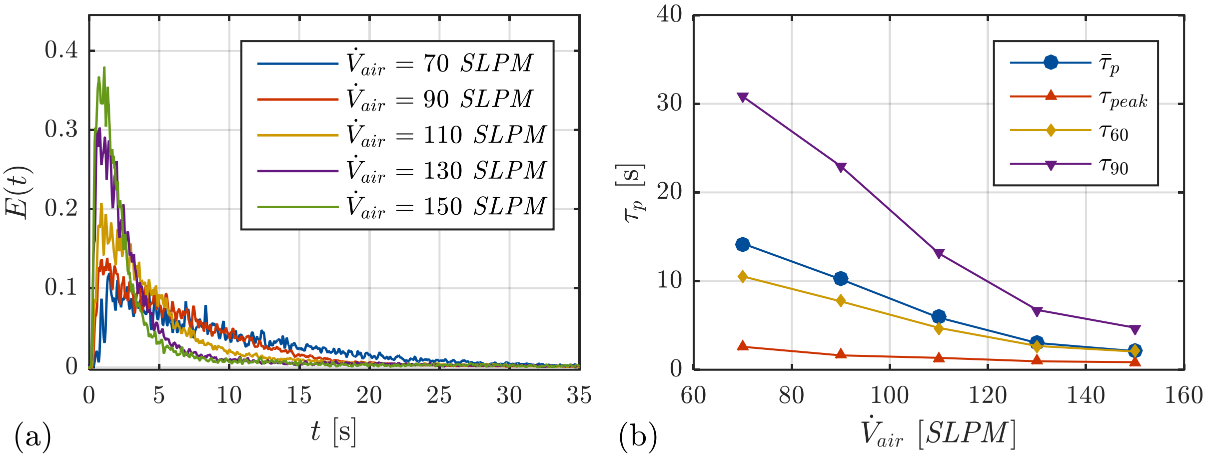


**Figure 5. (a) Smoothed particle residence time distributions, obtained from a moving average of 0.125 s of measured data. Conditions: particle size $d_p$ = 80 µm and 5 different air volumetric flow rates at constant inlet diameter; and (b) Key residence time parameters, $\overline{\tau_p}$, $\tau_{peak}$, $\tau_{60}$ and $\tau_{90}$, of the 5 particle RTDs as a function of air volumetric flow rate.**

### *3.2. Influence of particle size*

Figure 6 presents the particle RTDs measured for $\dot{V}_{air}$ = 90 *SLPM* and particle sizes $d_p$ = 80 µm and 40 µm. It can be seen that the smaller particle size has a narrower distribution of residence times and shorter tail than does the larger particle size. The values of $\overline{\tau_p}$ were calculated to be 10.20 s and 3.51 s, for $d_p$ = 80 µm and 40 µm respectively, while the values of τ90 were calculated to be 22.95 s and 7.50 s, respectively. These results indicate significantly different extents of particle recirculation for the two cases, where the larger particles have a wider distribution of residence times. This can be explained by the difference in Stokes number for the two cases. For the same air flow rate (and same inlet velocity) the Stokes numbers for the 80 µm and 40 µm cases are 3.34 and 0.84, respectively. This means that the smaller particles are more likely to follow the gas streamlines than the larger ones, particularly in the vicinity of the receiver outlet port. As proposed by Chinnici et al. (2015), the larger particles with greater inertia than the smaller particles will preferentially be retained in the receiver due to their weaker response to the flow gradients at the radially-oriented outlet port. They are thus less likely to leave the receiver and are preferentially recirculated in the receiver. The larger particles, with larger Stokes number therefore have longer residence time.

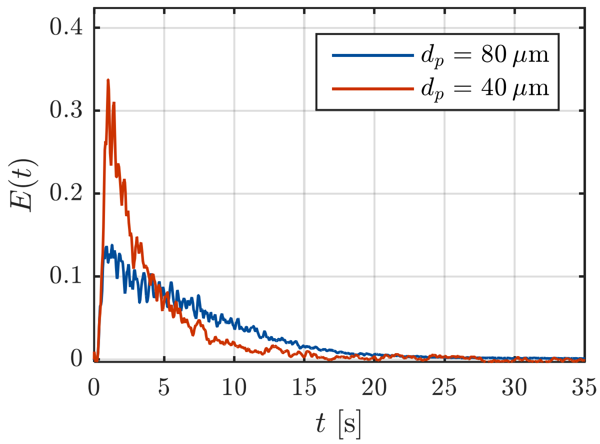


**Figure 6. Smoothed particle residence time distributions, obtained from a moving average of 0.125 s of measured data. Conditions: air volumetric flow rate $\dot{V}_{air}$ = 90 *SLPM* at constant inlet diameter and two different particle sizes $d_p$ = 80 µm and 40 µm.**

## 4. Conclusions

A method has been developed for determining particle-phase residence time distributions in a laboratory-scale vortex-based solar particle reactor using a modified tracer pulse method. The deconvolution of particle concentration measurements at the inlet and outlet of the receiver cavity has been used to calculate the particle RTD. Consistent with previously reported trends, it has been observed that the particle RTD features discrete fluctuations due to the discrete nature of particle concentration measurements. The particle RTD approximates a log-normal distribution, which is used to calculate key residence time parameters of each distribution for a given set of operational conditions.

The measurements quantify the influence of both air volumetric flow rate (with constant inlet diameter) and particle size on the particle residence time distribution with trends that are consistent with expectation. An increase in air flow rate has been shown to shift the distribution to shorter residence times and a narrower distribution of residence times. Specifically, for the current SEVR configuration, the mean residence time decreases from 14.23 s for $\dot{V}_{air}$ = 70 *SLPM*, to 2.10 s for $\dot{V}_{air}$ = 150 *SLPM*. The narrowing of the RTD with increasing air flow rate means that particles are more likely to have a uniform residence time. However these measurements did not maintain constant flow inlet velocity, which is required for future assessments to isolate the dimensionless parameters that have a fundamental controlling influence on the particle RTD.

A decrease in particle size, for a given air flow rate, has the effect of shifting the particle RTD to shorter residence times and narrowing the distribution of residence times. This is due to the decrease in Stokes number with smaller particle size, meaning that smaller particles are more likely exit the receiver and thus have shorter residence times. Further investigation of the effect of air flow rate and inlet velocity, particle size, and receiver geometry and configuration is required to comprehensively assess the behaviour or particles in a two-phase flow within vortex-based solar particle receivers.

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