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# CLC cold model testing and design development

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Fluidization test were made with double exit loop-seal cold model, picture of the cold model can be seen at appendix, Fig. 6. and 7. Goal of the fluidization test were to determinate if double exit loop-seal can divide solid mass flow, adjustability of distribution and solid mass flow between exits.

Tests were made with two sieved particle sizes, 180-250µm and 250-315µm, to estimate effect of the particle size to fluidization at the loop-seal. Smaller particles, 180-250µm, tend to have stepwise increase of the solid mass flow. Other significant differences between particle sizes were not found.

Results from test are promising. Solid mass flow can be divided and distribution between double loop-seal can be adjusted, Fig 8. and 9. Adjustability and operation area of cold model is restricted, because of size of the cold model. Scalability from small cold model gets complicated due length scale of particles and bubble size. Results still clarify fundamentals of the double loop-seal and possibilities to adjust solid mass flow.

Observations were made during commissioning and test about double exit loop-seal and the cold model. Dimensions for cold model were bit too small which probably increased wall effect. This may decrease stability of fluidization and resist flow near walls. Acrylic walls also accumulate static electricity which affect to fluidization. After commissioning cold model were grounded which decreased amount of static electricity, but did not fully removed it. Amount of influence is difficult to estimate.

Small dimensions caused problem with recycle chambers. Small difference at width between recycle chambers, made relatively bigger difference at geometry, because dimensions are small. This difference result some leakage of fluidization air from the FR-side to the AR-side, this can be seen at Fig. 2. and 3. When double exit loop-seal is scaled-up this kind of flow behavior should decrease, because horizontal dimension increase. Same kind of leakage was found from side to side before revision when sinter grate were united. At revision before tests, grate was divided with welding seam which closed horizontal shift of fluidization air at sinter grate.

These observations helped and made changes at design of full cold model system. From this point of view, these tests can be seen as successful. Cold model gave support to continue built continuously working cold model containing two interconnected CFBs with two double exit loop-seals.

Leaning on these cold model tests and observations, scaling studies and design of full reactor system cold model where made. Scaling and design were made during winter November-January and detailed assembly drawings were made at January-February. Overview picture of reactor system can be seen at Fig. 10. and 11. at appendix.

More detailed description about test procedure and results are presented at article. Additional pictures are presented at appendix.

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# SOLID FLOW ADJUSTABILITY AT DOUBLE EXIT LOOP-SEAL

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Abstract: Loop-seals has been used in an industrial scale circulating fluidized bed (CFB) boilers to return the solids to the furnace and as non-mechanical gas valve between a cyclone and the furnace. Solids fill to the loop-seal and prevent gas flow from the furnace to the cyclone. Solids at loop-seal have been fluidized from the bottom over a weir which is connected to a discharge pipe leading to the furnace.

With a double exit loop-seal combustion and heat transfer are distributed more evenly in the furnace when solids has been circulated via two feeding points instead of one. Typically a solid flow distribution between loop-seal exits has not been controlled by fluidization.

Double exit loop-seals have been also used at chemical looping combustion (CLC) reactor systems. This enables circulation and recirculation loops for oxygen carriers between air and fuel reactors. The solid flow ratio adjustability of the double exit loop-seal has not been widely represented at literature.

A cold model of the double exit loop-seal has been constructed from acrylic-glass. The width and the length of the loop-seal is 30mm. The loop-seal has been controlled by two separated airboxes, one for the each recycle chamber. The double exit loop-seal has been connected to two reactors.

Fluidization experiments to adjust solid flow of a double exit loop-seal has been carried out. The research objective has been to study adjustability of the double exit loop-seal and which fluidization conditions make possible to divide the solid flow to the wanted exit of the loop-seal. The experiments have been made with different particle size distributions.

Initial study of the solid flow at the double exit loop-seal has been made at the cold flow model. An affected property to adjustability has been observed. Study shows that solid flow can be adjusted between different exits at the double exit loop-seal by adjusting volume flow to the airboxes. The total mass flow through loop-seal increases when total volume flow increases.

Keywords: Loop-seal; hydrodynamics; fluidization; fluidized bed combustion; chemical-looping

## INTRODUCTION

Solid flow recirculation system is essential part of circulating fluidized bed (CFB) system. It controls solid circulation rate at the CFB system and separates gas space between the cyclone and the furnace. Stable control of solid recirculation is important for robust CFB process. Malfunction of the solid circulation system may cause hot solid accumulation to the standpipe and cyclone, or gas bypass to the cyclone. Depending on CFB process these may cause decreases in efficiency or even to an unwanted shutdown.

The solid flow circulation can be controlled by mechanical or non-mechanical valves. Loop-seal, L-, V- and J-valves are non-mechanical valves which are controlled by fluidization. Non-mechanical valves are not as sensitive to corrosive gases, abrasive particles, high temperatures and pressures as mechanical valves.

Double exit loop-seal differs from ordinary loop-seal as it has two recycle chambers and exits. This design enables to split of solid circulation flow to two separated streams. An advantage is to lead solid streams to wanted part of the furnace at CFB combustion process or different reactor at chemical-looping (CL) process. There are reactor systems that use double exit loop-seals at chemical-looping combustion (CLC)

(Bischi et al., 2011). These increase adjustability of process and may increase range of feasible operation conditions.

Literature (Basu et al., 2009a; Namkung et al., 2002; Kim et al., 1999, 2002) contains information and sizing instructions (Basu, 2006) for ordinary loop-seals. Information has been concentrated to pressure changes at solid circulation system and solid flux. Double exit loop-seal has similarities with the ordinary design. Basu (2009b) wrote about pressure changes and total mass flow capacity at double exit loop-seal system. Literature has lack of references about how solid flow is controlled; adjusted and how double loop-seal should be sized.

At present study a cold model of double loop-seal was constructed to obtain more understanding and information about adjustability and performance of double loop-seals. The cold model was used with two particle size distributions of sand particles.

## THEORY

A loop-seal, Fig. 1a, have usually three parts, a standpipe, a supply chamber and a recycle chamber. Double exit loop-seal differs from the ordinary loop-seal by additional recycle chamber and exit, Fig. 1b. Solid flow from a cyclone comes to the standpipe which is connected to the supply chamber. Solid flow goes through the slit opening to recycle chambers. Some designs have a horizontal passage between the supply chamber and the recycle chambers. From the recycle chamber solids are fluidized over a weir and led through a delivery pipe to the furnace.

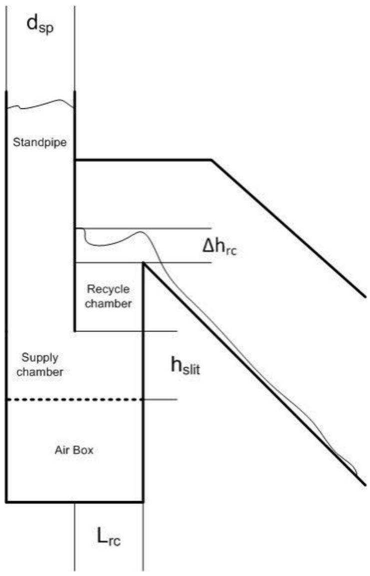


Figure 1a. Schematics of loop-seal

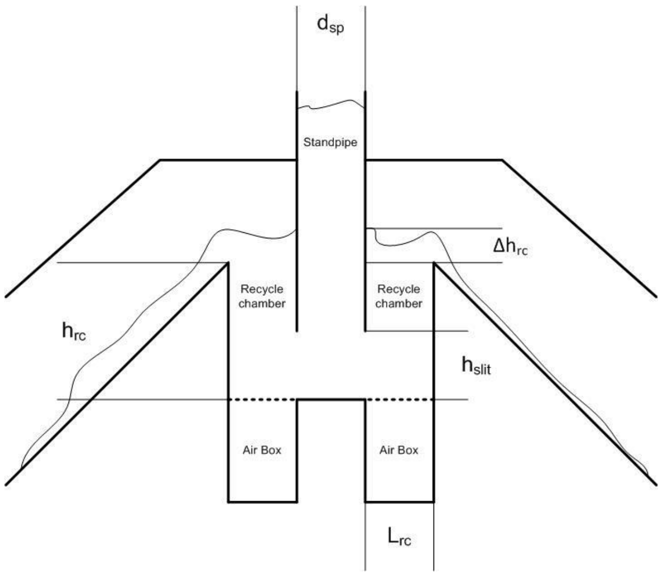


Figure 1b. Schematics of the double exit loop-seal used at experiments.

Solids which are at the standpipe, the supply and the recycle chamber prevent gas by-pass from the furnace to the cyclone at CFB combustion. The CLC reactors may have different pressure which increases possibility of gas leakage between the air reactor (AR) and fuel reactor (FR). In this case, solids also prevent by-pass of the gas to another reactor if double exit loop-seal is used.

Fluidization of the loop-seal can be different depending on design, on process and circulated solid. The standpipe may be fluidized as well, but it is not always necessary. Fluidization of the supply and the recycle chambers can be made with a shared or separated grate.

Basu et al. (2009b) mention that advantage of the double exit loop-seal is the increased total solid recycle rate, but this is not proportional to the increase of the solid flow area. The solid mass flow can be controlled by adjusting a fluidization volume flow, if aeration of recycle chambers is made separately. Usually at the ordinary loop-seal fluidization has been set to constant and fluidization flow is not controlled during operation.

The solid mass flow to the loop-seal comes from the standpipe and can be led to one or both exits at the double loop-seal. This has been done by separated control of the fluidization at recycle chambers. Theoretical solid flow and ratio between solid flows to different exits can be calculated. The total solid mass flow, $G_s$, can be determined from the standpipe, Eq. 1., if solid velocity, $u_{sp}$, in standpipe is known.

$$G_{s,sp} = (1 - \epsilon_{sp})\rho_s A_{sp} u_{sp} \quad (1.)$$

Solids are divided to the recycle chambers 1 and 2. The solid mass flow to the recycle chamber is same as the solid mass flow over the weir, $G_{rc,i}$, to the delivery pipe. This can be calculated from Eq. 2., where c is experimental constant, $\varepsilon_{rc,i}$ is voidage at recycle chamber, $\rho_s$ is a density of solids, g is a standard gravity, $\Delta h_{rc,i}$ is a height of bed over the weir and W is a the width of the weir. Basu and Botsio (2005) presents that c is in range of 0.065-0.08 for 150µm to 250µm particles.

$$G_{s,i} = \frac{2}{3} c(1 - \epsilon_{rc,i})\rho_s \sqrt{2g} \sqrt{\Delta h_{rc,i}^3} W \quad (2.)$$

King (1989) has presented approximation of the voidage depending on a superficial fluidization velocity, $u_i$, and an average rise velocity of the gas void or bubble, $u_v$, Eq. 3.

$$\epsilon_{rc,i} = \frac{u_i + \left(\frac{u_v}{2}\right)}{u_i + u_v} \quad (3.)$$

The height over the weir can be approximated from an assumption that mass at the recycle chamber does not change depending on the fluidization velocity, only bed height and voidage varies. Height over the weir is calculated, Eq. 4., depending on the fluidization and the bubble velocity at the recycle chamber at Eq. 3.

$$\Delta h_{rc,i} = h_{rc,i} \left( \left( \frac{1 - eps_{min}}{1 - eps_{rc,i}} \right) - 1 \right) \quad (4.)$$

The total solid flow from the standpipe is a sum of the flow over the weirs at the recycle chambers, which is presented at Eq.5.

$$G_{s,sp} = G_{rc,1} + G_{rc,2} \quad (5.)$$

The solid flow ratio between the recycle chamber exits is presented at Eq. 6.

$$ratio = \frac{G_{rc,1} - G_{rc,2}}{G_{rc,1} + G_{rc,2}} \quad (6.)$$

When solid flow is distributed evenly, ratio is 0. Ratios -1 and 1 present full distribution to the other recycle chamber exits. If the geometry of the double loop-seal is symmetrical, pressures after the recycle chambers and the volume flow of fluidization and properties are the same, distribution of the solid flow should be even between the recycle chambers. The fluidization volume flow and ratio between the recycle chambers affect to bed expansion, which changes solid distribution ratio and mass flow.

## EXPERIMENTAL

The fluidization experiments were made at the cold model, which was made from acrylic-glass. The cold model contains one double exit loop-seal and two reactors with solid containers. Solid flow to the standpipe has been handled by adjustable vibration feeding, which represents a cyclone.

Standpipe inner diameter, $d_{sp}$, is 21mm, which broadens to rectangular 10mm*30mm. Separated horizontal passage between the supply chamber and the recycle chambers does not exist. Height of the slit, $h_s$, between chambers is 10mm.

The height of the recycle chamber, $h_{rc}$, is 20mm. Both recycle chambers are 10mm*30mm rectangular. The width of the weir is 30mm. Rectangular standpipe end divide gas spaces between exits when the loop-seal is full of solids.

Fluidization flow has been made only at the bottom of the recycle chambers to increase adjustability and to prevent fluidization gas leakage to the unwanted exits of the loop-seal. Fluidization gases are adjusted separately to two airboxes seen at Fig. 1b. Grate is solid under the supply chamber to prevent horizontal gas shift at the grate.

Two different particle size distributions were used at the experiments. Particle properties are presented in Table 1.

Table 1 Particle properties at experiments.

| Particle | Apparent density ($kg/m^3$) | Nominal Size Distribution (µm) |
|---|---|---|
| Sand | 2600 | -315 +250 |
| Sand | 2600 | -250 +180 |

Solid mass flow over the recycle chambers were measured with a scale. Solid level at the standpipe was adjusted as constant with a vibration feeder. Different operation points were achieved by changing the solid mass flow from the vibrator feeder and changing the fluidization volume flow. Air was used as fluidization gas and the fluidization volume flows were adjusted with flow rate regulators. Stable fluidization conditions were defined by online scales and visual inspection.

Solids were fluidized through the double loop-seal to the solid containers and continuous weight sampling was made. Solid flow distribution ratio and total solid flow was determined from the solid mass flow to different containers. Mass flows were determined from average value of the continuous weight change. Calculations were made only from stable fluidization conditions and timespan of measure were between 2-5 minutes.

Solid flow over the weir at the recycle chamber was controlled with fluidization volume flow from the grate. Both recycle chambers were controlled separately. Increase of the volume flow increased a bed expansion. The volume flow of solids increased as bed expanses over the weir.

## RESULTS AND DISCUSSION

Fluidization velocity affects to the solid mass flow over the double loop-seal. FR-side of the double loop-seal is more stable for fluidization changes than opposite recycle chamber. At Fig. 2a and c. can be seen that mass flow to FR-side is not affected by fluidisation from AR-side. Leakage of a fluidization air from FR-side to AR-side can be seen at Fig. 2b and d. When FR mass flow increases it increases AR-side mass flow. Minimum fluidization velocities are calculated from largest particle size at particle size distribution.

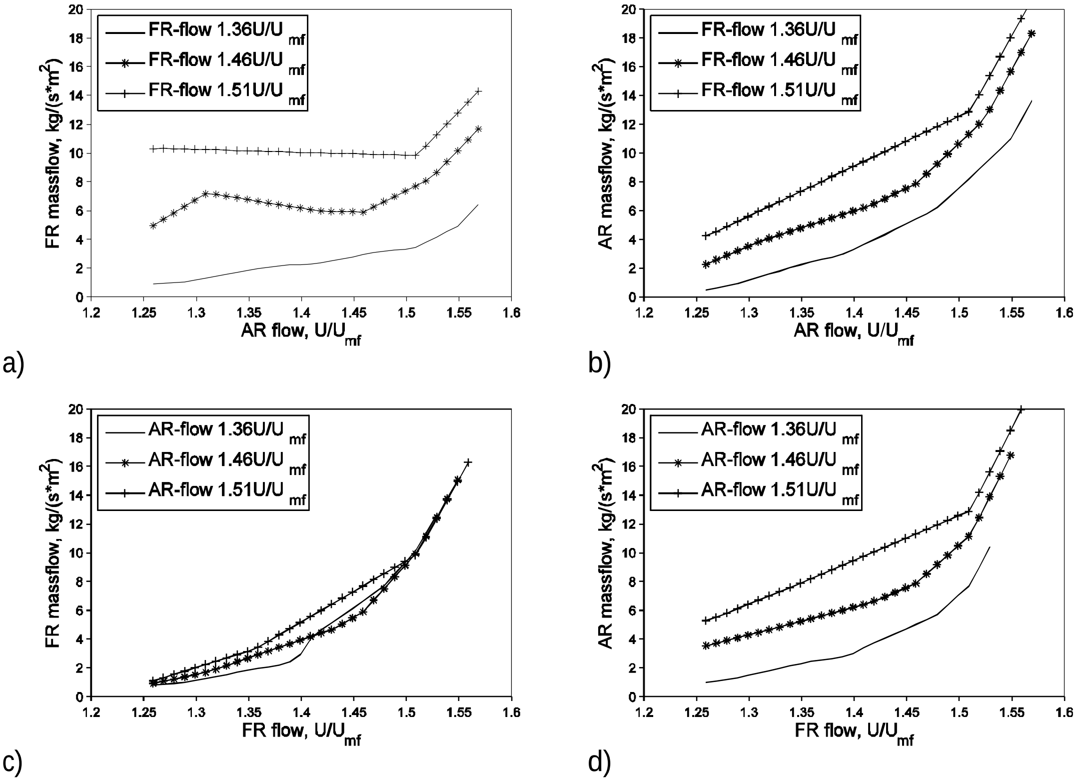


Figure 2. Effect of fluidization velocities to solid mass flow at different recycle chamber, sand 250-315µm. a) mass flow to the FR-side depending on fluidization flow to AR-side, b) mass flow to the AR-side depending on fluidization flow to AR-side, c) mass flow to the FR-side depending on fluidization flow to FR-side, d) mass flow to the AR-side depending on fluidization flow to FR-side.

Same kind of "stable" leakage was not found with smaller sand distribution, 180-250µm. Sometimes during measurement other recycle chamber got blocked up and fluidization volume flow was funneled to another recycle chamber. This generated high solid flow and made fluidization control unstable and difficult. Reason for funneling is unknown, but electrostatic forces and wall effects may affect to fluidization.

Effect of the fluidization velocity to the mass flow has been studied. It can be seen that mass flow distribution between recycle chambers can be controlled by fluidization volume flow. From Fig. 3. it can be seen that control area of mass flow distribution was relatively small and mass flow does not distribute evenly at used double loop-seal.

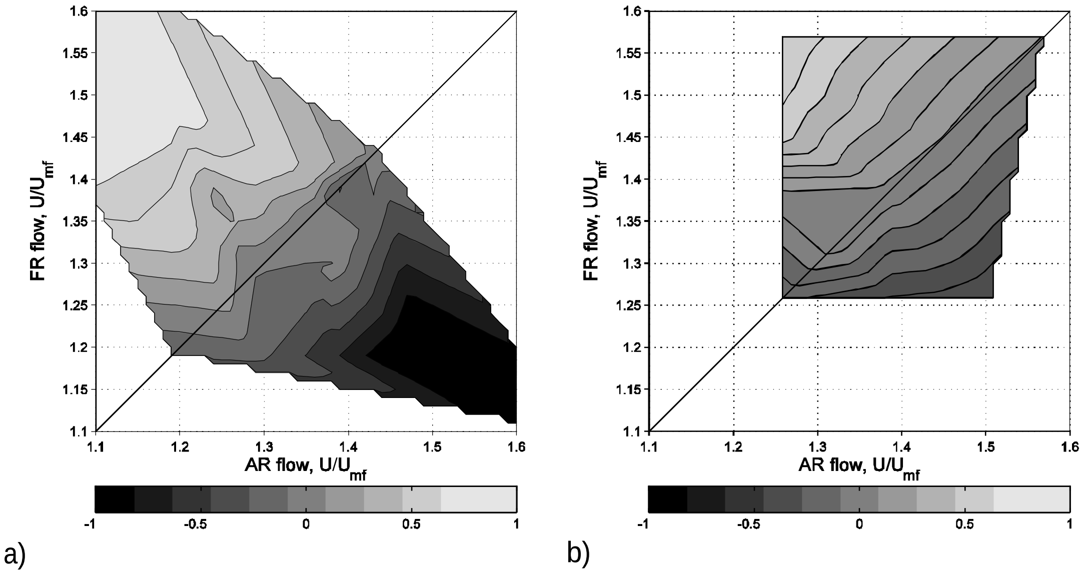


Figure 3. Fluidization velocity effect to mass flow distribution between recycle chambers, a) sand 180-250μm, b) sand 250-315μm. 1 all solids to FR-side, -1 all solids to AR-side, 0 even distribution between recycle chambers.

An increase of the particle size makes solid mass flow control more robust and increases adjustment area. From Fig. 4. can be seen that both particle sizes behave similarly below 1.4Umf. Smaller particles, 180-250μm, tend to have stepwise increase of the solid mass flow. For bigger particle size, 250-315μm, change was steadier. Any other changes of the fluidization were not observed to be connected to particle size distribution changes.

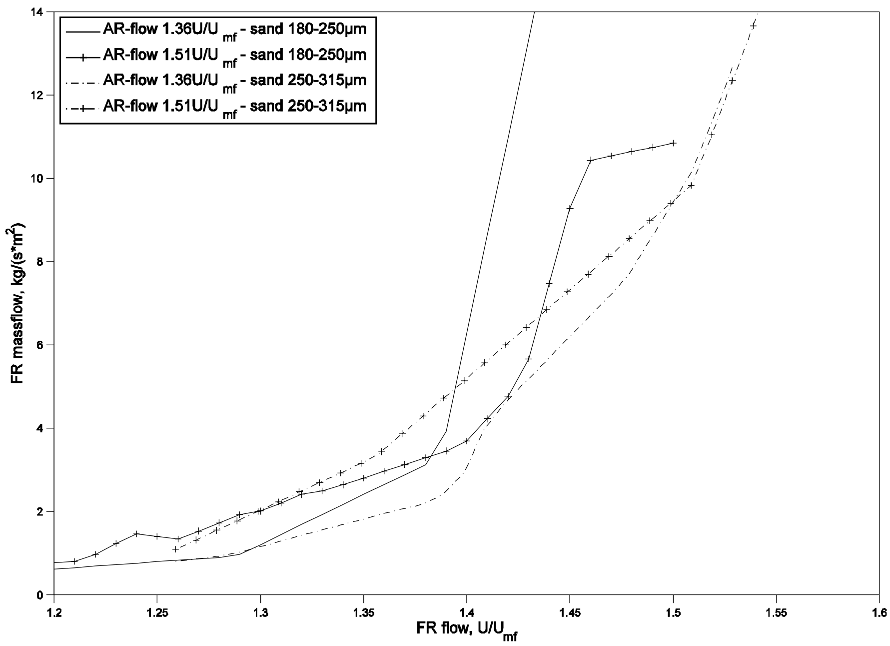


Figure 4. Solid mass flow to the FR-side with different particle size distribution.

## CONCLUSIONS

Known theory of the loop-seal and sizing instructions do not fully fit to the double loop-seal. Increase of adjustability of solid recirculation would make processes more versatile and also make different kind of process connections possible.

Solid mass flow can be controlled between recycle chambers by adjusting fluidization volume flow, which can be seen in Fig. 2. Geometry and dimensions limit adjustment range. Solid mass flow adjustments between recycle chambers do not affect each other, if gas leakage between recycle chambers can be eliminated with correct geometry. The operation area of the solid flow at used cold model is narrow, which makes adjustability challenging. Narrow area of adjustability is connected to small size of cold model. Geometry which decreases stepwise behavior, seen at Fig. 4, of the solid flow control curve would increase adjustability.

Similarity between different particle size distributions were that controllability of process and mass distribution were easiest below $1.4U_{mf}$. Needed mass distribution controllability can be achieved with fluidization velocity of $1\text{-}1.4U_{mf}$. In this control area total mass flow over used double loop-seal varies from 1-10 kg/(s*m$^2$). From visual inspection during measurements after $1.4U_{mf}$ bubble size at the recycle chamber increased which caused slugging type of flow and made flow unstable. This suggests that adjustability of the solid flow distribution is also affected by size and geometry of the double loop-seal.

The fluidization flow leakage between recycle chambers affects to mass flow and distribution. Leakage from FR-side to AR-side is connected to the geometry and cold model size. It is likelihood that leakage does not happen when size and geometry are optimized. Geometry optimization is essential part to eliminate unwanted leakage at the double loop-seal. Good geometry will also increase controllability and area of operation. Size of used cold model was small which increased wall effects. Scalability from small cold model gets complicated due length scale of particles and bubble size. Results still clarify fundamentals of the double loop-seal and possibilities to adjust solid mass flow.

To get better knowledge about double loop-seal sizing and controllability, different double loop-seal configurations and particle materials and sizes need to be tested. This will provide instructions for robust double loop-seal sizing for different processes.

## ACKNOWLEDGMENTS

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## Notation

Symbols:

| | | |
|---|---|---|
| A | area | $m^2$ |
| c | constant | - |
| d | diameter | m |
| g | standard gravity | $m/s^2$ |
| h | height | m |
| Δh | height over the weir | m |
| G | flow rate density | kg/s |
| U,u | velocity | m/s |
| W | width of weir | m |

Subscripts

| | |
|---|---|
| 1 | recycle chamber, 1 |
| 2 | recycle chamber, 2 |
| i | species |
| mf | minimum fluidization |
| min | minimum |
| rc | recycle chamber |
| s | solids, slit |
| sp | stand pipe |
| v | void |

Greek letters

| | | |
|---|---|---|
| $\varepsilon$ | solid volume fraction | - |
| $\rho$ | density | $kg/m^3$ |

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APPENDIX

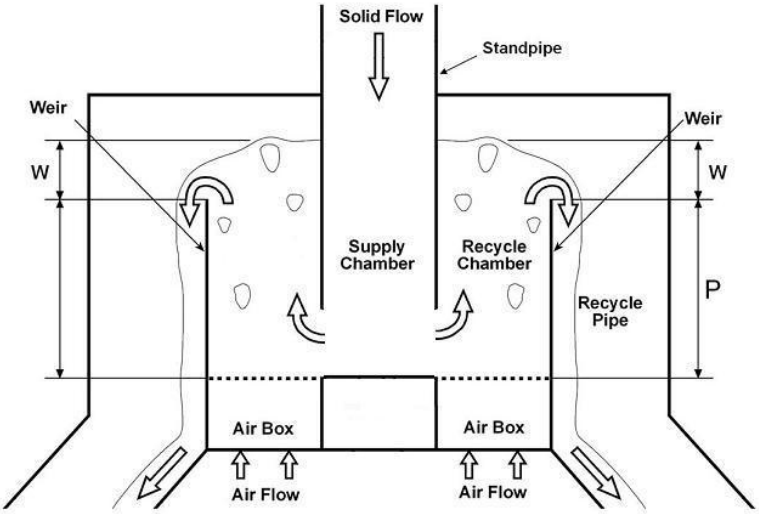


Figure 5. Schematics of the double exit loop-seal used at experiments.

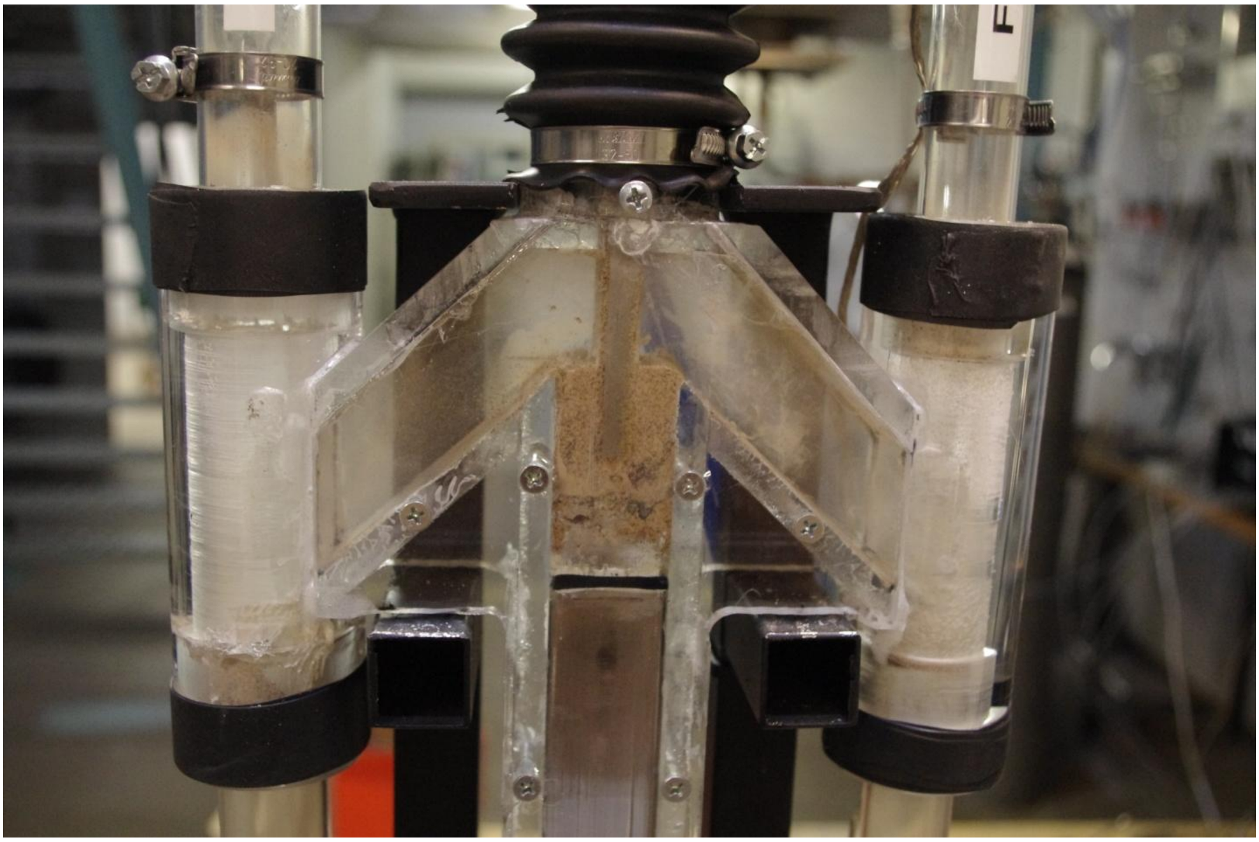

Figure 6. Double exit loop-seal; recycle chambers filled with sand

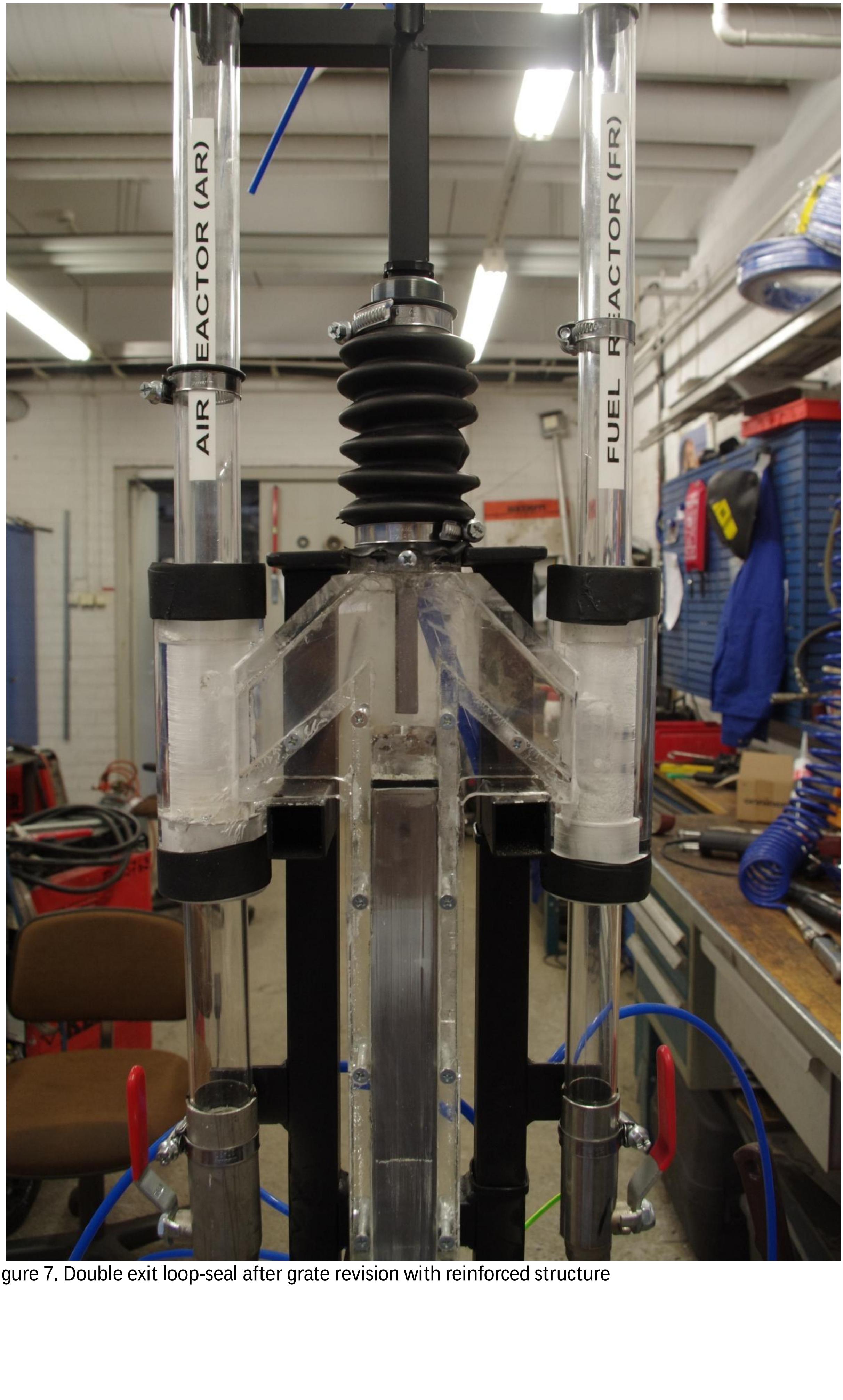

Figure 7. Double exit loop-seal after grate revision with reinforced structure

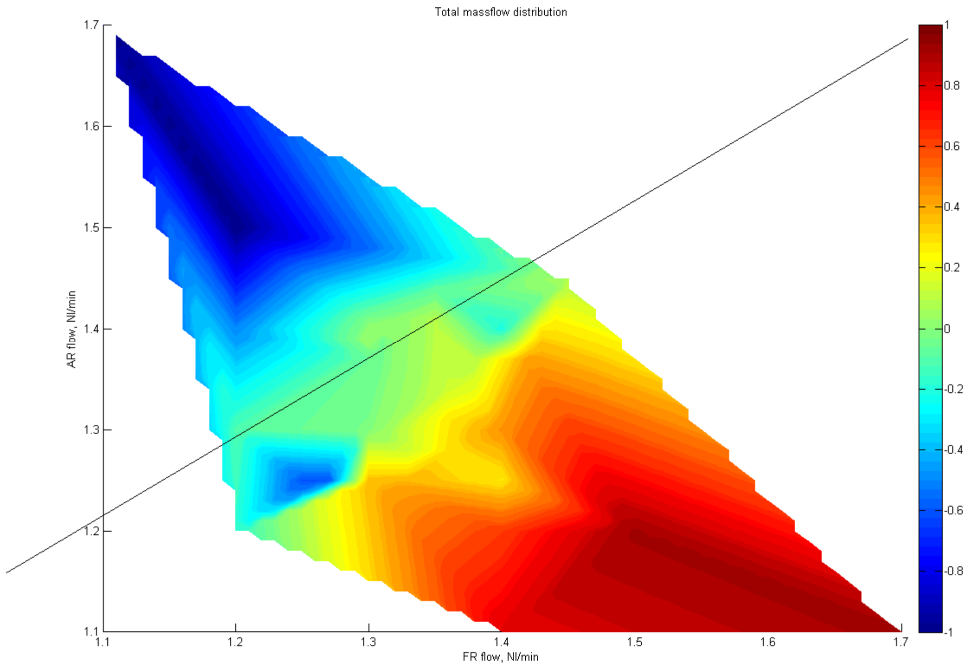


Figure 8. Fluidization velocity effect to mass flow distribution between recycle chambers, sand 180-250µm. 1 all solids to FR-side, -1 all solids to AR-side, 0 even distribution between recycle chambers. Line presents approximate 0-level where distribution is even. 0-level is shifted to AR-side because of leakage of fluidization air from FR-side.

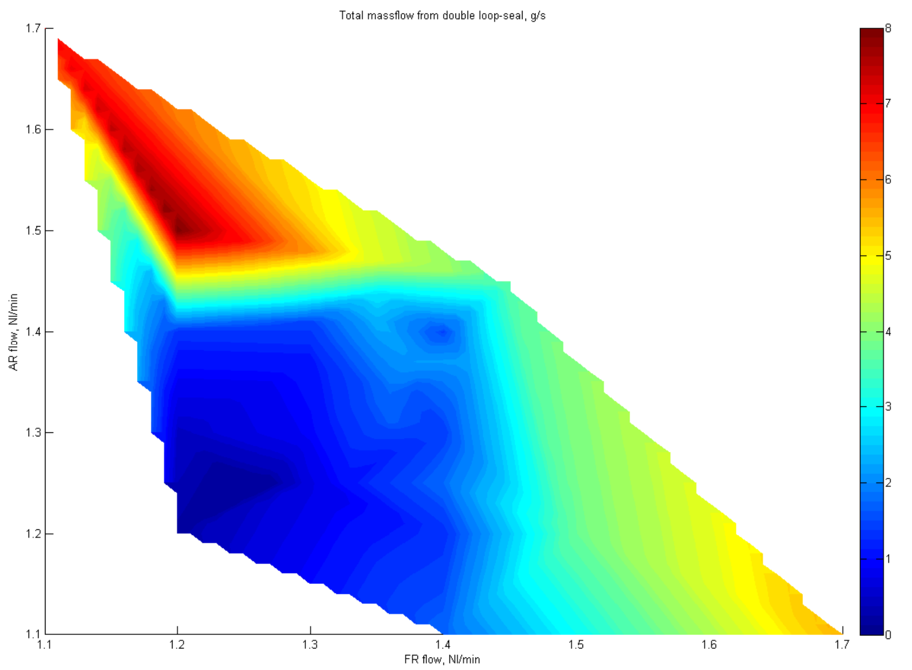


Figure 9. Fluidization velocity effect to mass flow over double loop-seal (g/s), sand 180-250µm. Blue area contains area where fluidization is stable and well controlled, below 1.4 Nl/min ≈ $1.45U/U_{mf}$.

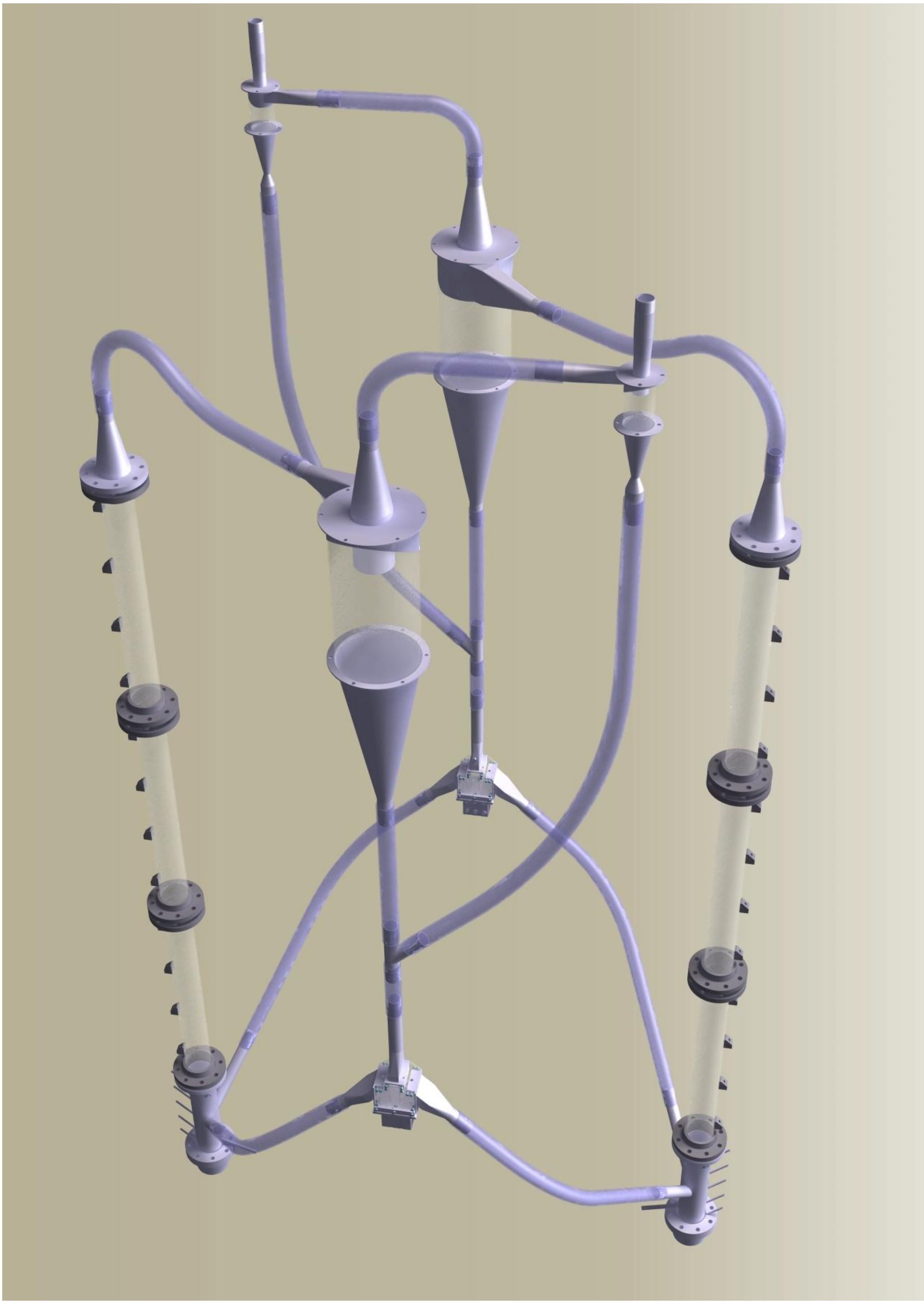

Figure 10. 3D overview of reactor system