Mechanisms for Residence Volume Reduction in Shallow Sump

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ABSTRACT

Gas turbine aero-engines employ fast rotating shafts that are supported by bearings at several axial locations along the engine. Due to extreme load and heat, oil is injected to the bearings to aid lubrication and cooling. The oil is then shed to the bearing chamber before it is extracted out by a scavenge pump. Scavenging oil from the bearing chamber is challenging due to high windage induced by the fast rotating shafts as well as the two-phase nature of the flow. A deep sump has been found to increase scavenge performance due to its ability to shelter the pooled oil from the bulk rotating air flow thus minimizing two-phase mixing. However in many cases, a deep sump is not an option due to conflicting space requirements. The space limitation becomes more stringent with higher bypass ratio engines as the core becomes smaller. Therefore it is imperative to have a high performing shallow sump. However shape modification of a shallow sump is too constrained due to limited space and therefore has minimal impact on the

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scavenge performance. This research presents several alternative concepts to improve scavenge performance of a generic baseline shallow sump by augmenting it with attachments or inserts. These augmentations attempt to exploit two known mechanisms for reducing the residence volume: momentum reduction and sheltering. The experimental results show that some augmentations are able to reduce the residence volume of a shallow sump by up to 50% or more in some cases.

INTRODUCTION AND BACKGROUND

Immediately after leaving the bearings, oil droplets in a bearing chamber are subjected to three-dimensional air flow while travelling from the rotating elements to the peripheral chamber wall. Upon impact with the wall, film is formed accompanied by splashing creating a turbulent frothy flow. Subsequent oil film flow is a result of the tangential momentum that the droplets bring to the impact, the shear of the air on the oil, and the impact or splashing of subsequent droplets. Other forces include gravity, as well as capillary effects. Ideally oil flows out of the bearing chamber without unnecessary delay. However high flow momentum, shaft windage and three-dimensional air flows can often impede the oil flow exiting the chamber. In order to improve oil scavenge, a bearing chamber incorporates a geometric feature known as the sump to provide a collection point where oil can be captured and separated from the bulk rotating flow. Oil is then extracted out from the sump through an off-take port by a scavenge pump. Aero-engines usually operate with a significant amount of air leaving through the scavenge port along with the oil, giving rise to the concept of scavenge ratio, the ratio of the total volume flowrate at exit compared to the volume flowrate of oil at exit. Figure 1 shows a highly schematic illustration of a bearing chamber including the sump.

The sump geometry can significantly affect the scavenge performance. It was observed that two-phase flow at exit including where there is dispersed gas in the liquid can severely reduce the scavenge pump effectiveness in extracting the oil out resulting in high oil residence time and volume. When both liquid and gas phases are present, the scavenge pump will often preferentially draw out the gas as it has less resistance due to the much lower density compared to the liquid. Therefore the sump is often designed with aim to minimize liquid-gas mixing. An ideal sump might be defined as one that can create a condition where no ingested air is present in the oil at the immediate vicinity of the scavenge off-take. In order to create such condition, the momentum of the liquid entering the sump must be reduced [1-3]. In addition, once the liquid is gathered in the sump, it needs to be sheltered from the bulk rotating flow to minimize stripping and entrainment. A deep sump such as that found in the internal gearbox of a 3-shaft civil aero-engine can easily achieve both the momentum reduction and the sheltering [4, 5], but a shallow sump can rarely manage to provide sufficient momentum reduction and sheltering. As a rough guide, a shallow sump is defined as a sump with sump depth of less than 10% of the chamber diameter.

A parametric study of shallow sumps [6] has yielded an optimised shallow sump geometry. It was not a complete surprise that its shape is similar to that of the Rolls-Royce AE3007 center sump (see Figure 2b) as this was the result of an extensive prior study [7]. The AE3007 center sump has curved walls both into and out of the sump, and is also quite deep; it proved to have a superior scavenge performance compared to some other existing engine sumps. A prominent feature of the AE3007 sump is its downstream almost-vertical wall. Upon impact with this wall, the incoming liquid flow losses most of its momentum. In addition, the relatively deep pocketed region of the sump shelters the collected liquid from the bulk rotating air flow thus reducing the chance for stripping and entrainment. Kurz [8] studied experimentally a ramp sump fitted with a cover and showed significant reduction in wall film thickness. Recently, other variants of AE3007 sump were modelled and simulated numerically by Zhao et al. [9] and these have also shown superior performance especially the deeper variant.

In most cases, the optimised shallow sump has lower residence volume compared to other shallow sump variants tested in the parametric study. Its vertical downstream wall, albeit shorter than that of AE3007 sump, is able to reduce the flow momentum of the incoming liquid. However it lacks the depth of the AE3007 sump and therefore cannot provide a sufficient sheltering mechanism.

Initial attempts utilizing augmentations to improve scavenge performance of a shallow sump proved to be successful [10] in varying degrees. Four different types of augmentations were tested experimentally: grille cover, stepped spillway, perforated plate, and porous insert. In general, the flow regime in a bearing chamber can be described as a combination of two extremes: *wall film* and *airborne droplets* [11]. The *wall film* flow regime is mostly gravity dominated and occurs at lower shaft speeds. However the *airborne droplets* flow regime becomes windage dominated at high shaft speed [12]. The effectiveness of each augmentation can therefore vary depending on the flow regime and the shaft speed.

Further efforts to improve the effectiveness of three types of augmentations (grille cover, stepped spillway, and perforated plate) are presented in this paper. Based on the lessons learned, modifications were proposed and tested experimentally. The residence volume was used as the main indicator. Greater reduction in the residence volume compared to baseline is implied as an improvement of the scavenge performance.

EXPERIMENTAL SETUP

Water, rather than oil is used in this experiment. The density and viscosity of water at room temperature are similar to those of oil (Mobil Jet Oil II) at 150°C (typical bearing chamber temperature). It is acknowledged however that the surface tension of water at room temperature is much higher than that of oil at engine operating condition. In previous work by Radocaj [13], surfactant was added to the water to reduce its surface tension. It was noted that general flow behaviors with and without surfactant were indistinguishable. This is due to fact that the film is highly disturbed and strongly driven by the shearing air flow resulting in high Bond number flow. Furthermore, surfactant may trigger severe foaming. Therefore a decision was taken here that surfactant would not be added to the water.

In the test rig, water runs in a closed loop and air runs through an open loop as shown in Figure 3. The test chamber is made of transparent acrylic to provide visual access (Figure 4). There is a breather hole on the chamber face to allow air to freely flow into or out of the chamber. Without this breather hole, the suction from the scavenge pump will reduce the chamber pressure. The volumetric flowrate of the ingested air is assumed to be equivalent to that of the escaping air in the reservoir which acts as a separator.

The scavenge ratio, *SR* is defined as $SR = 1 + Q_g / Q_l$. In an aero-engine the scavenge ratio is largely controlled by the speed of scavenge pump because positive displacement pumps are used, driven at a speed proportional to shaft speed. Ideally the pump speed, hence the pump required power should be as low as possible. However setting the scavenge ratio to one may risk flooding as air bubbles in the fluid are inevitable. Therefore the scavenge ratio is always set to higher than one (scavenge ratio of four is a typical value for an aeroengine at cruise). With increased scavenge ratio more air is ingested until scavenge performance is not improving or in some cases becomes worse. A good sump would require minimum scavenge ratio but is still able to sustain effective scavenge. Scavenge ratio is one of the experimental variables in the experiments reported here.

The scavenge effectiveness can be determined by two parameters: residence time and residence volume. The residence time indicates how long the oil stays in the chamber, while the residence volume indicates how much oil is present in the chamber at an instantaneous time. A minimum residence time and volume are necessary to allow the oil to perform its secondary functions such as chamber wall heat transfer. However, keeping the residence time and volume from becoming excessive is not trivial. Excessive residence time would lead to oil degradation and potentially coking, while excessive residence volume may cause flooding and leakage. In this experiment, residence volume is used as the primary indicator of the scavenge performance. It is obtained by utilizing several pneumatic pinch valves to divert the inlet flow and isolate the water in the chamber. Future work may include residence time measurement.

The water is introduced to the chamber via one of two methods, either a Film Generator (FG) or droplet generating system integrated into the rotating shaft here referred to as the Rotating Inlet Distributor (RID). Some details of those inlet injection systems are in previous publication [11]. Each injection system simulates a flow regime in the bearing chamber. FG creates a *wall film* flow regime, whereas RID creates an *airborne droplets* flow regime. Those two flow regimes represent two extremes of flow regimes occurring in a bearing chamber. A typical bearing chamber flow is likely to be a combination of wall film and airborne droplets. However, as an initial step towards understanding the fundamentals, it is useful to study the flow in each of these extreme flow regimes.

The baseline shallow sump is the same as the one used in the previous work [10]. The geometry is shown in Figure 5. The chamber axial length is a quarter of its diameter. The sump depth is 8% of the chamber diameter. The upstream and downstream walls' radius of curvature is the same as the sump depth. The off-take diameter is 8 mm and is located at the centre of the sump base. The shaft diameter is half of the chamber diameter.

For each flow regime, the residence volume of the baseline shallow sump was measured at different liquid inlet flow rates, scavenge ratios, and shaft speeds (see Table 1). It is clear that the sump performs better in the *wall film* flow regime. This is true for many sump geometries due to higher flow complexity in the *airborne droplets* flow regime.

The first type of augmentation is the grille cover (Figure 6). Grille Cover 1 has been tested previously [10]. The design was proposed to reduce the momentum of the incoming flow as well as to encourage drainage from the top surface of the cover. It features inline slats with triangular profile. In addition, the cover is expected to provide some sheltering mechanism. Grille Cover 2 is a new design. It incorporates perpendicular slats to encourage further momentum reduction.

The second type of augmentation is the stepped spillway (Figure 7). Stepped Spillway 1 can reduce the residence volume only in the *airborne droplets* flow regime and gravity dominated [10]. It was noticed that the wall film became detached upon impact with the first step. Stepped Spillway 2 is a new design. It features shallower angled steps with each step pointing towards the centre of the next. Furthermore, it features far fewer steps than the first iteration. These modifications were based on civil hydraulics dam design to obtain more energy dissipation by encouraging nappe flow instead of skimming flow [14].

The third type of augmentation is the perforated plate (Figure 8). Perforated Plate 1 reduces the residence volume of the baseline shallow sump in *airborne droplets* flow regime [10]. In the *wall film* flow regime, the effect is negligible because the film is thinner than the plate stand-off distance and therefore the film simply flows underneath the plate unhindered. Perforated Plate 1S is the next iteration of the optimization process. It has the same formation and porosity but is positioned on top of the sump. In addition to reducing the momentum of the incoming flow, Perforated Plate 1S also functions as a cover to provide a sheltering mechanism.

RESULTS AND DISCUSSION

Grille Covers

The residence volumes were measured and compared to the values of the baseline shallow sump. The differential residence volumes with the grille covers are shown in Figure 9 (*wall film* flow regime) and Figure 10 (*airborne droplets* flow regime). In the *wall film* flow regime, Grille Cover 1 performs well. It reduces the residence volume in all variations of flow rate, scavenge ratio, and shaft speed. Further reduction of up to 50% is achieved by Grille Cover 2. More prominent reduction is achieved at high shaft speed. This indicates the effectiveness of the perpendicular slats to enhance momentum reduction.

In the *airborne droplets* flow regime, Grille Cover 2 helps to further reduce the residence volume at low shaft speed. Similar to Grille Cover 1, the residence volume also increases at high shaft speed although not as severely. This behaviour suggests that the grille covers are beneficial only in gravity dominated flow (low shaft speed). In a windage dominated flow (high shaft speed), the perpendicular slats help to reduce the flow momentum but not enough to cause reduction in the residence volume. It is not clear whether the grille covers can provide sufficient sheltering mechanism in windage dominated flow. The increase in residence volume may be attributed to droplets' atomization upon high speed impact with the slats thus more droplets are trapped in the bulk rotating flow.

Stepped Spillways

The differential residence volumes with the stepped spillways are shown in Figure 11 and Figure 12 for the *wall film* flow regime and the *airborne droplets* flow regimes respectively. In the *wall film* flow regime, the graph show that both stepped spillways generally do not perform well. In almost all cases, Stepped Spillway 2 performs better than Stepped Spillway 1. This confirms that a nappe flow can dissipate more energy than a skimming flow. However the achieved reduction in residence volume is considered insignificant. Although a stepped spillway helps to dissipate more energy, it can encourage aeration thus more air bubbles are trapped in the film flow [14].

In the *airborne droplets* flow regime, both stepped spillways perform similarly. The stepped spillways do not provide a sheltering mechanism and therefore their effectiveness in airborne droplet flow regime can be limited. Significant residence volume reduction (up to 25%) is shown only at Q_l = 4 lpm and Ω = 5,000 rpm. At this high liquid flow rate but low shaft speed (gravity dominated flow), a higher liquid proportion is in the wall film thus a stepped spillway is more effective in reducing the flow momentum.

Perforated Plates

Figure 13 and Figure 14 shows the differential residence volumes with the perforated plates in the *wall film* and *airborne droplets* flow regimes. In the *wall film* flow regime, Perforated Plate 1 does not affect the flow since it is essentially not interacting with the film (its stand-off distance is higher than the film thickness). Some improvement can be gained with Perforated Plate 1S. This minor improvement can be attributed to the shielding mechanism provided by Perforated Plate 1S. With the plate positioned on top of the sump where liquid pooling occurs, chance for stripping and entrainment is reduced. Moreover if the incoming film flow misses the sump, it will be scooped and directed to the sump.

In the *airborne droplets* flow regime, Perforated Plate 1 improves scavenge performance consistently throughout all tested conditions. Up to 30% reduction in residence volume can be achieved. Perforated Plate 1S can further improve the scavenge performance at low shaft speed (gravity dominated flow). However at high shaft speed (windage dominated flow), Perforated Plate 1S increases the residence volume. Previous work on downstream perforated plates also shows increased residence volume at high shaft speed [10]. This suggests that in a windage dominated flow, the perforated plate needs to be located upstream of the sump. Putting it on top of the sump, although it will provide shielding, is not overall beneficial as the reduced momentum flow seems to “miss” the sump.

Comparing the Augmentations

A fundamental challenge with a study of this kind is that each of the augmentation proposed performs differently in the different flow regimes – but an aeroengine operates across a whole range of conditions. The question then is whether any of these augmentations is worthy of future development. A high percentage reduction in residence volume is obviously a good indicator, but if the baseline is already low then such a reduction may be less valuable than a smaller percentage of a larger initial value.

To quantify the overall effect of each augmentation, it is necessary to consider some kind of bulk parameter. Looking at Table 1 it is apparent that the *airborne droplets* flow regime is the more challenging with residence volumes here being typically three times those of the wall film regime. Focusing on the *airborne droplets* flow regime we can calculate the average reduction in residence volume across all the cases (2 levels of liquid flow rate, 2 levels of scavenge ratio, and 2 levels of shaft speed) and represent this as a percentage of the average residence volume for the airborne droplets baseline cases (167.3 ml). So, for example, the average change in residence volume for all droplets regime cases for grille 2 is -14.9 ml giving a percentage change of -9%. This is made up of some cases where residence volume is reduced and some where it is increased. Calculating values for all the augmentations yields the data in Table 2. A larger negative value represents a larger average reduction in residence volume.

Examination of Table 2 shows us that for the challenging *airborne droplets* flow regime the two perforated plates and Grille Cover 2 look the most promising. It is perhaps here also worth noting that Grille Cover 2 is essentially a more open perforated plate and it is not so surprising that it yields data close to that of Perforated Plate 1S. The interesting result here is that Perforated Plate 1, positioned upstream of the sump and not in any way covering it, is the one that yields consistently the best performance in the droplets regime. It is therefore strongly suggested that further work is conducted that combines perforated plates 1 and 1S, providing an element of modification to the film flow and droplet film impact behavior both upstream of the sump and over it. Further optimization work could also include investigating variations of porosity, perforation shape and size, scoop design, and plate length.

CONCLUDING REMARKS

Three types of augmentations (grille cover, stepped spillway, and perforated plate) for improving the scavenge performance of a shallow sump have been studied. These augmentations exploit two fundamental mechanisms for reducing the residence volume: momentum reduction and shielding.

This work has assumed two extremes of flow regime: *wall film* and *airborne droplets*. In reality, depending on how the oil enters the chamber, the flow in an aeroengine chamber will be some kind of combination of both. The baseline study shows that the airborne droplets regime is the more challenging for scavenge with residence volumes being typically three times those for the equivalent wall film case.

Focusing on the effect of the augmentations on residence volume in the droplets cases we conclude that some kind of perforated plate has the most promise for reducing residence volume over a range of engine conditions with the best performing augmentation tested here yielding an average reduction in residence volume of 18%. This is a gain worth having and it is strongly recommended that perforated plate augmentations are further investigated both for plate geometry and extent as well as placement within the bearing chamber.

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NOMENCLATURE

Q_g	gas volumetric flow rate
Q_l	liquid volumetric flow rate
SR	scavenge ratio
Ω	shaft rotational speed

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Table Caption List

Table 1

Flow Regime	Q_l [lpm]	SR	Ω [krpm]	Residence Volume mean [ml]	Residence Volume ± [ml]
Wall Film	2.7	1.5	5	33.0	0.5
			15	55.7	1.2
		4	5	28.8	0.9
			15	47.7	1.0
	4	1.5	5	60.2	0.5
			15	85.5	1.6
		4	5	45.3	1.8
			15	74.8	2.8
Airborne Droplets	2.7	1.5	5	173.7	1.6
			15	150.2	1.2
		4	5	143.5	1.1
			15	121.5	0.9
	4	1.5	5	239.2	4.0
			15	162.2	1.3
		4	5	222.2	5.1
			15	126.2	0.8

Table 2 (sized for 2 columns)

Q_l [lpm]	*SR*	Ω [krpm]	Baseline Residence Volume [ml]	Change in Residence Volume [ml]					
				GC 1	GC 2	SS 1	SS 2	PP 1	PP 1S
2.7	1.5	5	173.7	-2.0	-55.7	-11.2	6.2	-31.7	-43.2
		15	150.2	49.0	36.2	8.3	11.5	-37.2	18.5
	4	5	143.5	-1.2	-55.7	-0.8	10.0	-16.5	-65.7
		15	121.5	48.2	19.0	10.0	-13.7	-28.8	3.7
4	1.5	5	239.2	-24.0	-43.5	-51.5	-59.2	-34.2	-38.5
		15	162.2	40.0	9.3	8.2	-4.3	-42.4	23.8
	4	5	222.2	-7.2	-31.8	-32.7	-44.2	-22.2	-41.8
		15	126.2	44.3	3.0	13.7	-12.7	-24.2	19.7
MEAN [ml]			167.3	18.4	-14.9	-7.0	-13.3	-29.6	-15.4
MEAN CHANGE [%]				11.0	-8.9	-4.2	-7.9	-17.7	-9.2

Figure Captions List

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Fig. 13	Differential residence volumes with perforated plates (wall film flow regime)
Fig. 14	Differential residence volumes with perforated plates (airborne droplets flow regime)

Figure 1

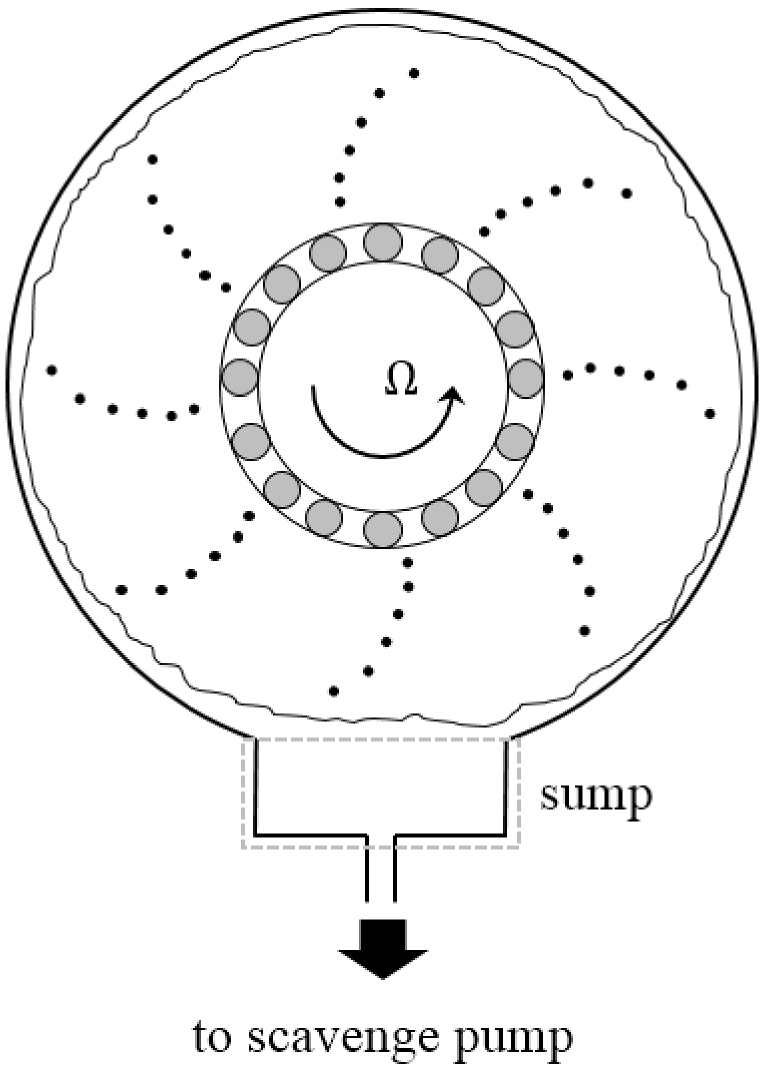


Figure 2

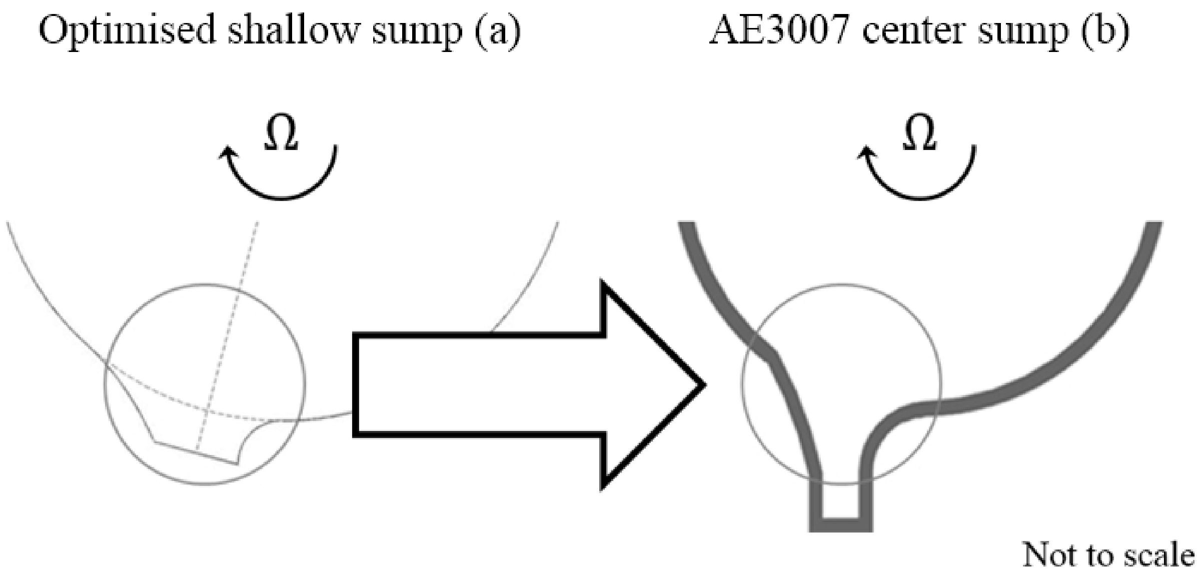

Optimised shallow sump (a)
AE3007 center sump (b)
Ω
Ω
Not to scale

Figure 3 (sized for 2 columns)

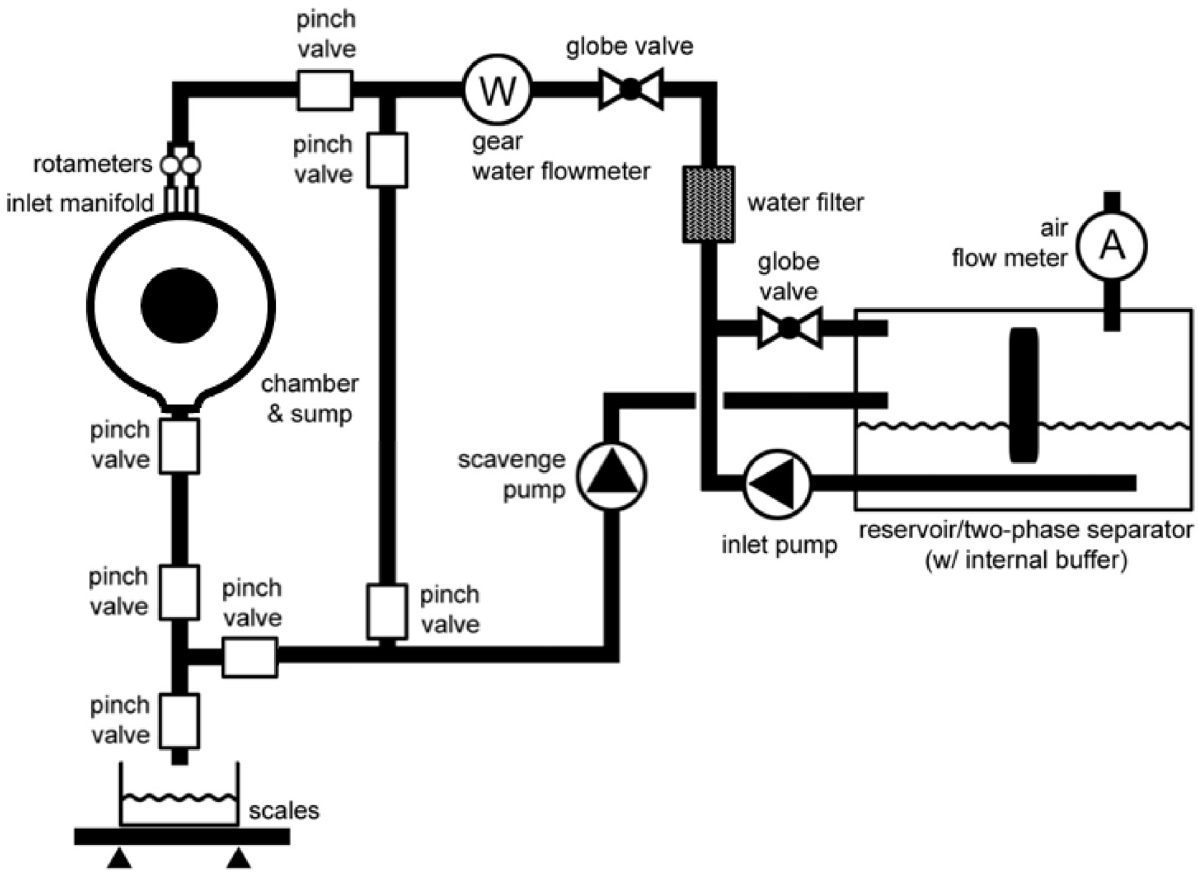


Figure 4

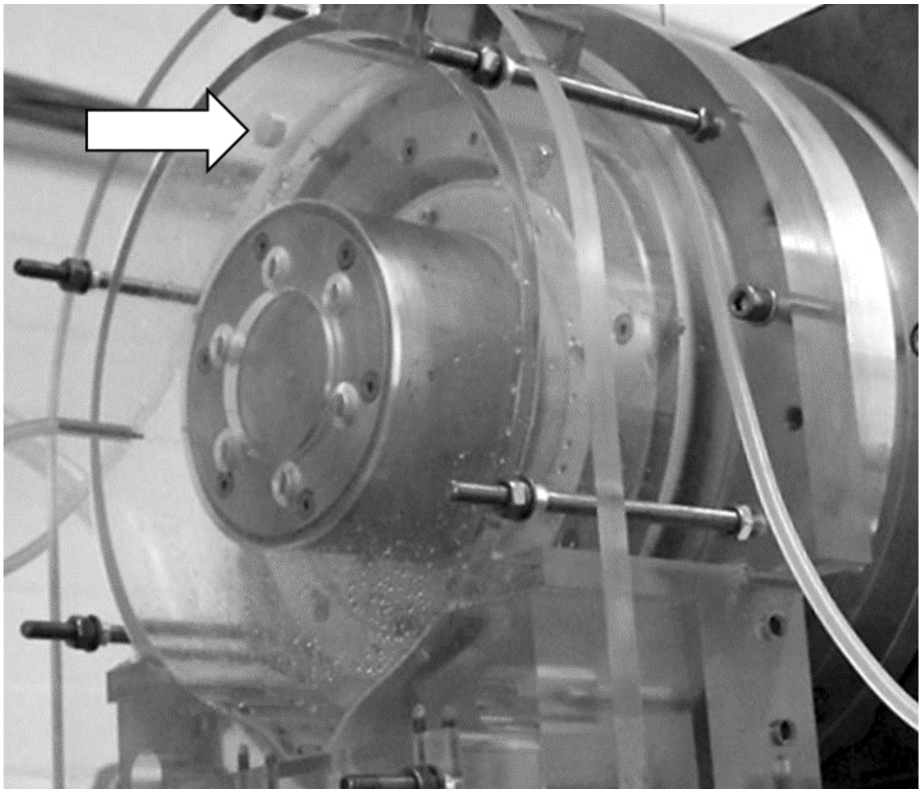


Figure 5

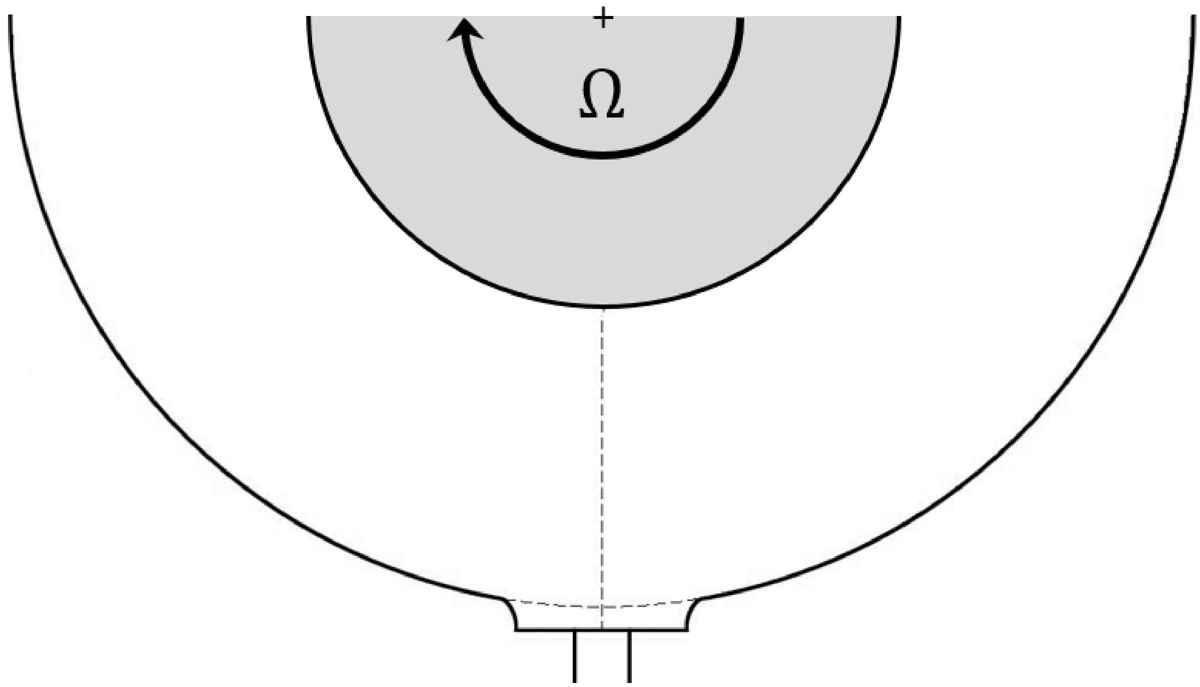


Figure 6

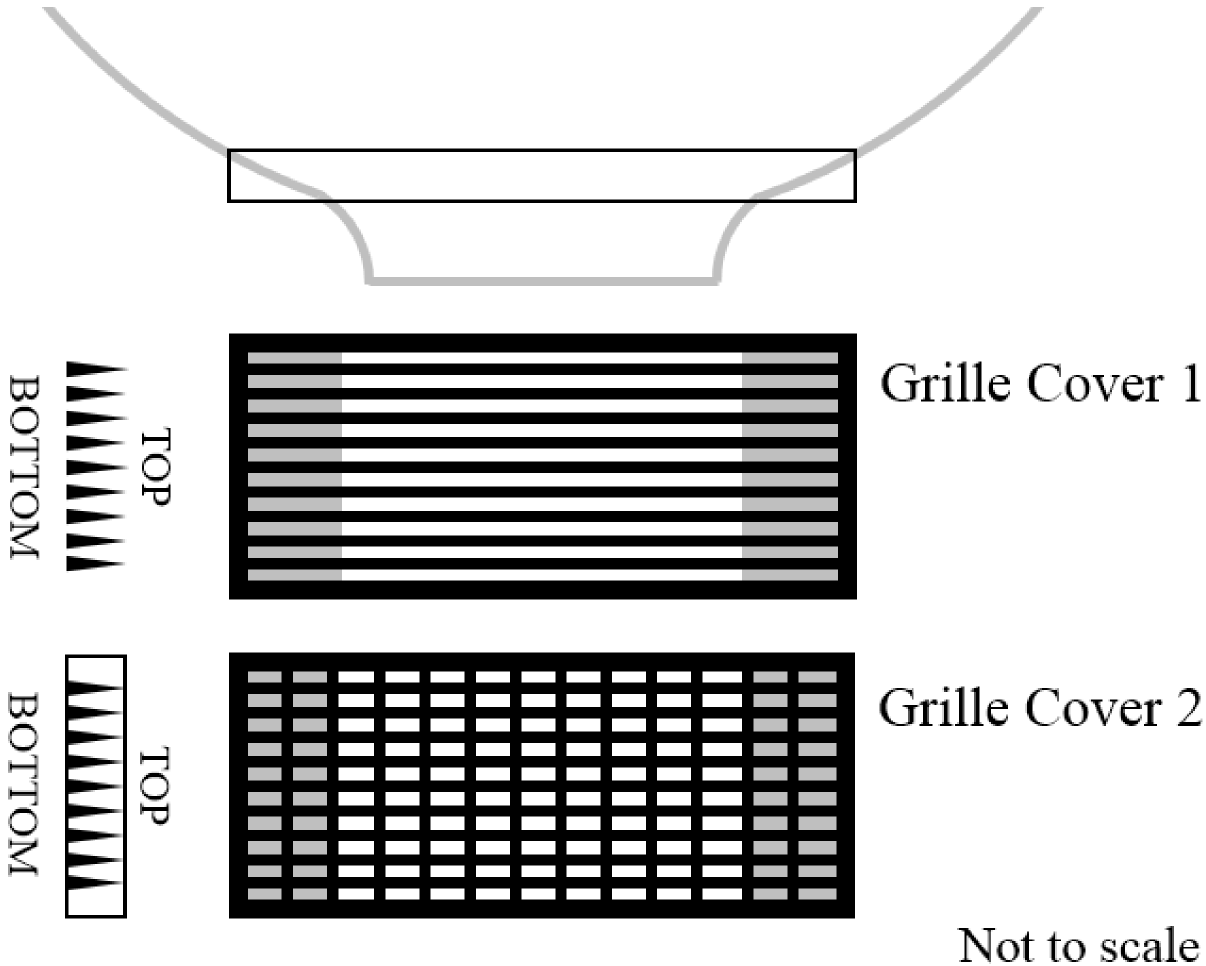

Grille Cover 1
Grille Cover 2
TOP
BOTTOM
TOP
BOTTOM
Not to scale

Figure 7

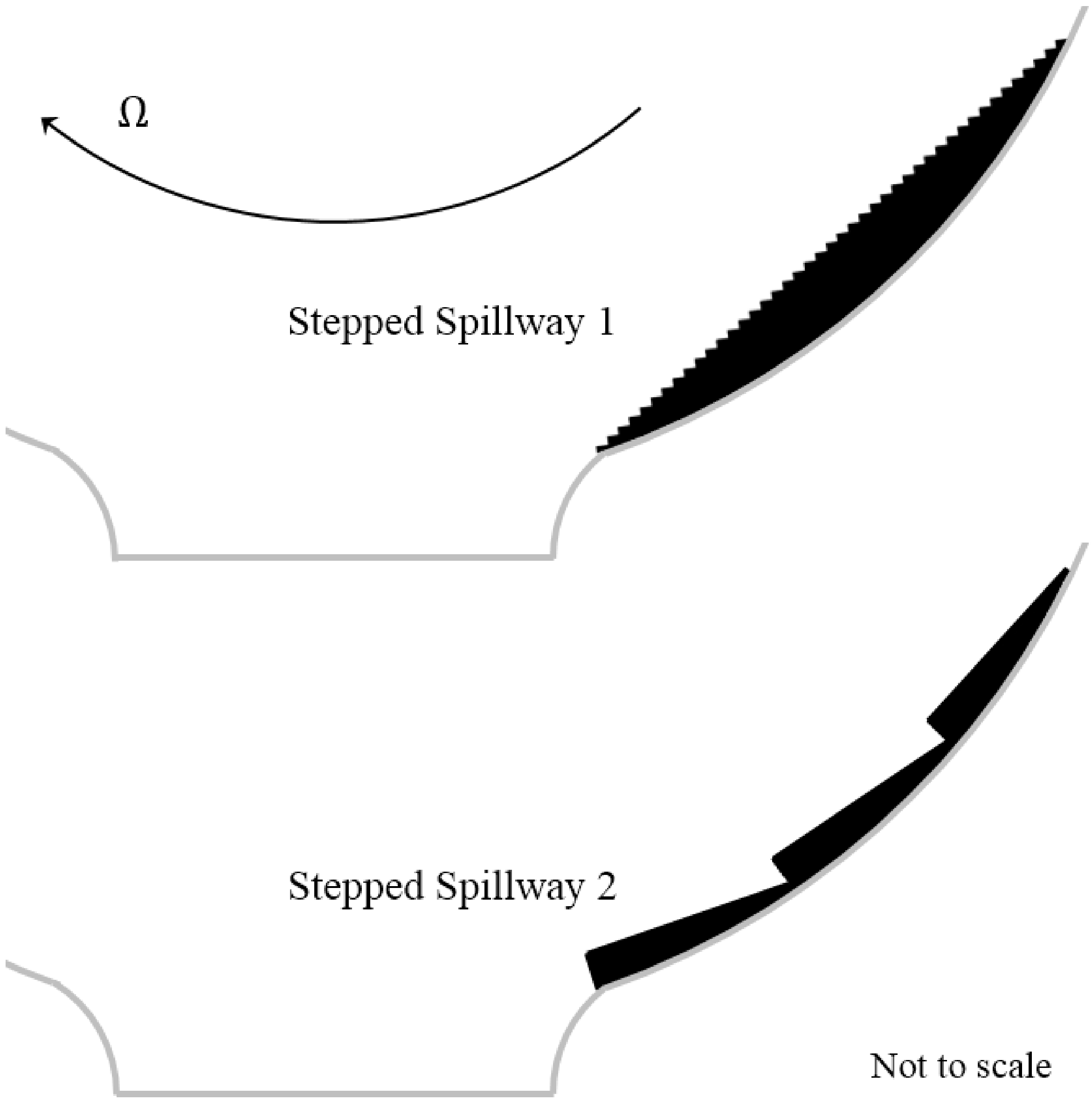


Figure 8

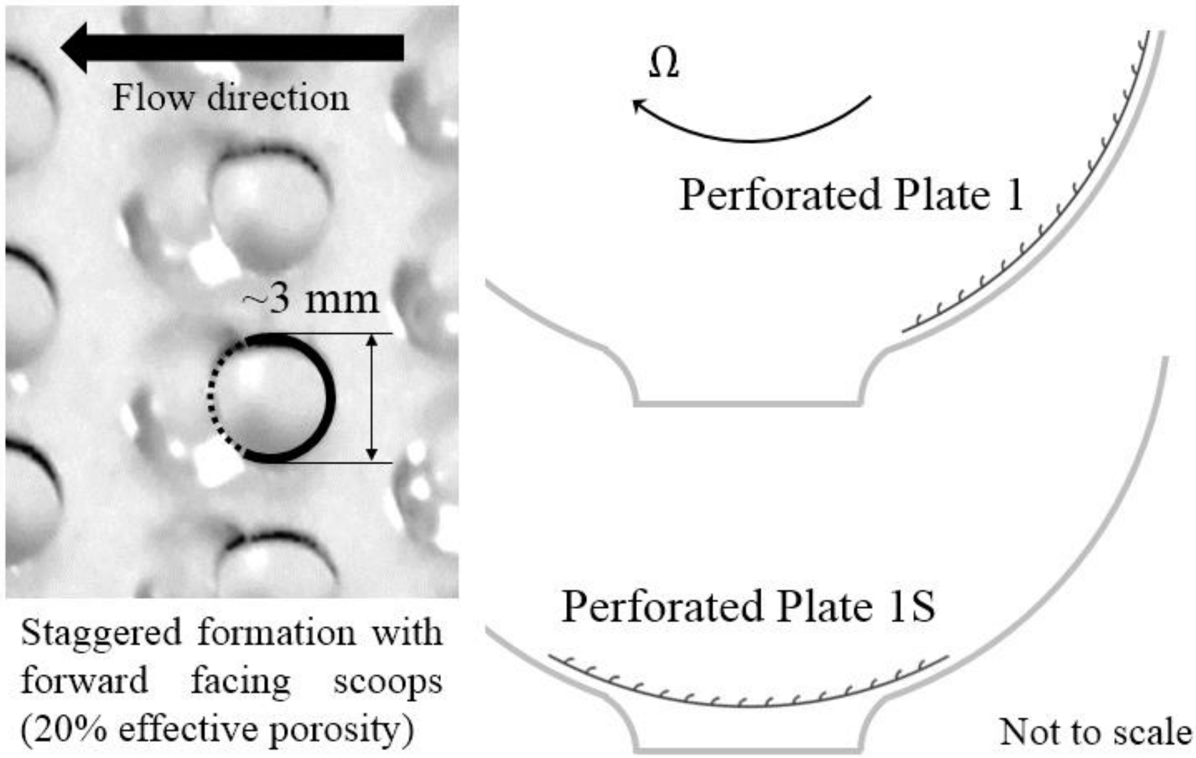
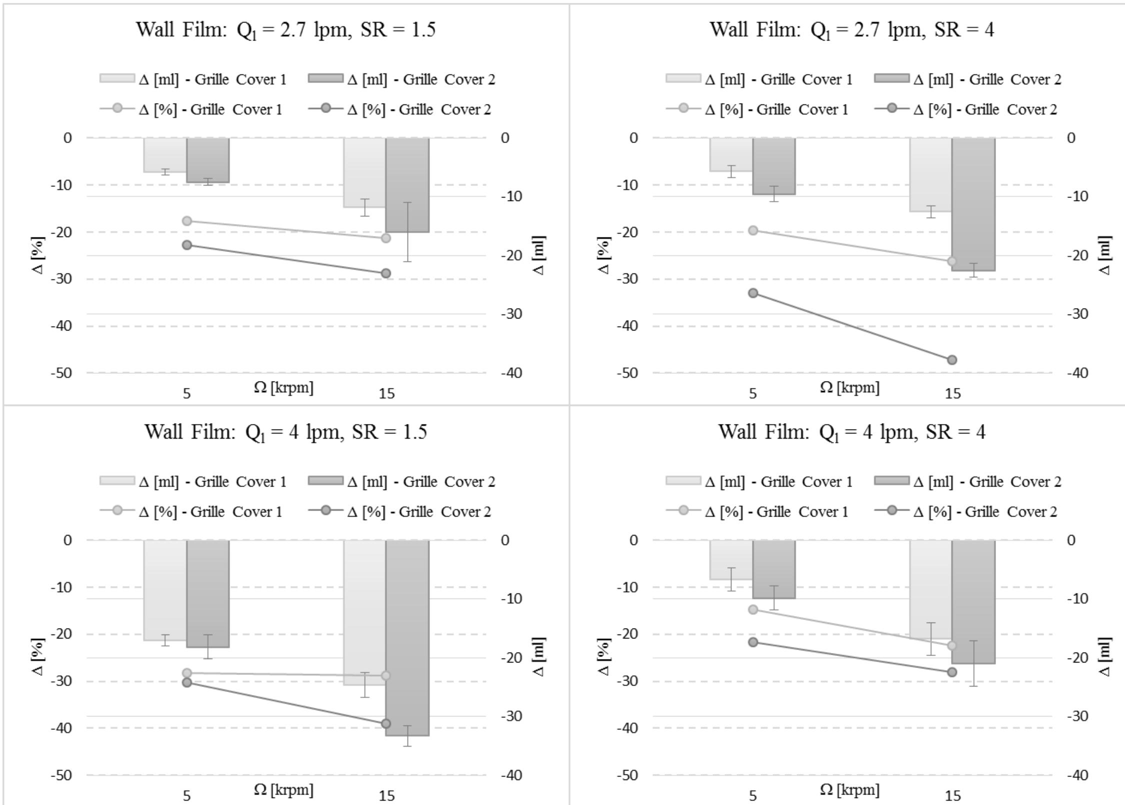

Flow direction
~3 mm
Staggered formation with forward facing scoops (20% effective porosity)
Ω
Perforated Plate 1
Perforated Plate 1S
Not to scale

Figure 9 (sized for 2 columns)



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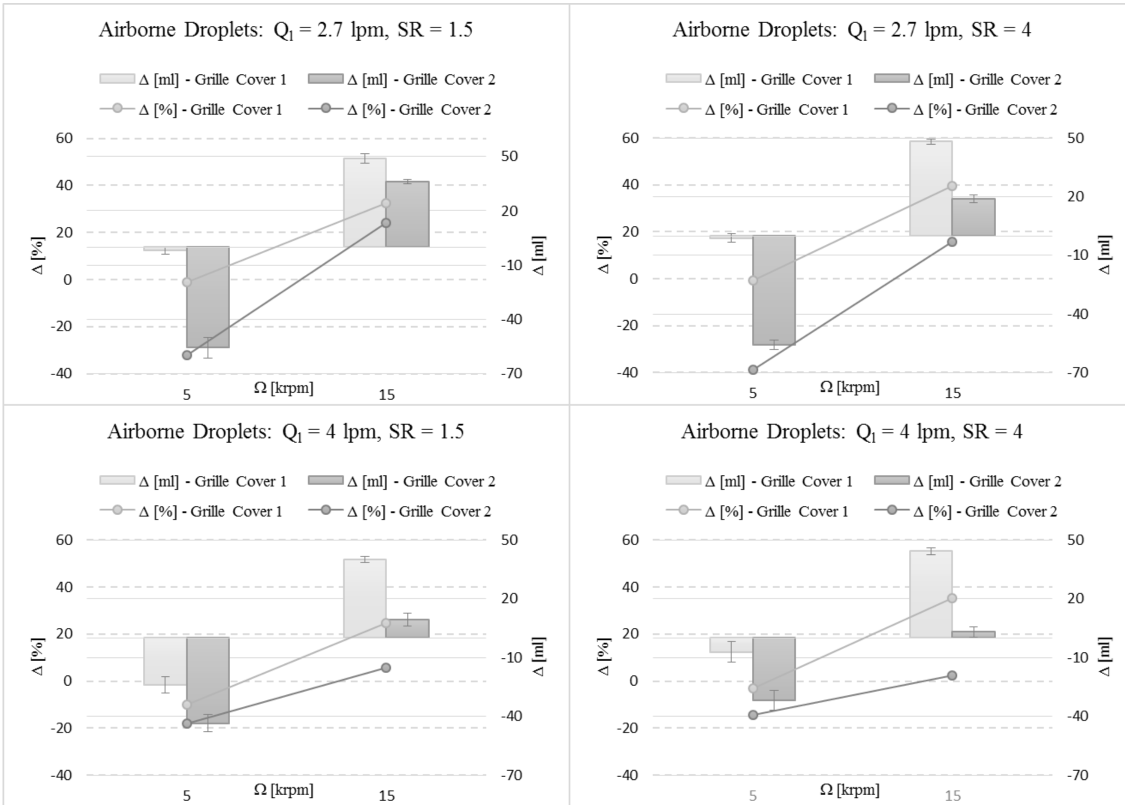
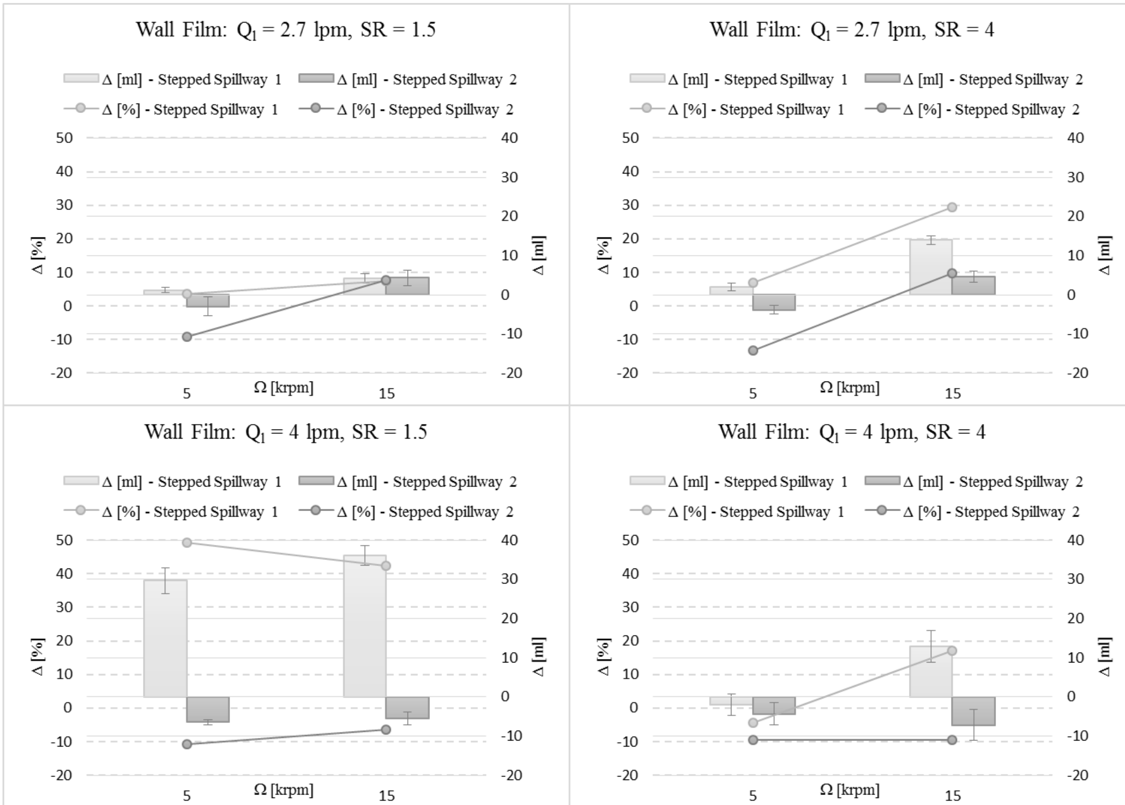


Figure 11 (sized for 2 columns)



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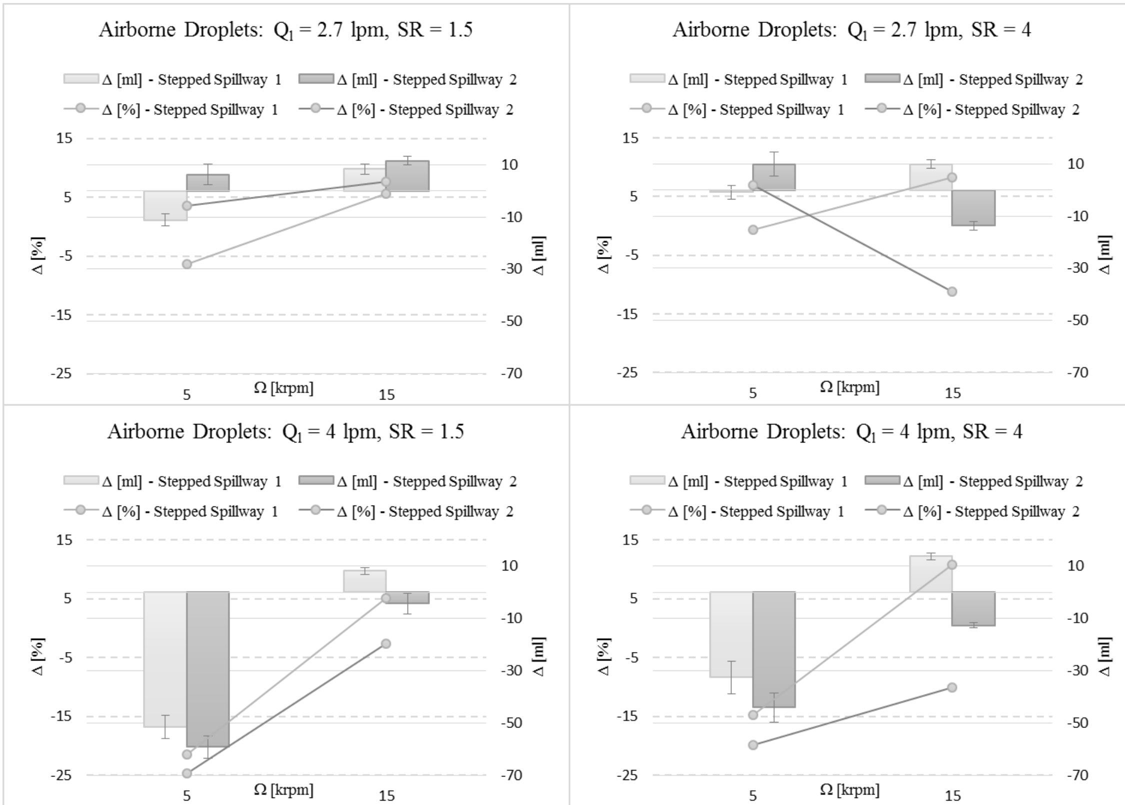

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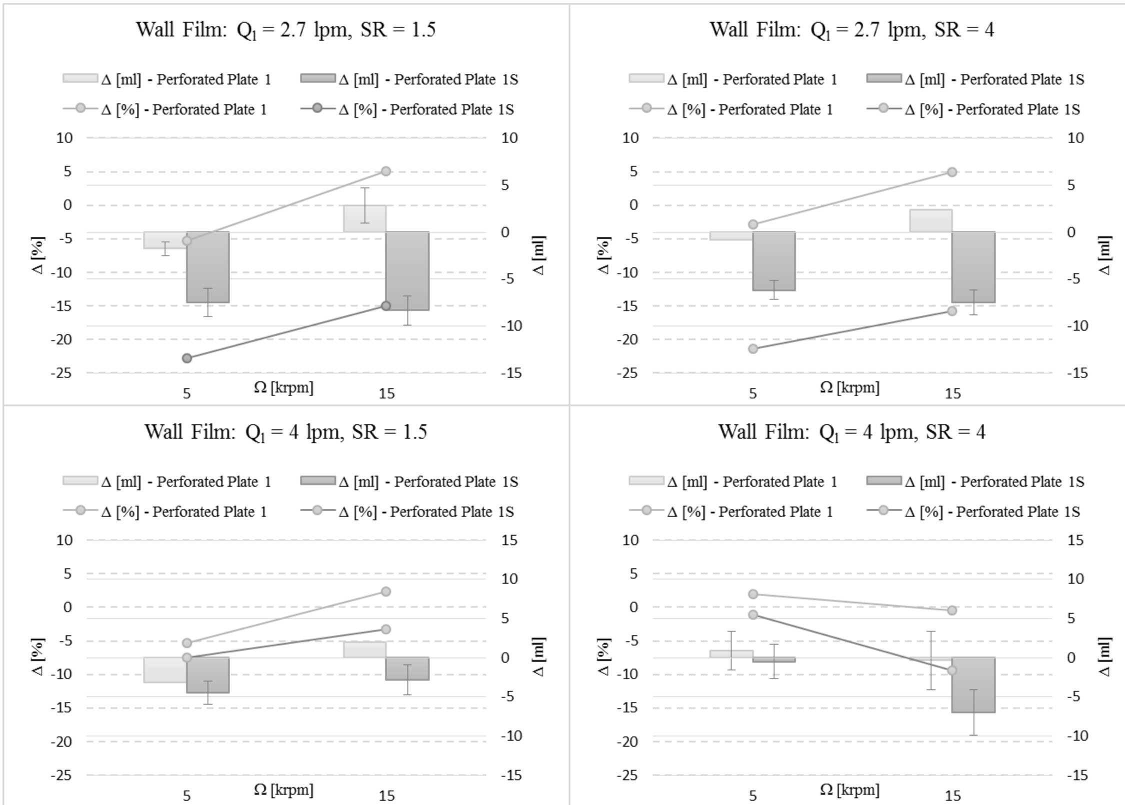

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