SCAVENGE PERFORMANCE OF AN OPTIMIZED SHALLOW SUMP AT VARIOUS FLOW CONDITIONS

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ABSTRACT

Oil scavenge flow in aero-engine bearing chamber remains largely a challenging problem for many engine designers. Research campaign on scavenge flow has been conducted by G2TRC – Gas Turbine and Transmissions Research Centre (previously Rolls Royce University Technology Centre in Gas Turbine Transmission Systems) at the University of Nottingham. It was recognized that a deep sump performs better than shallower one due to its ability to "shield" the collected oil in the sump from the shaft windage thus reducing the amount of oil being picked up by the bulk air rotation. However, such a deep sump design cannot be employed in some engines and especially at certain locations where space is limited.

A parametric study combined with phenomenological approach on shallow sump geometry has been conducted and presented in the previous publication where a certain optimized shallow sump variant was proposed depending on whether the flow in the chamber is wall film dominated or airborne droplets dominated. The parametric phenomenological approach was employed since it can be done relatively quicker than typical data gathering through an experiment. However the approach relies on qualitative interpretation of the flow features, and its application in bearing chamber flow research has never been validated before. This paper presents the results of quantitative measurements of residence volumes of an optimized shallow sump variant identified in the parametric phenomenological study. Comparison was then made with the residence volumes of some existing engine sumps.

It was found that the optimized shallow sump for wall film dominated flow has lower residence volumes compared to some existing engine sumps. In some cases, the residence volume can be reduced by up to 75%. An optimized shallow sump variant for airborne droplets dominated was also identified in the previous parametric phenomenological study, although the residence volume measurement is yet to be conducted. The optimized shallow sump for wall film dominated flow was also identified as a good sump regardless of the flow regime. However when it was tested in airborne droplets dominated flow, its residence volumes are higher than some of the existing engine sumps. This highlights the importance of considering the flow regime in the bearing chamber in any attempt to optimize a sump geometry.

Keywords: bearing chamber, sump, scavenge, two-phase flow

NOMENCLATIURE

Q_G	Gas flow rate
Q_L	Liquid flow rate
R	Chamber radius
R_u	Upstream sump wall radius
R_d	Downstream sump wall radius
Re_G	Gas Reynolds number
Re_L	Liquid Reynolds number
SR	Scavenge ratio
We_L	Liquid Weber number
d	Sump depth
l	Droplet diameter
r	Shaft radius
u	Shaft speed

w	Sump width
z	Chamber axial width
θ	Sump orientation
ν_G	Gas kinematic viscosity
ν_L	Liquid kinematic viscosity
ρ_L	Liquid density
σ_L	Liquid surface tension

INTRODUCTION

Bearings in aero-engines support the mechanical operation of rotating shafts. Oil is injected to the bearings to lubricate as well as to remove heat. After it has done its work, oil leaves the bearings and enters the bearing chamber. The flow within the bearing chamber is highly rotating since it is exposed to the shaft. Oil entering the chamber is immediately exposed to this strong windage before joining the bulk rotating air flow. If oil stays too long within the chamber, its temperature will increase and may affect the oil properties leading to increased risk of oil coking or even worse, oil fire [1]. Furthermore, excessive amount of oil in the bearing chamber may lead to seal failure and oil leakage.

A sump is a geometrical feature within the bearing chamber employed to facilitate oil collection and removal. It is generally shaped as a pocketed region around the bottom dead centre of the bearing chamber. A scavenge pump is used to remove the collected oil out of the sump and transfer it to various elements such heat exchangers, filters, etc. within the oil system to be recirculated. Removing or scavenging oil out of the bearing chamber is not trivial. Oil collected in the sump is highly mixed with the air in the chamber. Simply increasing the pump suction will mainly increase the capacity to remove the gas phase, while oil removal is little affected or not happening at all. Previous experiments on generic sumps as well as some existing engine sumps showed reduced insensitiveness of residence volume as the scavenge ratio (or pump suction) is increased. Residence volume is defined as the volume of oil in the bearing chamber at any given time. Furthermore, a simple thought exercise can be made on the effect of density of gas and liquid to their respective ability to accelerate a column of each fluid given an identical differential pressure. In general, gas density is much lower than liquid density therefore a column of gas would accelerate faster than a column of liquid under the same suction.

A carefully designed sump geometry can improve scavenge performance. Research campaigns on various sump geometries have been conducted by Gas Turbine and Transmissions Research Centre (G2TRC), previously Rolls Royce University Technology Centre in Gas Turbine Transmission Systems at University of Nottingham. Some of earlier work were also performed at Institut für Thermische Strömungsmaschinen at Karlsruher Institut für Technologie (KIT) and Purdue University.

One of the pioneering experimental work by KIT was on the characterization of bearing chamber film flow using ultrasonic and oil droplets including their heat transfer coefficients [2]. LDV was used to obtain the film velocity and an analytical method for finding the oil film flow characteristics was proposed [3]. Droplet sizes and velocities were also measured, and a method to analyze bearing chamber droplet flow was developed by combining numerical and experimental approaches [4]. Further film thickness measurements were conducted in various geometries of bearing chambers for a wide range of engine relevant conditions [5, 6]. They concluded that the geometry of the chamber, the vent and scavenge ports, as well as the operating conditions can strongly impact the film flow. The experimental and numerical work at Purdue University focused on the optimization of the centre sump of Rolls-Royce AE3007 which evolved from a tangential sump to a conventional radial sump but with prescribed upstream and downstream wall curvatures [7-11]. The final iteration of the optimized sump has proven to be exhibiting superior scavenge performance with relatively low residence volumes.

G2TRC started a study on bearing chamber flow using CFD where velocity profile of the rotating windage was simulated including use of bespoke droplet tracking and wall film velocity code [12]. Later on, further numerical work was conducted. PIV was used to validate the simulations [13]. Further CFD work was on the modelling of thin film flow on the chamber's wall [14, 15], and then also on the heat transfer [16]. Experimental work at G2TRC started with a study on generic deep sumps, with dimensions similar to Rolls-Royce Trent engine's internal gear box [17]. The residence volume as well as the wall film thickness were measured in various operating conditions [18, 19]. It was found that a deep sump generally performs well. Liquid collected in a deep sump is less exposed to the shaft windage thus minimizing the amount of re-entrainment into the bulk rotating flow. A deep sump can be employed if there is sufficient design space, however in cases where design space is limited, such as in HP-IP bearing chambers, a shallower sump must be used.

A parametric study on shallow sump was conducted. With the aid of Design of Experiment (DOE), a phenomenological analysis was conducted on several flow features. The main flow feature investigated in the phenomenological study is the severity of hydraulic uplift in liquid pooling [20]. Oil pooling typically occurs in the sump or just before the sump. It is where the fast moving film meets the relatively stagnant liquid in the sump. It was hypothesized that the severity of hydraulic uplift (size of the oil pooling) has a direct correlation with the residence volume. The study identified an optimized shallow sump variant based on the dominant flow regime. This study assumes two extrema of expected flow regimes in the chamber: wall film dominated flow and airborne droplets dominated flow. In a typical bearing chamber, the flow would be a combination of the two. By studying them separately, the authors believe that this approach would give non-convoluted insights. Other flow features, such as flow detachment, dry-out, and secondary flow were also studied [21].

The parametric phenomenological approach was employed since it can be done relatively quicker than typical data gathering through an experiment, e.g. measuring the residence volume at each test condition. However the approach relies on qualitative interpretation of the flow features, and its application in bearing chamber flow research has never been validated before. This paper presents the results of quantitative measurements of residence volumes of an optimized shallow sump variant identified in the parametric phenomenological study. Previously, residence volumes of some existing engine sumps were measured [22]. Therefore we can now compare the residence volumes of the optimized shallow sump with some of the existing engine sumps. The direct residence volume comparisons can provide insight into how effective the parametric phenomenological approach is in identifying a good shallow sump.

METHODOLOGY

An experimental facility was built at G2TRC to conduct research on scavenge flow in bearing chambers. The test rig consists of an electric motor driving the shaft, flow circuit and interchangeable bearing chambers. Figure 1 shows the scavenge flow test rig. The rig is housed in a test cell and operated from an adjacent control/observation room. All bearing chambers are constructed out of acrylic to allow for full visual observation.

All tests were carried out at ambient pressure. Water was chosen as the working liquid due to its ease of handling, safety and costs. Some of relevant properties of water at room temperature are similar to those of oil (Mobil Jet Oil II) at typical operating temperature in aero-engines bearing chambers. Water density at 20°C is about 1000 kg/m3 and oil density at 150°C is about 970 kg/m3. Also the viscosity of water at 20°C and oil at 150°C are similar (0.001 Ns/m^2).

It is realized that however, surface tensions are not similar. Water at 20°C has surface tension of about 0.07 N/m, and oil at 150°C has surface tension of about 0.03 N/m. Film flow observed in the bearing chamber is highly disturbed and mainly driven by the windage, not the surface tension, especially at high shaft speeds. Nevertheless, surface tension can have significant effect on the airborne droplets as it is estimated that the Bond number of a droplet is less than one. However once the droplets impact the chamber's wall, it forms a film with characteristic Bond number in the order of hundreds thus it is assumed that the flow is not strongly affected by the surface tension. Whilst this study presents qualitative data as well as quantitative measurements of residence volumes, those results are not intended to be used as direct validations, but rather to inform on the overall behaviour through trend analysis due to changes in various flow and geometric parameters.

Combined with CFD approach, this experimental method of employing water as surrogate working liquid has been used successfully in for example in the redesign of Rolls-Royce AE3007 centre sump (US Patent #7789200). It is acknowledged that further study is needed, particularly on the effect of surface tension when the flow is in airborne droplets dominated regime. This would first require characterization of the shedding oil. G2TRC is currently working on characterization of bearing oil shedding and subsequent breakups [23, 24]. In the meantime, the study of scavenge flow assumes two extrema of expected flow in a typical bearing chamber: wall film flow and airborne droplets dominated flow. In a typical bearing chamber, the flow would be a mix of the two assumed flow regimes.

Figure 2 shows the fluid flow circuit. Water flows in a closed loop, whereas air flows in an open loop. Air can enter the bearing chamber through a vent on the front face of the chamber, and leaves the circuit through a vent port on the reservoir tank where its flow rate is measured. The reservoir has an internal baffle to separate the liquid and the gas.

Water enters the chamber via either one of the two types on inlet systems: Film Generator (FG) and Rotating Inlet Distributor (RID). FG generates a relatively uniform liquid film on the chamber's wall hence the flow is wall film dominated. FG injects water at the same direction as the shaft rotation. RID is a bespoke atomizer to simulate droplets shedding in the chamber. The rotating shaft is a part of the RID itself. A spindle with jet nozzles delivers water to the inner surface of the shaft. RID is used to generate airborne droplets dominated flow. Details of both inlet systems were given in previous publication [19].

Clusters of pneumatic pinch valves are used to enable measurements of residence volume. Initially pinch valves #2, #6, #7 are closed to allow water completes a continuous loop through the chamber. To take measurement, pinch valves #1, #3, #4 are closed whilst #2, #5, and #7 are closed simultaneously. This arrangement also allows for void fraction measurement in the off-take pipe by first opening pinch valves #4 and #6 to let the trapped water in a section of the pipe drain to a container, which then can be weighted. And finally, pinch valve #3 can be opened to measure the residence volume by letting the trapped water in the chamber drain to the container and weighted.

Scavenge ratio (SR) is defined as the ratio of total flow rate of liquid and gas in the off-take pipe to the liquid flow rate.

$$SR = \frac{Q_G + Q_L}{Q_L} = 1 + \frac{Q_G}{Q_L} \qquad (1)$$

The scavenge ratio can be set by adjusting the speeds of inlet pump and the scavenge pump. The inlet pump controls the water flow rate, whereas the scavenge pump controls the total volumetric flow rate. Scavenge ratio of unity should be avoided due to risk of water build-up in the chamber (flooding).

Parametric Shallow Sumps

The parametric study was based on Curved Wall Deep Sump (CWDS), i.e. the optimized centre sump of Rolls-Royce AE3007 also known as the Indy sump [8]. Previous study [22] found that CWDS has better scavenge performance compared to some existing engine sumps, in terms of the residence volume.

In this study, CWDS design was adapted to a shallower sump dubbed as Curved Wall Shallow Sump (CWSS). The CWDS defining features, such as its curved upstream and downstream sump walls are retained and parametrized, along with its depth, width and orientation (Figure 3). The sump off-take is located in the center of the sump base. The shaft (not shown on the figure) rotates in clock-wise direction.

A two-level half fraction factorial design was employed to reduce the number of required test cases whilst maintaining sufficient resolution to analyze the main effects and secondary interactions. Table 1 lists the extrema of each parameter.

A sump with low level of hydraulic uplift severity is hypothesized to have low residence volume [20]. Therefore only the hydraulic uplift severity was used as a criteria in finding a sump with good scavenge performance. Depending on the inlet system, hence the flow regime in the chamber, one sump design may perform better or worse than the other. Therefore there is a need to identify the best sump for each inlet system. For FG inlet system where wall film is the dominant feature of the flow, a sump with designated CWSS-FG was found to be the best. Figure 4 shows profile of CWSS-FG compared to CWDS. Notice the similarity of the sump walls curvatures and its offset from vertical (orientation). CWDS is a good performing sump compared to some of the existing engine sumps [22]. It is reassuring that the parametric phenomenological study produces a sump with similar features. For RID inlet system where the flow in the chamber is predominantly airborne droplets, CWSS-RID was found to be the best (Figure 5).

Existing Engine Sumps

Several existing sump designs used in various aero-engines have been experimentally tested at G2TRC [22]. They are CWDS, Lidded Shallow Sump (LSS), Channel Sump (CS), and Swirl-inducing Channel Sump (SCS) shown in Figure 6 – 9. CWDS is also known as Indy sump, which is an optimized centre sump of Rolls-Royce AE3007 and was a result of joint research of Rolls-Royce Indianapolis and Purdue University [8]. The sump prescribes certain curvatures to the upstream and downstream sump walls. The upstream wall curvature helps to encourage the incoming wall film to stay attached. The relatively blunt downstream wall helps to reduce the momentum of any body of liquid that skips the sump and let it fall back to the sump. LSS features a lid on top of the sump, and the sump off-take is at an angle. The lid is intended to isolate the oil collected in the sump from the windage, thus reducing the amount of oil re-entrainment in the bulk rotating flow.

CS directs incoming flow through an increasingly narrower channel to keep the flow supercritical. Film flow into a sump is analogous to open channel flows. Channel flows can exist as thin, fast moving flow (supercritical) or thick, slow moving flow (subcritical) depending on the Froude number. The CS design is intended to keep the flow supercritical, thereby keeping the film thin and minimizing stripping and entrainment. When the flow enters the scoop region, the energy is “dumped” and hydraulic uplift occurs. Transition to subcritical flow is designed to occur at the bowl region of the sump to minimize the severity of hydraulic uplift upstream. At this point the flow is away from the bulk rotating flow of the main chamber.

SCS is a variant of CS with features to encourage onset of swirling off-take flow. For single phase flow exiting through an off-take pipe, the liquid level will be higher when the flow is swirled than where there is no swirl [25]. However for air and liquid leaving together through a single off-take, a swirl might be a good feature, by separating the two phases, and pushing the liquid phase to the pipe walls and allowing air to exit through a channel in the core. On the other hand, the cross-section area occupied by the liquid phase may get smaller, impeding the flow.

RESULTS

The shaft speed determines the windage in the bearing chamber along with the size of the chamber and the shaft itself. Reynolds number of the gas phase is defined as:

$$Re_G = \frac{u(R-r)}{\upsilon_G} \qquad (2)$$

In a wall film dominated flow (inlet system is FG), the liquid Reynolds number is obtained by normalizing the liquid flow rate to the chamber's axial width assuming complete coverage.

$$Re_L = \frac{Q_L/z}{\nu_L} \qquad (3)$$

If the inlet system is RID, the flow is dominated by airborne droplets. Research at G2TRC is focusing on the characterization of the shedding droplets [23, 24]. In the meantime, a Weber number for the droplets is defined by assuming constant droplet size, identical to the diameter of each outlet hole on the RID. The droplet velocity is assumed to be the same as the shaft velocity.

$$We_L = \frac{\rho_L u^2 l}{\sigma_L} \qquad (4)$$

The airborne droplets form a film flow upon impact with the chamber's wall, therefore the liquid Reynolds number as defined in Equation (3) is still relevant. The measured residence volume is normalized to the circumferential wall area of the chamber.

CWSS-FG with FG Inlet System

Figure 10-13 show the residence volume comparisons between CWSS-FG and the existing engine sumps. Current data allows for direct comparisons at Re_L = 1330 and Re_G = 167600 and 251400. The residence volumes of CWSS-FG are lower than those of LSS, CS, and SCS (Figure 10-12). This suggests that CWSS-FG is a better sump than those existing engine sumps, given the flow is wall film dominated.

The residence volumes of CWSS-FG and CWDS at Re_L = 1330 and Re_G = 167600 are at the same level (Figure 13) but still substantially below that of the other existing engine sumps. CWSS-FG and CWDS have similar upstream and downstream wall curvatures. CWSS-FG is shallower than CWDS, but its residence volume is not higher. This suggests that sump depth is not a factor at Re_G up to 167600. The upstream and downstream wall curvatures of CWSS-FG are sufficient to contain the liquid in the sump with minimal re-entrainment (Figure 14).

At Re_L = 1330 and Re_G = 251400, however, CWSS-FG has higher residence volumes than CWDS. The strong windage at higher shaft speed can increase the liquid film momentum as it flows towards the sump. As the fast moving film approaches the sump upstream wall, a highly curved wall can encourage flow detachment. CWDS upstream wall is less curved therefore it has better ability to keep the incoming flow stay attached (Figure 15).

In CWSS-FG, the detached film impacts the sump base or downstream wall where it is still radially close to the shaft. Any splashes due to the impact are exposed to the shaft windage. The relatively high shaft windage can carry some of the droplets and ligaments from the splashes further downstream or re-entrain them back to bulk rotation, hence higher residence volume. In CWDS, the point of impact is radially further away from the shaft due to the relatively deeper sump. Although the shaft windage is still present at this point of impact, it is not as strong as in CWSS-FG, and therefore droplets or ligaments are less susceptible to be carried upstream by the windage. Most carried-over will fall back into the sump due to gravity.

Residence volumes comparison of CWSS-FG and the existing engine sumps with FG inlet system (wall film dominated flow) proves that the parametric phenomenological study is capable of identifying a good shallow sump. CWSS-FG has lower residence volumes than LSS, CS, or SCS. At up to Re_G = 167600, the scavenge performance of CWSS-FG is similar to CWDS.

CWSS-FG with RID Inlet System

Analysis of variance was conducted by combining all phenomenological data for both inlet systems. By combining the geometric similarities of the best three sumps, a sump was generated [20]. Coincidentally the generated sump has identical geometric parameters with CWSS-FG. It is therefore interesting to see if CWSS-FG, which was optimized for FG inlet system (wall film dominated flow), would fare if the inlet system is RID (airborne droplets dominated flow).

Residence volumes of CWSS-FG are higher than those of the existing engine sumps at high scavenge ratio (SR = 4). At low scavenge ratio (SR = 1.5), the residence volume of CWSS-FG are also higher, or at best similar to those of the existing engine sumps. There exists a strong downstream hydraulic jump directing the liquid back to the bulk rotating flow (Figure 20)

At SR = 1.5, CWSS-FG and CWDS have similar level of residence volumes. However at SR = 4, CWSS-FG has higher residence volumes than CWDS. In CWDS, increasing the scavenge ratio from 1.5 to 4 can greatly reduce the residence volume. In CWSS-FG, on the other hand, increasing the scavenge ratio from 1.5 to 4 can only slightly reduce the residence volume. This suggests that a deeper sump can help to lower the residence volume by enhancing the suction effectiveness at higher scavenge ratio.

At SR = 1.5, CWSS-FG and CWDS have higher residence volumes compared to CS and SCS. At this low scavenge ratio, the liquid outflows are likely in outlet-controlled rather than in vessel-controlled regime [26]. It can be concluded that CWSS-FG would not be a good choice of shallow sump for RID inlet system or in airborne droplets dominated flow.

CONCLUSIONS

The paper presents the result of residence volumes measurement of an optimized shallow sump obtained through a parametric phenomenological study, and their comparisons with the residence volumes of some existing engine sumps. Two extrema of expected flow in the chamber were simulated: wall film flow and airborne droplets dominated flow. In a typical bearing chamber, the flow would be a combination of the two. An optimized shallow sump for each flow regime was found through the parametric phenomenological study. The residence volumes comparison suggests that the parametric phenomenological approach is capable of finding a good sump when the flow is wall film dominated. In some cases, the residence volume of CWSS-FG is only 25% of the residence volume of an existing engine sump.

In the past work, analysis of variance was conducted across all parametric sumps with FG and RID inlet systems. By combining the features of the best three sumps, coincidentally CWSS-FG was also identified as the best sump regardless of the inlet system. However when tested with RID inlet system (airborne droplets dominated flow), CWSS-FG has higher or at best similar residence volumes with some of the existing engine sumps. Therefore CWSS-FG would not be a good choice for droplets dominated flow. This also highlights the limitation of the approach using analysis of variance.

More residence volume measurements of CWSS-FG can be taken in the future, to include other matching flow conditions used in the residence volume measurements of the existing engine sumps. Future work can also include residence volume measurements of CWSS-RID and the comparison with existing engine sumps. Furthermore, identifying the best overall sump regardless of the inlet system can be attempted through studying the main effects in DOE. However such attempt to find the best overall sump may prove to be elusive since a given sump performance is likely to depend on the flow regime and characteristics in the chamber.

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Table 1 Extrema of geometric parameters

Parameter	**Low**	**High**
R_u	d	R
R_d	d	R
d	0.04 R	0.15 R
w	0.1 R	0.3 R
θ	0°	15°

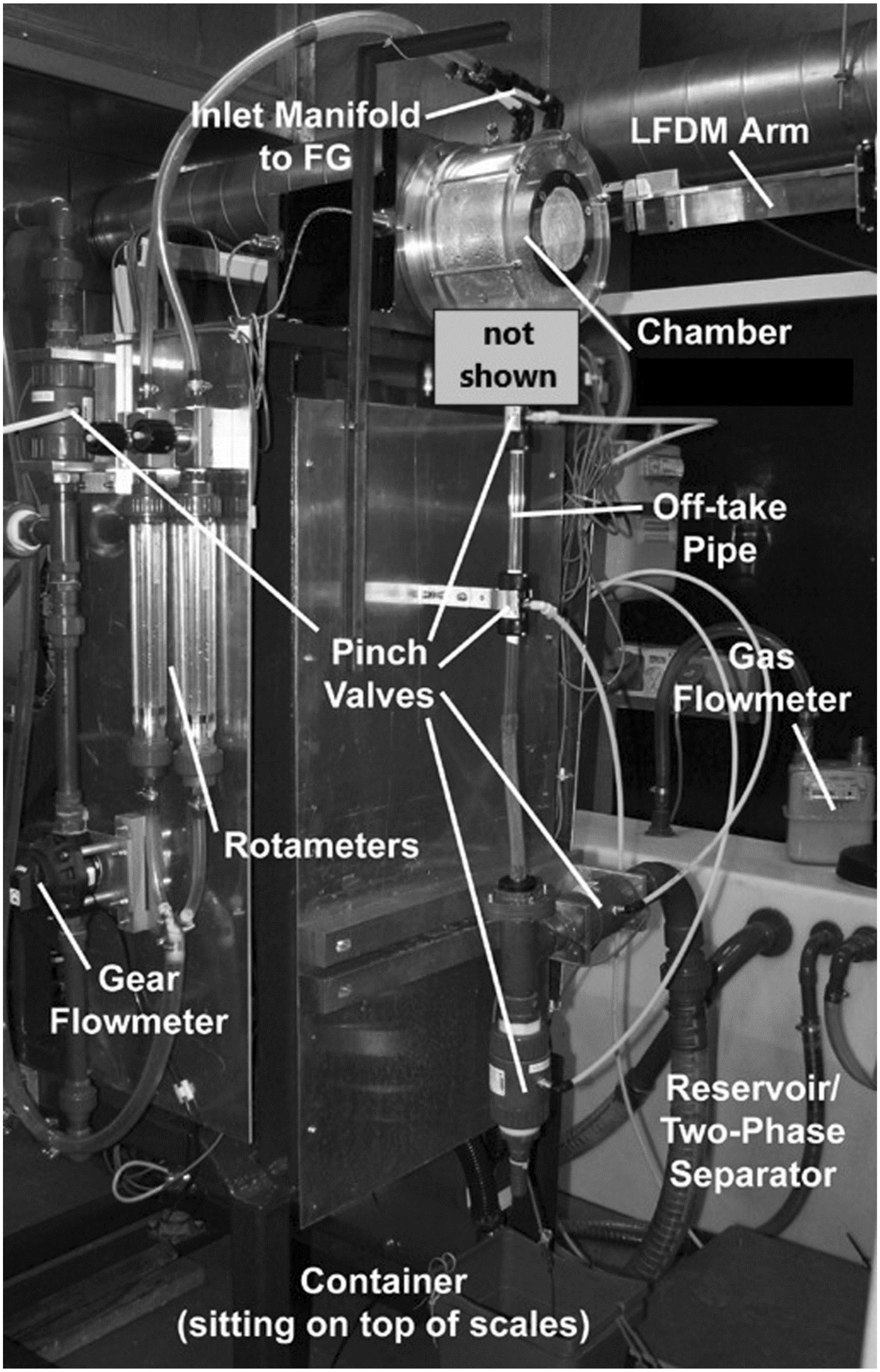


Fig. 1 Scavenge flow test rig

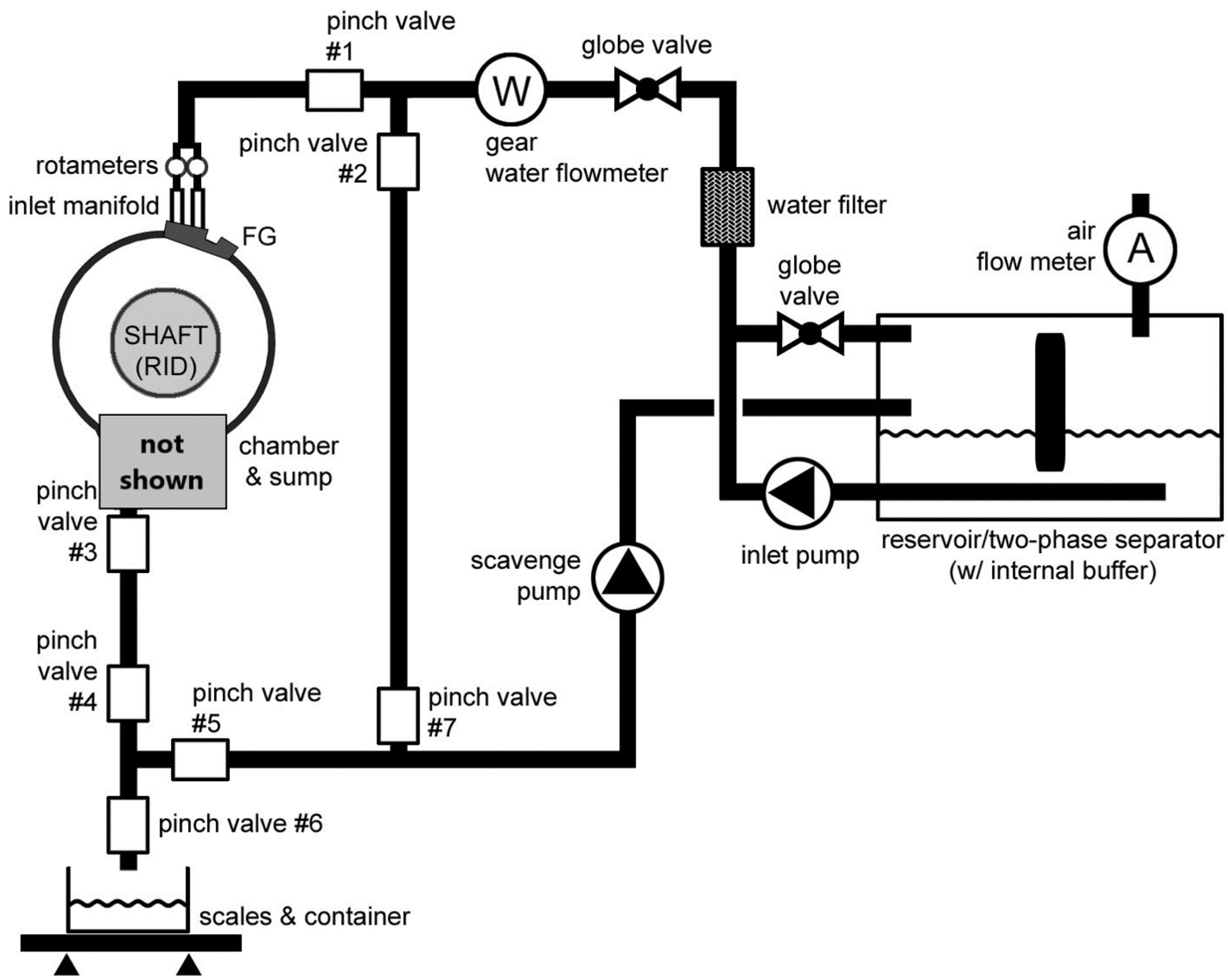


Fig. 2 Flow circuit

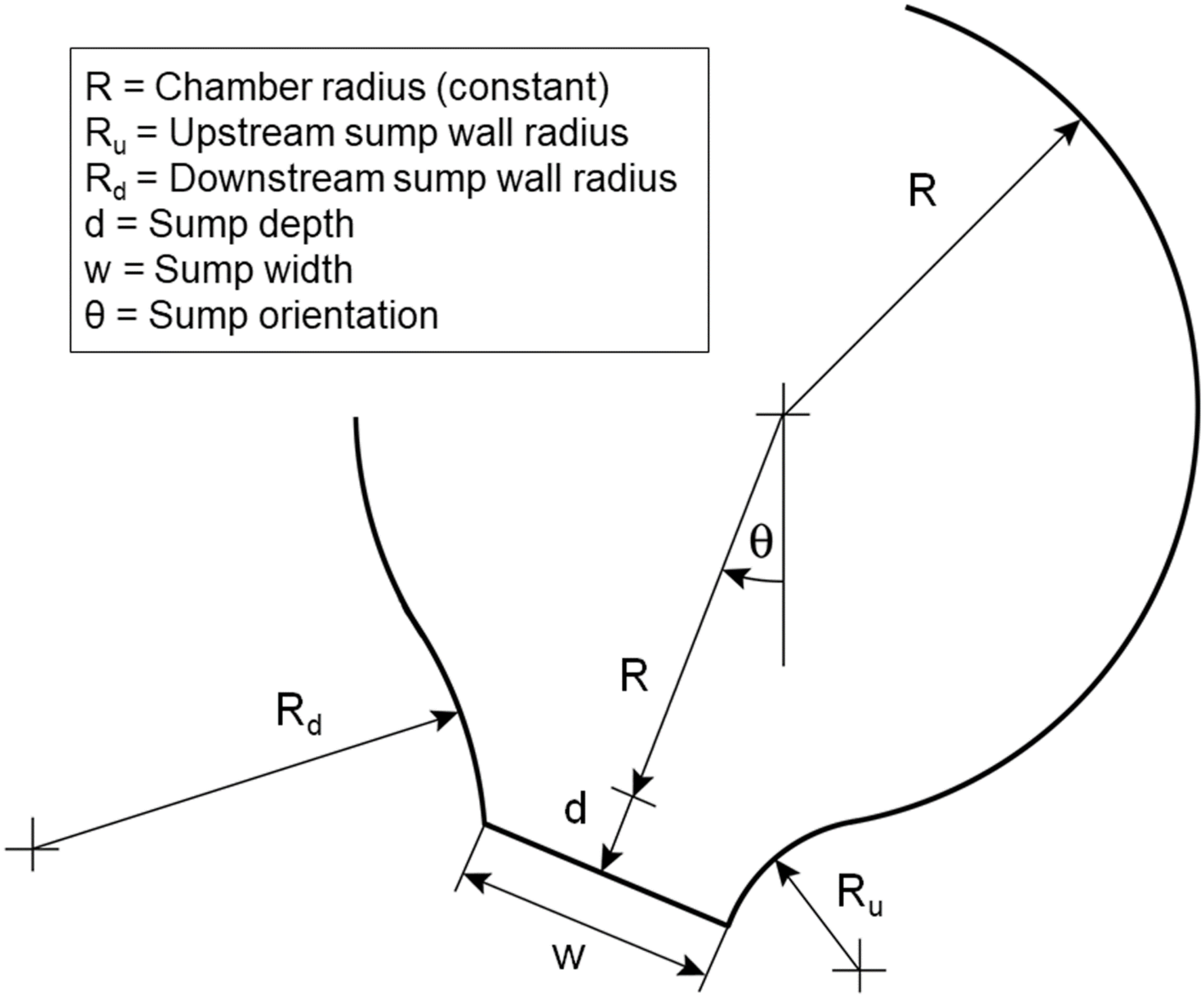


Fig. 3 Parameters of CWSS (shaft rotates clock-wise)

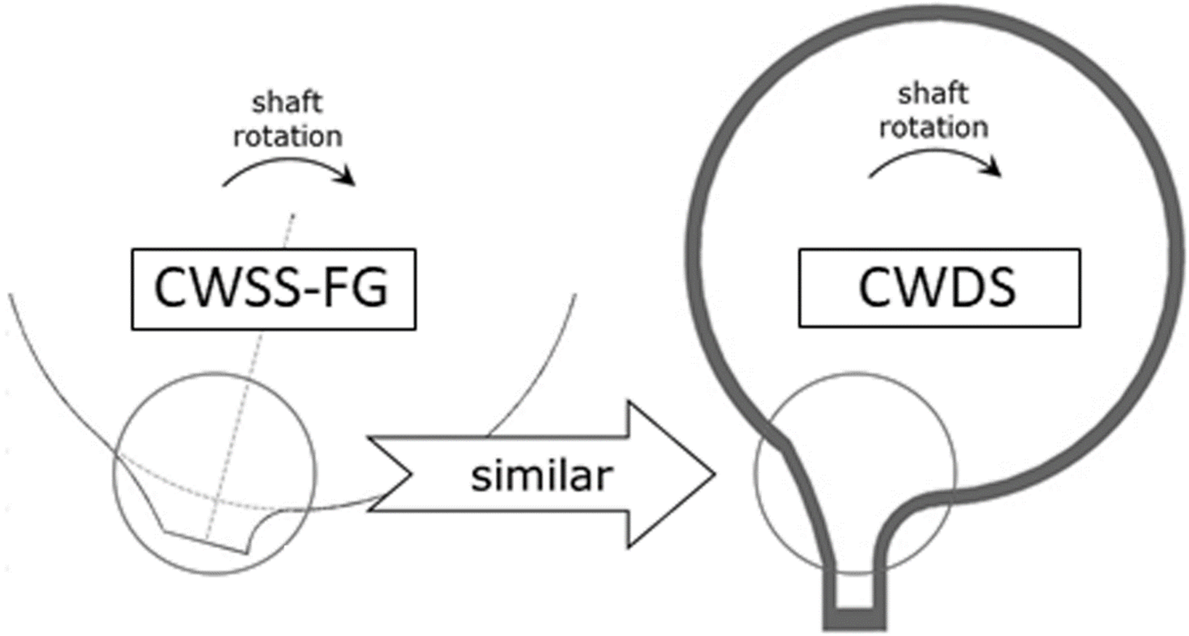


Fig. 4 CWSS-FG similarity to Indy sump

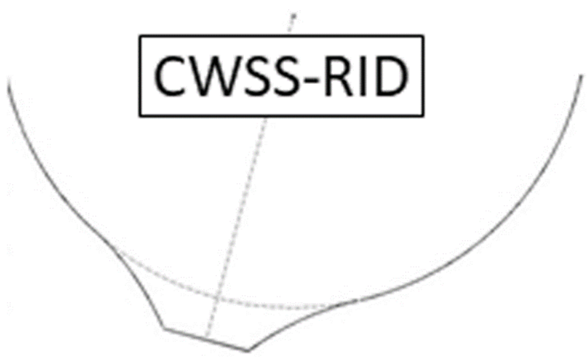


Fig. 5 CWSS-RID

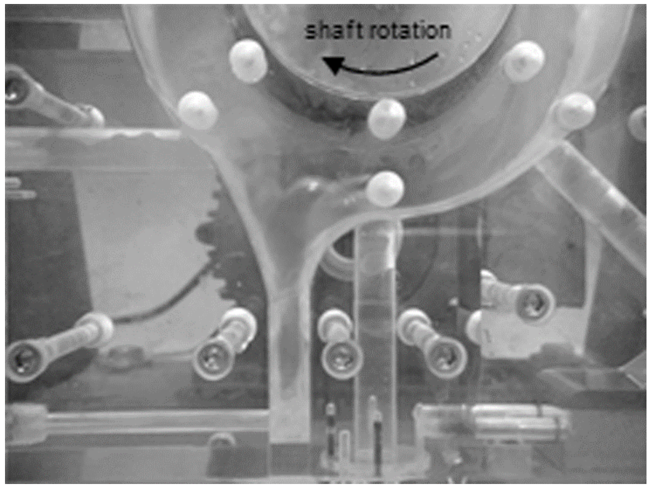


Fig. 6 CWDS (tested at Purdue University)

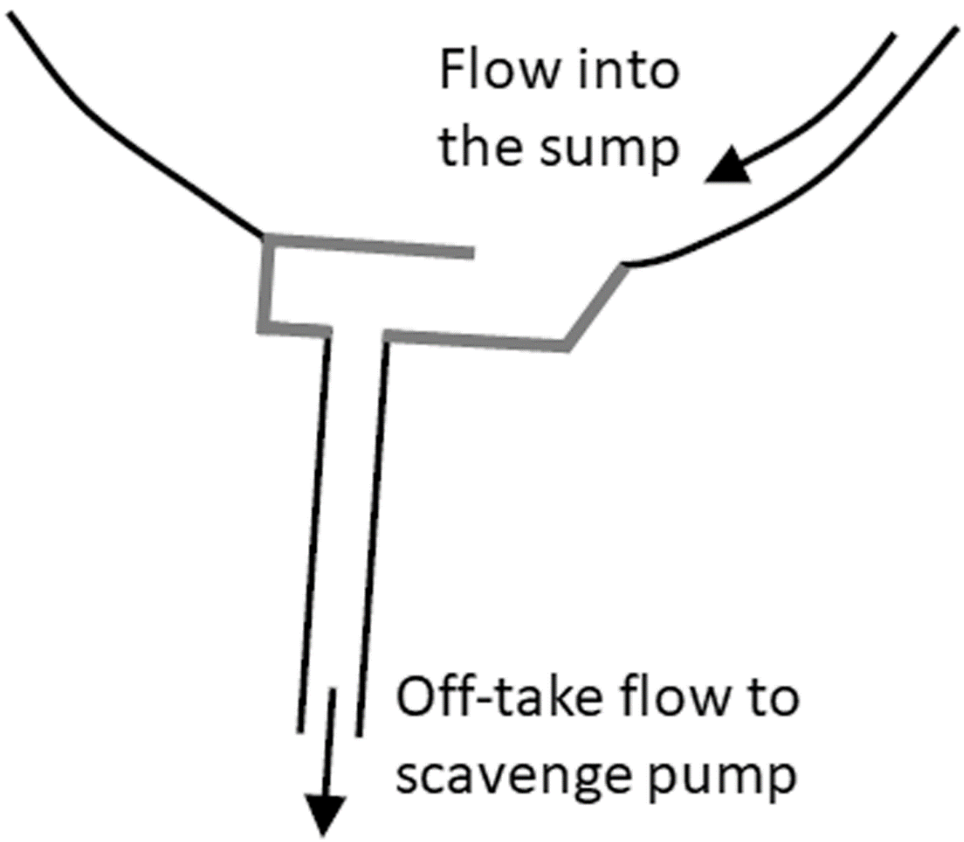


Fig. 7 Schematic representation of LSS

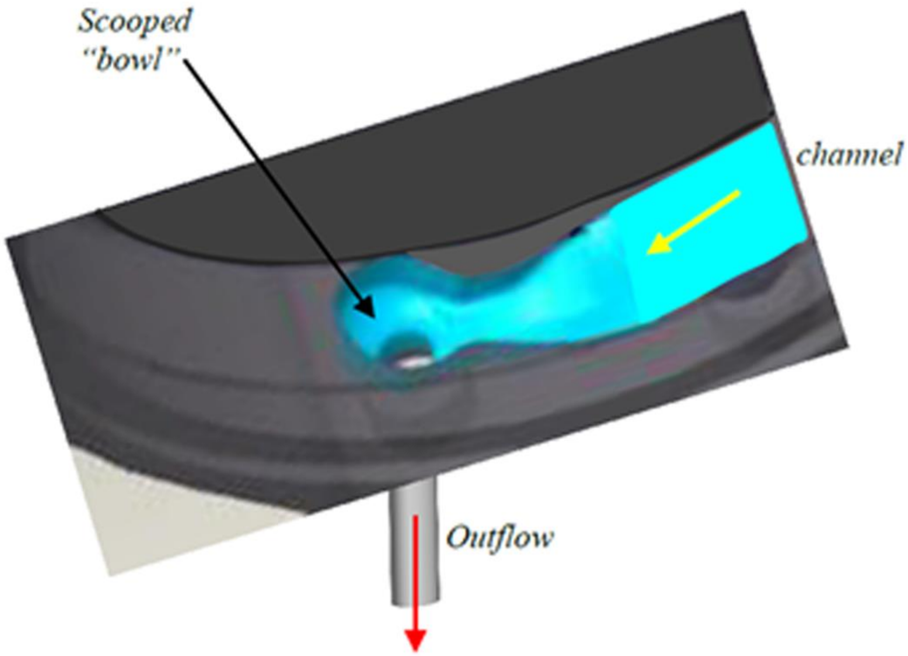


Fig. 8 Schematic representation of CS

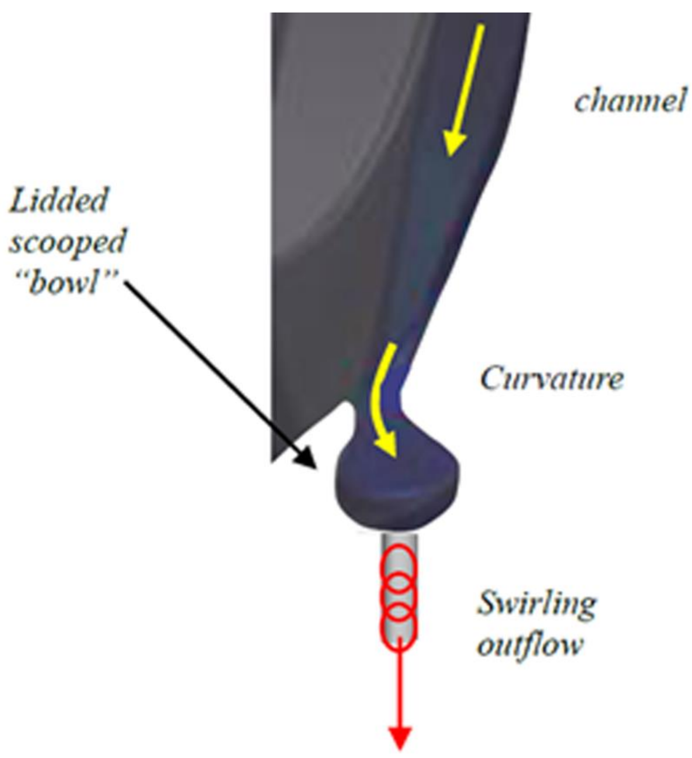


Fig. 9 Schematic representation of SCS

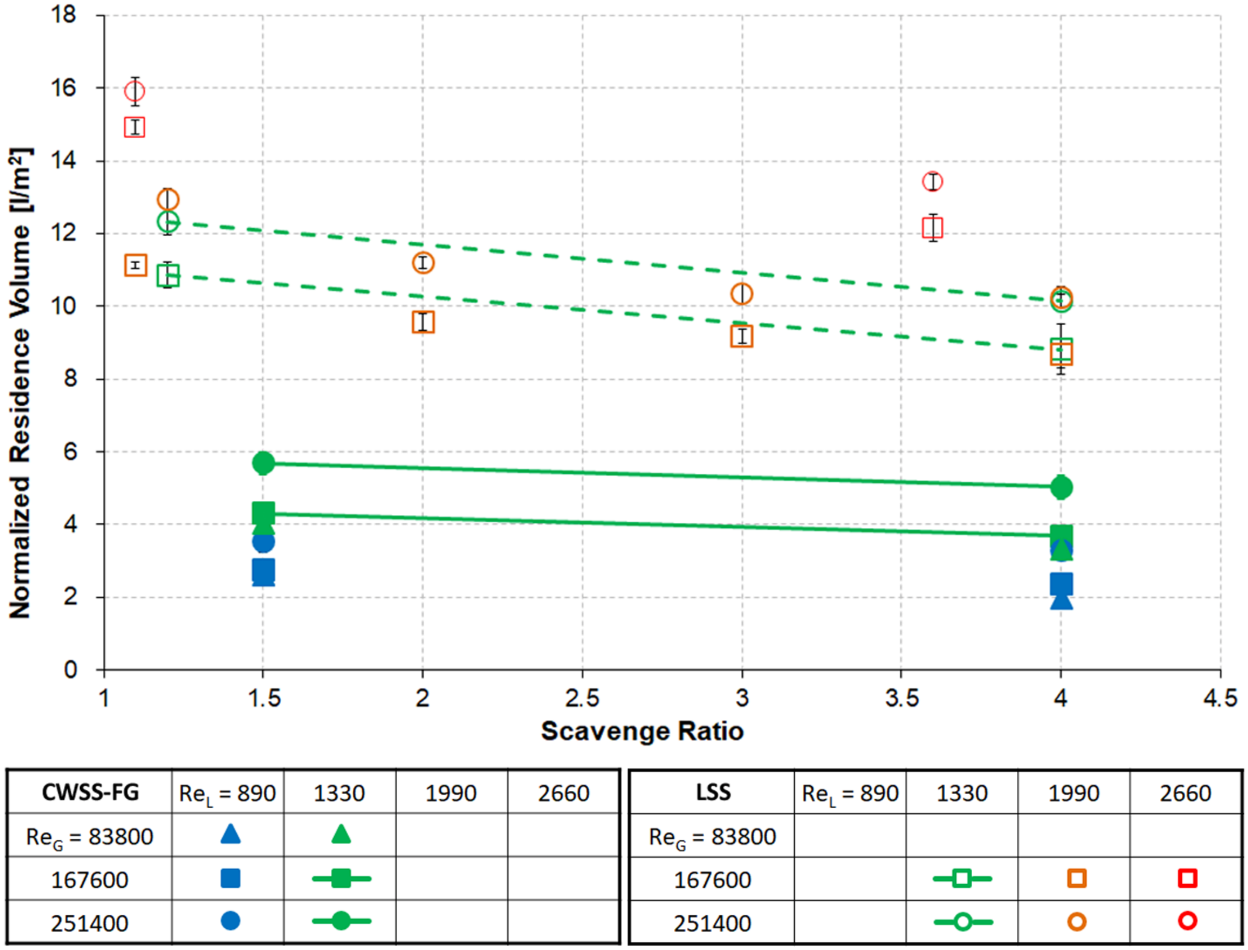


Fig. 10 Residence volumes of CWSS-FG and LSS with FG inlet system

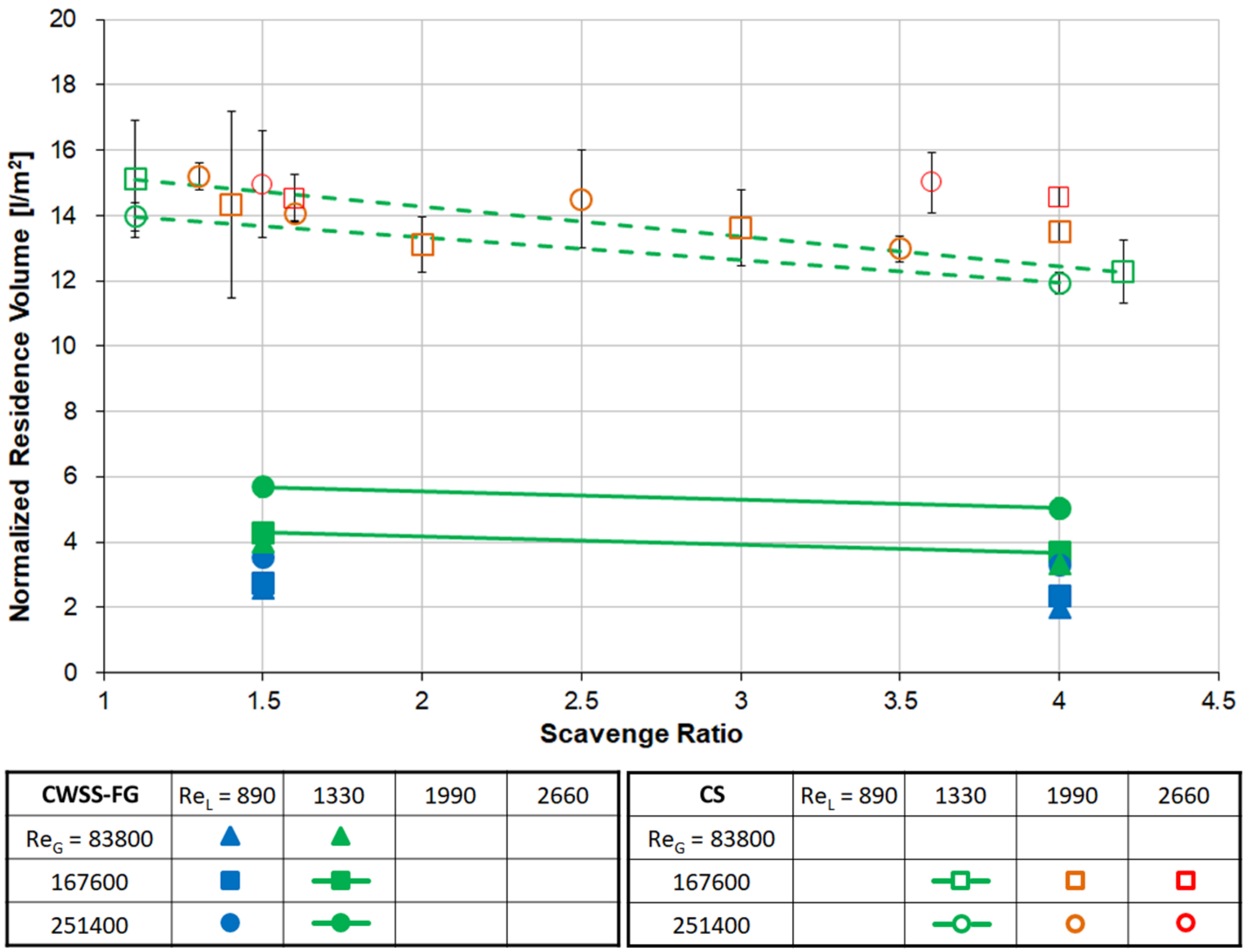


Fig. 11 Residence volumes of CWSS-FG and CS with FG inlet system

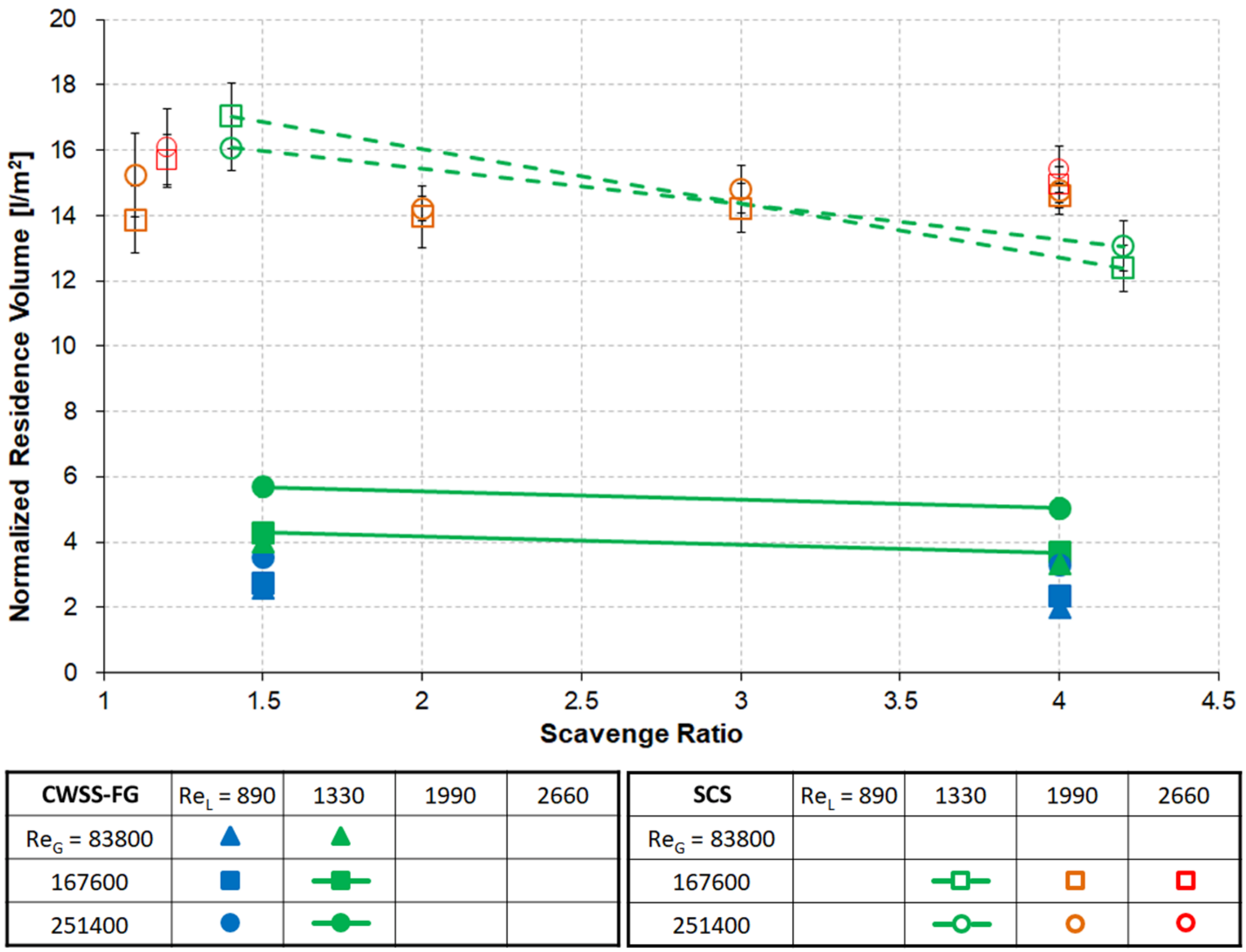
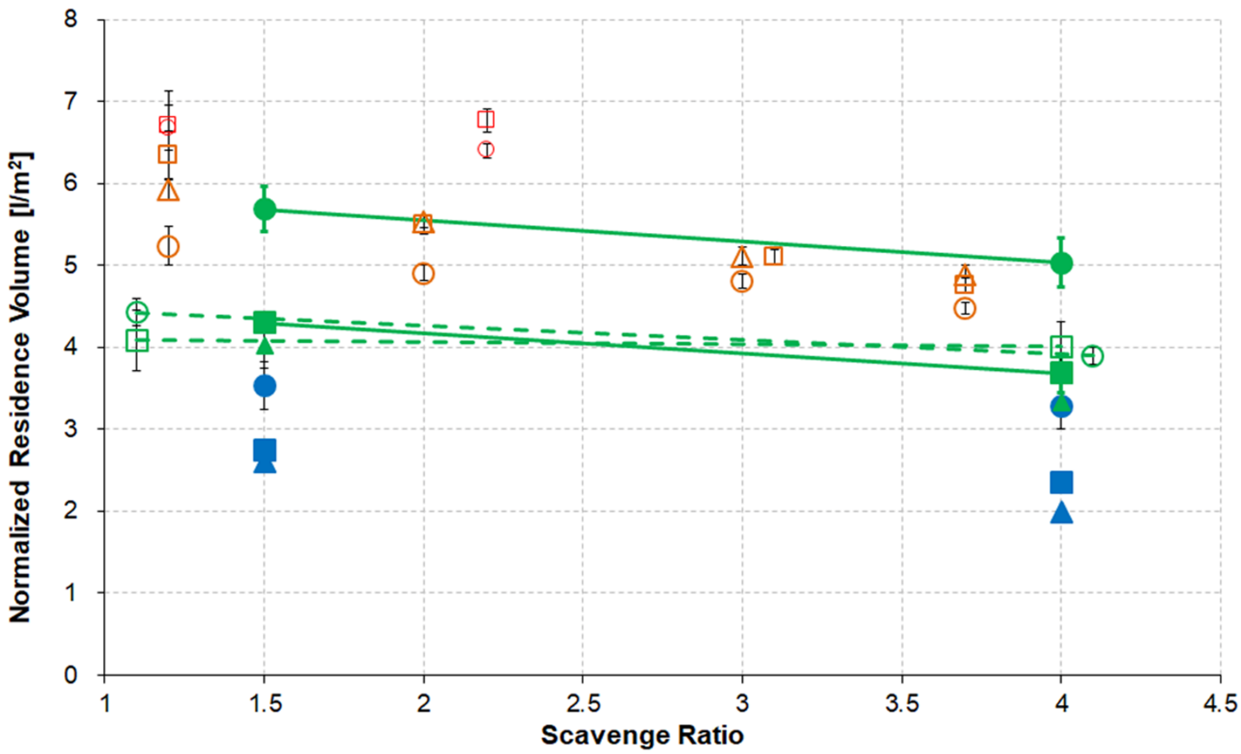


Fig. 12 Residence volumes of CWSS-FG and SCS with FG inlet system



CWSS-FG	Re_L = 890	1330	1990	2660
Re_G = 83800	▲ (blue)	▲ (green)		
167600	■ (blue)	■ (green, line)		
251400	● (blue)	● (green, line)		

CWDS	Re_L = 890	1330	1990	2660
Re_G = 83800				
167600		□ (green, line)	□ (orange)	□ (red)
251400		○ (green, line)	○ (orange)	○ (red)

Fig. 13 Residence volumes of CWSS-FG and CWDS with FG inlet system

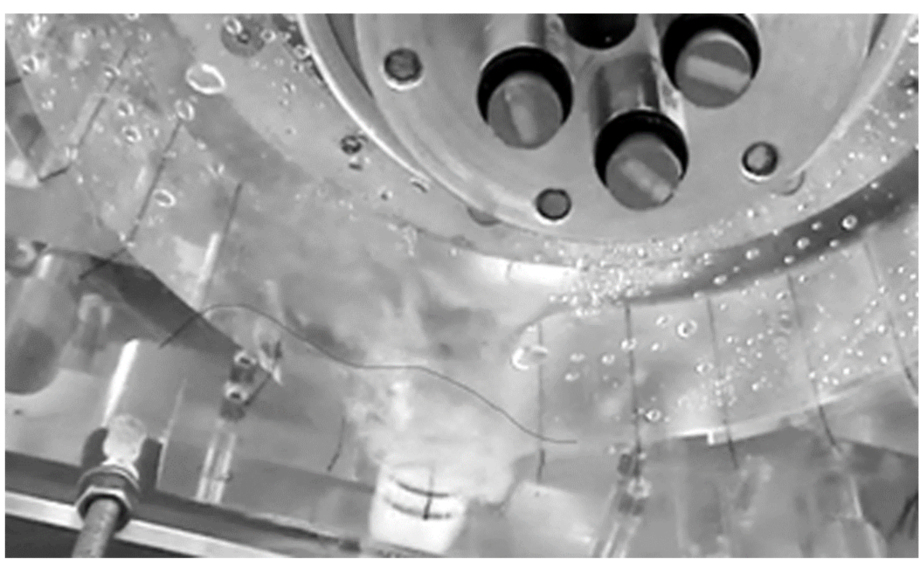


Fig. 14 Liquid pooling in CWSS-FG with minimal or without re-entrainment

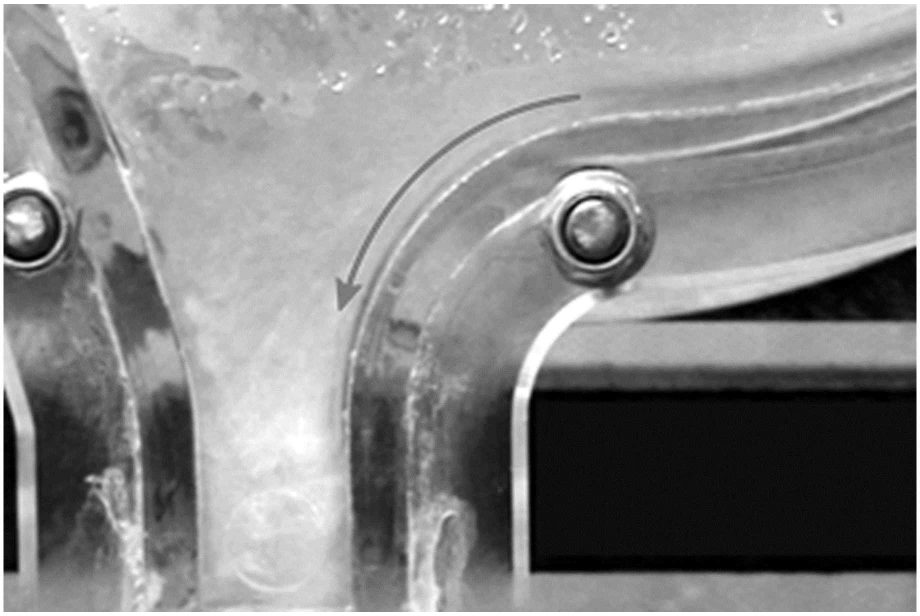
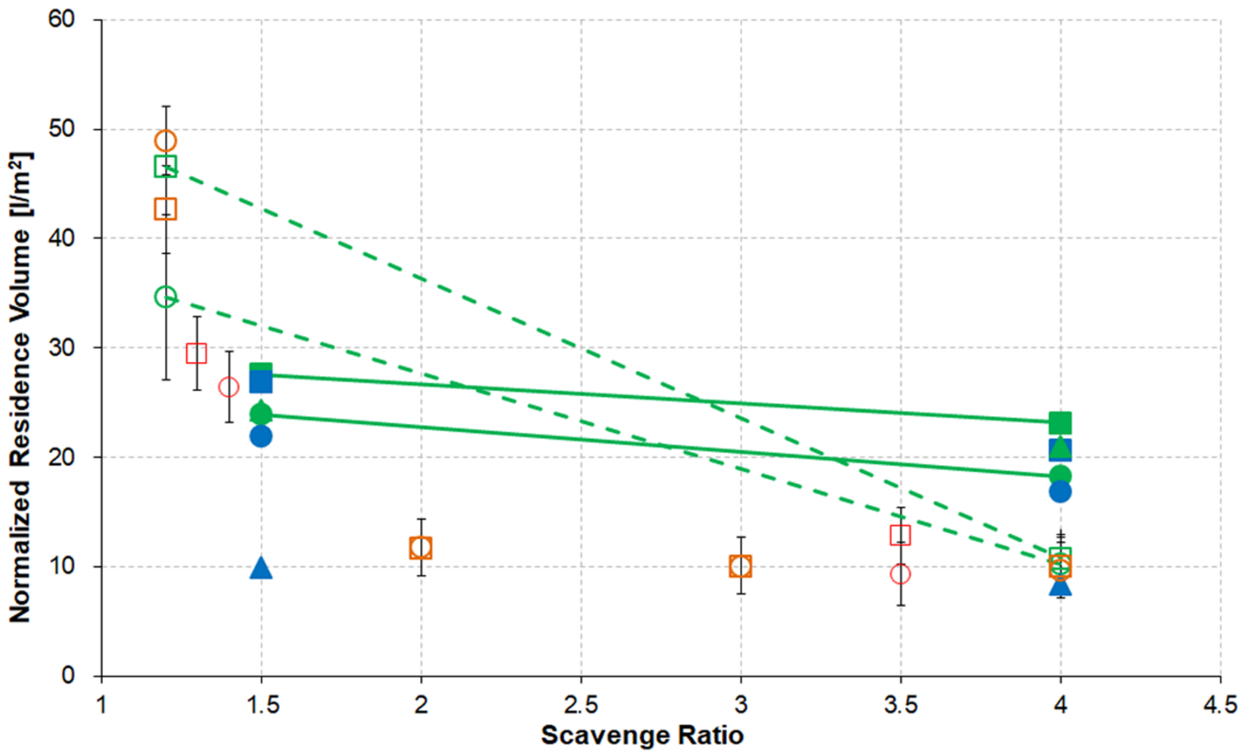


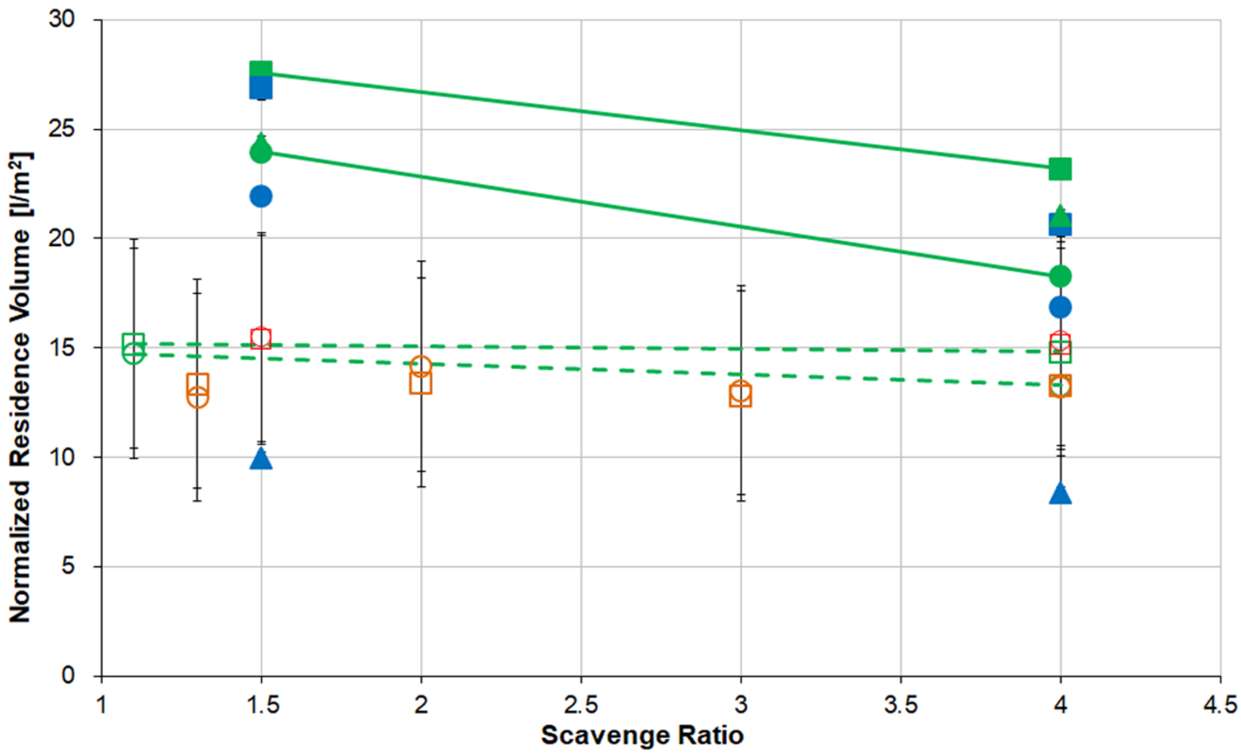
Fig. 15 Gentle sloping upstream wall of CWDS helps incoming flow to stay attached



CWSS-FG	We_L/Re_L =			
Re_G = 83800	11 ▲	7 ▲		
167600	44 ■	29 ■		
251400	99 ●	66 ●		

LSS	We_L/Re_L =			
Re_G = 83800				
167600		29 □	20 □	15 □
251400		66 ○	44 ○	33 ○

Fig. 16 Residence volumes of CWSS-FG and LSS with RID inlet system



CWSS-FG	We_L/Re_L =			
Re_G = 83800	11	7		
167600	44	29		
251400	99	66		

CS	We_L/Re_L =			
Re_G = 83800				
167600		29	20	15
251400		66	44	33

Fig. 17 Residence volumes of CWSS-FG and CS with RID inlet system

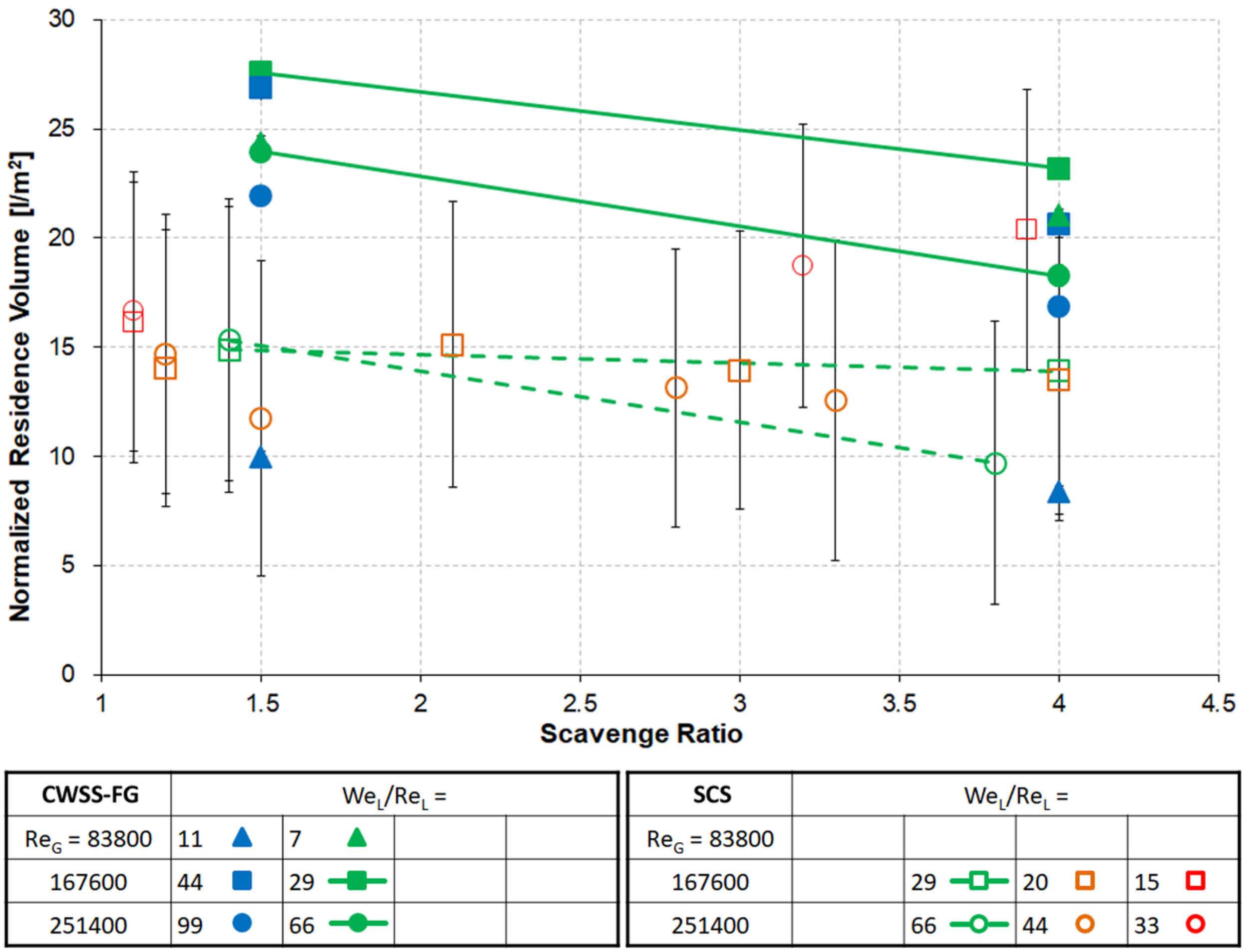
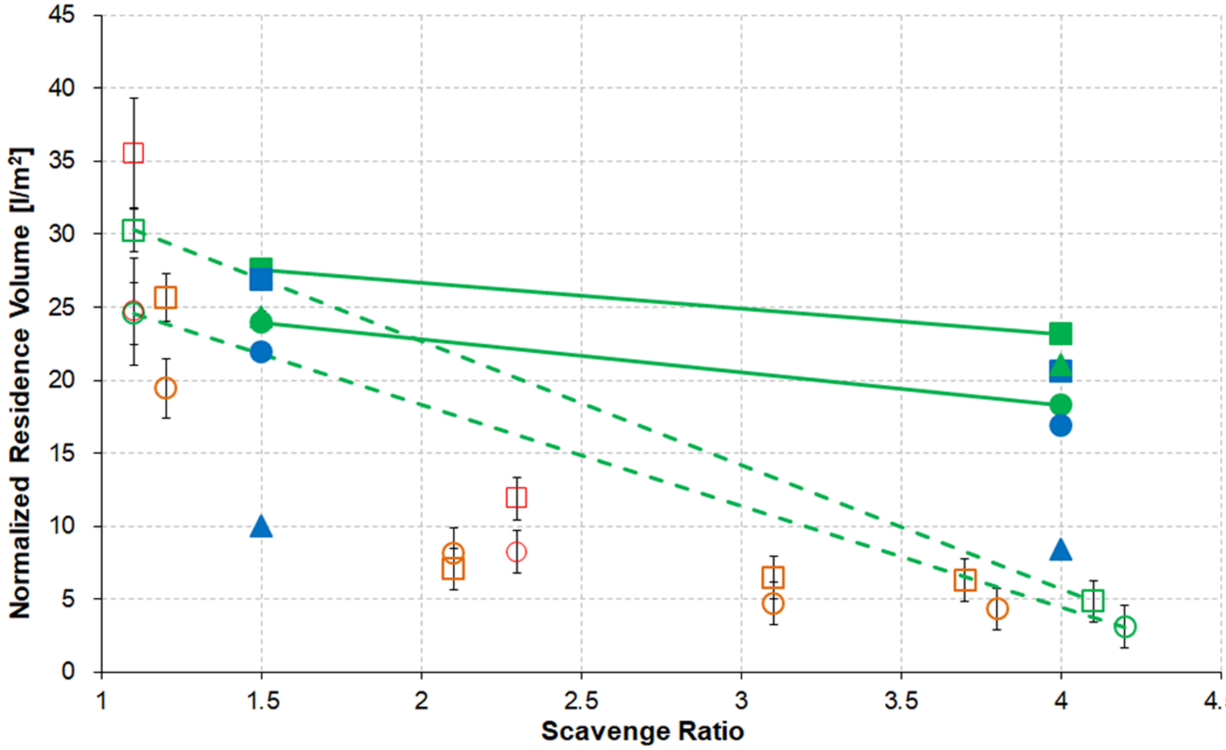


Fig. 18 Residence volumes of CWSS-FG and SCS with RID inlet system



CWSS-FG	We_L/Re_L =				CWDS	We_L/Re_L =			
Re_G = 83800	11 ▲	7 ▲			Re_G = 83800				
167600	44 ■	29 ■			167600		29 □	20 □	15 □
251400	99 ●	66 ●			251400		66 ○	44 ○	33 ○

Fig. 19 Residence volumes of CWSS-FG and CWDS with RID inlet system

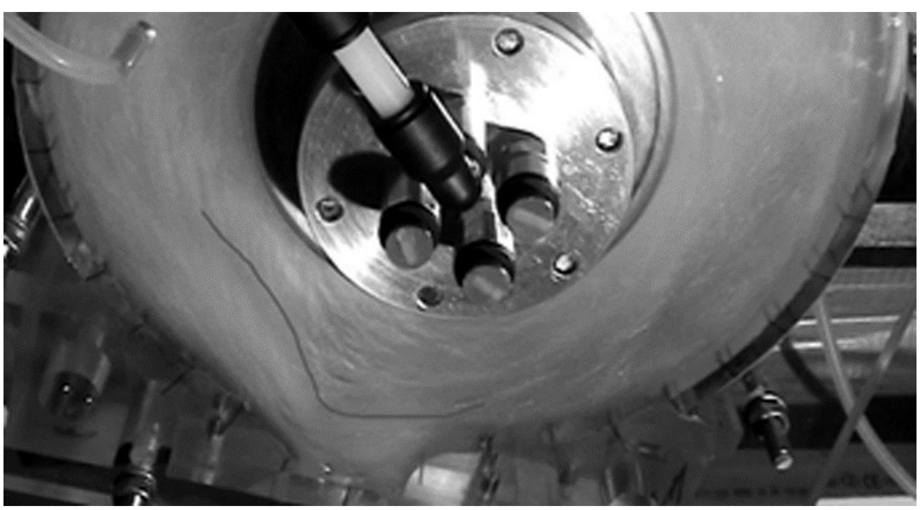


Fig. 20 CWSS-FG with RID inlet system