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TURBULENCE STRUCTURES IN THE FLOW THROUGH EMERGENT VEGETATION

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ABSTRACT

A thorough understanding of the turbulence structures associated with the flow through plant canopies is of high interest for river and coastal restoration schemes or the creation of flood retention activities. In this paper, the flow through a matrix of emergent cylinders is simulated by Large Eddy Simulations (LES) according to the experimental configuration of Fairbanks and Diplas (1998). The code MGLET (Tremblay et al, 2000) is used to solve the filtered Navier Stokes equations on a staggered, non-uniform Cartesian grid. In order to represent solid objects in the flow, the immersed boundary method is employed. The computational domain is idealized with a box containing 4 emergent circular cylinders and periodic boundary conditions are applied in both streamwise and spanwise directions. The main objective of this work is to study the effect of emergent vegetation on the mean and instantaneous flow and the accompanied turbulence structures. The Reynolds number based on the channel depth h and the bulk velocity ub is approximately Reh ≈ 15000. Due to flow separation at the cylinder, vortices are shed and the formation of a von Karman type vortex street is visible downstream of each cylinder. In this paper the mean and instantaneous flow field is analyzed and further insight into the complex nature of flow through vegetation is provided based on Large Eddy Simulation.

Keywords: LES, cylinders, vegetation

1. INTRODUCTION

Aquatic and riparian plants obstruct the flow and significantly reduce the mean flow velocities relative to non-vegetated regions. The additional form drag exerted by plants influences strongly the mean and instantaneous velocity distributions, turbulence quantities and Reynolds stresses as well as transport processes and system morphology. Furthermore, the flow through vegetated channels is characterized by significant velocity gradients and strong secondary currents. Detailed knowledge about the small and large scale effects of vegetation on the flow has become central to river and coastal restoration schemes, the creation of flood retention space and coastal protection projects. A greater understanding of the fluid/plant interaction is needed and will improve our ability to accurately model flow and sediment transport through vegetation and to predict head losses, flow velocities and bed shear stresses at the field scale.

A large number of research activities on vegetation effects in the benthic and riparian environment have been devoted to laboratory flume experiments and many researchers (for example: Kouwen et al., 1969; Dunn et al., 1996; Nepf and Vivoni, 2000 to name only a few) have observed that the mean streamwise velocity profile within an emergent or submerged vegetated layer (irrespective of whether the vegetation is rigid or flexible) no longer follows the universal logarithmic law. The instantaneous flow field through vegetation is extremely complex and is characterized by organized flow structures whose origins and mechanisms are a consequence of flow-vegetation interaction. Up till now detailed laboratory studies on the instantaneous flow field are rare since measurements of time dependent 2D and/or 3D flow fields are difficult and expensive.

Computational Fluid Dynamics (CFD) models have been developed to solve the 3D steady or unsteady Reynolds-averaged-Navier-Stokes (RANS) equations, which are able to resolve local flow and turbulence features of the time-averaged turbulent flow field. Flow over or through vegetation can be predicted with steady RANS models by adding additional source terms to the RANS and turbulence transport equations to account for vegetative drag effects and are the most practical approaches offering reasonable accuracy of the time-averaged turbulent flow field. Such methods for multi-dimensional flow problems have been developed by Shimizu and Tsujimoto (1994), Neary (2000), Fischer-Antze et al. (2001) and Lopez and Garcia (2001) using two-equation turbulence closure models to simulate rigid and emergent vegetation in simple-section and compound-section channel arrangements. Modified k-ε or k-ω turbulence closure models were used, introducing drag-related sink terms into the turbulent transport equations. Laboratory experiments by Dunn et al. (1996), Tsujimoto and Kitamura (1998), or Pasche and Rouve (1985) were used to validate the models. Naot et al. (1996) and Choi and Kang (2001) used a higher order anisotropic turbulence closure, the Reynold's Stress model (RSM), to simulate the flow through rigid submerged vegetation elements.

However, RANS models can only resolve time-averaged flow features (Stoesser et al., 2004) but coherent structures play a dominant role in redistributing mass and momentum in the flow and are believed to be the driving mechanisms for sediment transport within the riparian zones. Recently, Large Eddy Simulation (LES) models have been developed to solve the unsteady, filtered 3D Navier-Stokes equations. LES is able to provide an almost complete description of the instantaneous unsteady 3D turbulent flow field, resolving large-scale unsteadiness and asymmetries (large eddies) resulting from flow instabilities. LES results of channel flow through vegetation were presented by Cui and Neary (2002, 2008), Stoesser et al. (2006) and Palau et al. (2007). Stoesser et al. (2006) and Palau et al. (2007) were the first to fully resolve each individual vegetation element and demonstrated that LES can elucidate the large-scale coherent structures described above, their important role in vegetative resistance, and their interaction and feedback with Reynolds stresses and lift forces that initiate sediment transport and bed form development.

In this paper we present Large-Eddy simulations of turbulent channel flow through a matrix of emergent cylinders. The flow around the individual cylinders is fully resolved by a high resolution grid and the cylinder-matrix can be regarded as an idealized stand of vegetation. The time-averaged velocity field is presented and we will provide evidence for the existence of large scale coherent structures being a result of the local flow-vegetation-interaction.

2. NUMERICAL FRAMEWORK

The LES code MGLET, originally developed at the Institute for Fluid Mechanics at the Technical University of Munich (Tremblay et al., 2000), is used to perform the Large Eddy Simulations. The code solves the filtered Navier-Stokes equations discretised with the finite-volume method and is based on a staggered Cartesian grid. Convective and diffusive fluxes are approximated with central differences of second order accuracy and time advancement is achieved by a second order, explicit Leapfrog scheme. The Poisson equation for coupling the pressure to the velocity field is solved iteratively with the SIP method of Stone (1968). The subgrid-scale stresses appearing in the filtered Navier-Stokes equations are computed using the dynamic approach of Germano et al. (1991). The no-slip boundary condition is applied on the surface of the cylinders and the immersed boundary method (e.g. Verzicco, 2000) is employed. This method is a combination of applying body forces in order to block the cells that are fully inside the cylinder geometry with a Lagrangian interpolation scheme of third order accuracy, which is used for the cells that are intersected by the cylinder surfaces to maintain the no-slip condition.

3. SETUP AND BOUNDARY CONDITIONS

The geometry and the Re number, of approximately Re=15000, based on the channel depth and bulk velocity, are chosen to be in a similar range than previous experimental laboratory investigations (e.g. Tsujimoto et al., 1992). To simulate the flow through a stand of emergent vegetation, a number of rigid cylinders are placed in a staggered arrangement on a smooth wall. The present simulation is a part of a series of LESs investigating the effect of cylinder spacing on the flow and turbulence (Figure 1). In here the spacing between cylinders is 10D in streamwise direction. The cylinder Reynolds number based on the bulk velocity and the cylinder diameter D, ReD, is approximately 1400. The computational flow domain spans 20D in streamwise, 10D in spanwise and 11.2D (corresponding to the water depth) in vertical direction, respectively. The grid consists of 1348 x 676 x 124 grid points in streamwise, spanwise and vertical directions, respectively, which sums to a total of approximately 113 Million grid points. Appropriate near wall grid resolution can be estimated with help of dimensionless grid spacings based on the locally prevailing shear velocity $u*$ and the kinematic viscosity υ. The grid spacings in terms of wall units in streamwise and spanwise direction are $\Delta x+ = \Delta y+ \approx 20\text{-}30$ in the areas between the cylinders and $\Delta x+ = \Delta y+ \approx 1$ near the cylinder surface (where the local $u*$ was obtained at about mid-cylinder height). In the vertical direction the grid is stretched likewise and values of $\Delta z+ \approx 40$ near the water surface and $\Delta z+ \approx 1$ near the channel bed are obtained. Periodic boundary conditions are applied in the streamwise and spanwise directions. At the channel bed the no-slip condition is used and the free surface was set as a frictionless rigid lid mathematically treated as a plane of symmetry.

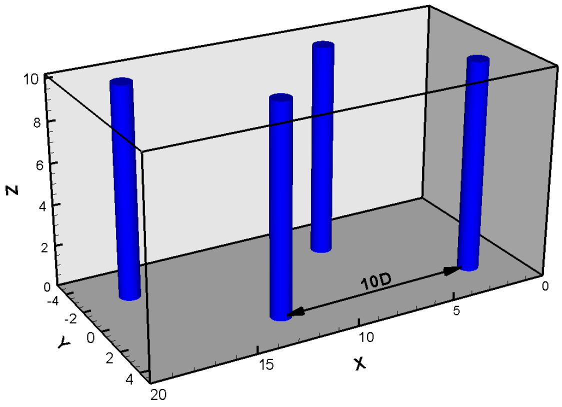

Figure 1: Geometrical arrangement of the vegetational elements for the three vegetation densities investigated

4. RESULTS

In Figure 2, the distribution of time-averaged streamwise velocities in two selected longitudinal planes (position is indicated in the sketch in the upper left corner) is presented. The left part of Figure 2 presents a slice through the cylinder axis. Over the entire flow depth the velocities are almost constant and are considerably higher in planes where no cylinders are present. In the rear of the cylinders recirculation over the entire cylinder height occurs (see also Figure 4). Behind the cylinder and near the bed the recirculation region is smaller than above a feature also observed in submerged vegetation flow (Stoesser et al., 2006). The reason for this will be discussed later. The streamlines of the flow in the cylinder axis indicate another interesting feature: At the edge of the recirculation region fluid is transported upwards until about 2/3 of the water depth.

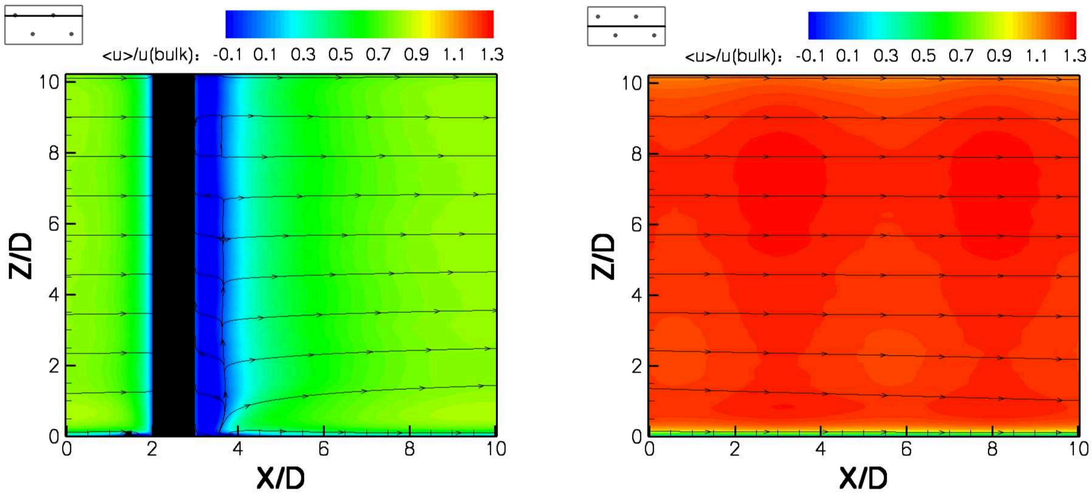

Figure 2: Distribution of the time-averaged streamwise velocity component in two selected longitudinal planes: The left side presents a slice through the cylinder axis and the right side presents a slice halfway between cylinders (the position is indicated in the sketch in the upper left corner).

Figure 3 presents the distribution of time-averaged wall-normal velocities in two selected longitudinal planes (position is indicated in the sketch in the upper left corner). Whilst between the cylinders there is no vertical movement on average (Figure 3, right), there is considerable movement in the vicinity of the cylinders. In front of the cylinder near the bed there is downward movement an indication of the presence of a horseshoe vortex. Near the bed behind the cylinder there is strong upward movement near the bed prevailing until 2/3 of the water depth (as indicated by the streamlines in Figure 2). Near the water surface an opposite behaviour can be seen. In front of the cylinder there is a weak upflow, whereas behind the cylinder fluid is washed downwards. This movement reflects the watersurface elevations (not captured here due to the use of the rigid lid) with a stagnation point and an impound in front of the cylinder and a depression of the water surface behind the cylinder.

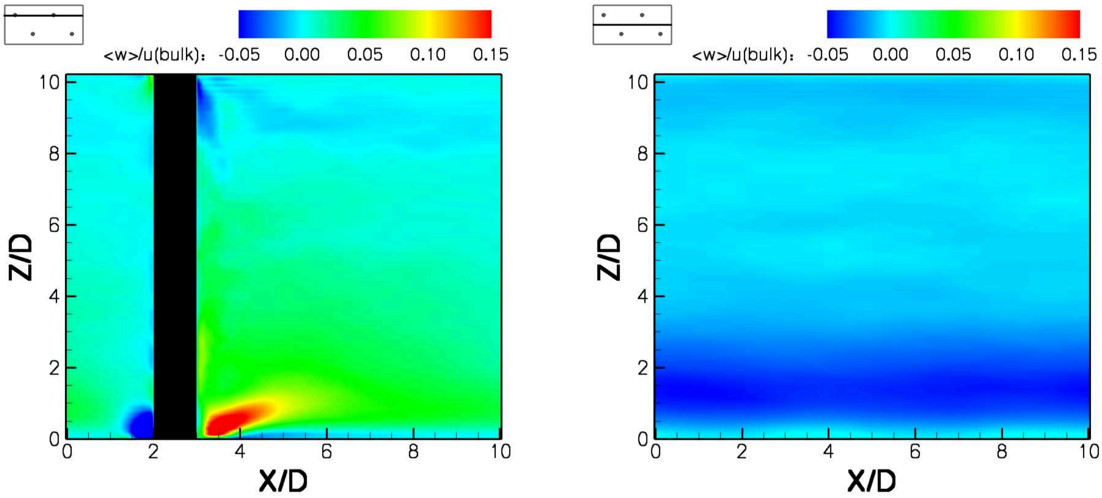

Figure 3: Distribution of the time-averaged wall-normal velocity in the two selected longitudinal planes (the position is indicated in the sketch in the upper left corner).

Figure 4 presents time-averaged streamwise velocities together with streamlines in selected horizontal planes at two different heights (i.e. Z/D=0.5 and Z/D=5). The distribution of velocity clearly confirms that the wake from the upstream cylinder prevails until the downstream cylinder irrespective of plane height. There is an apparent region of high velocity that forms between the cylinders, which is in contrast to the flow through submerged vegetation where the flow in the canopy layer is almost uniform (Stoesser et al., 2006). The wake flow behind the cylinder and the accelerated flow between cylinders causes rather strong lateral velocity gradients. The recirculation region behind the cylinders is characterized by a pair of recirculation bubbles, the size of which does not vary at all over the depth.

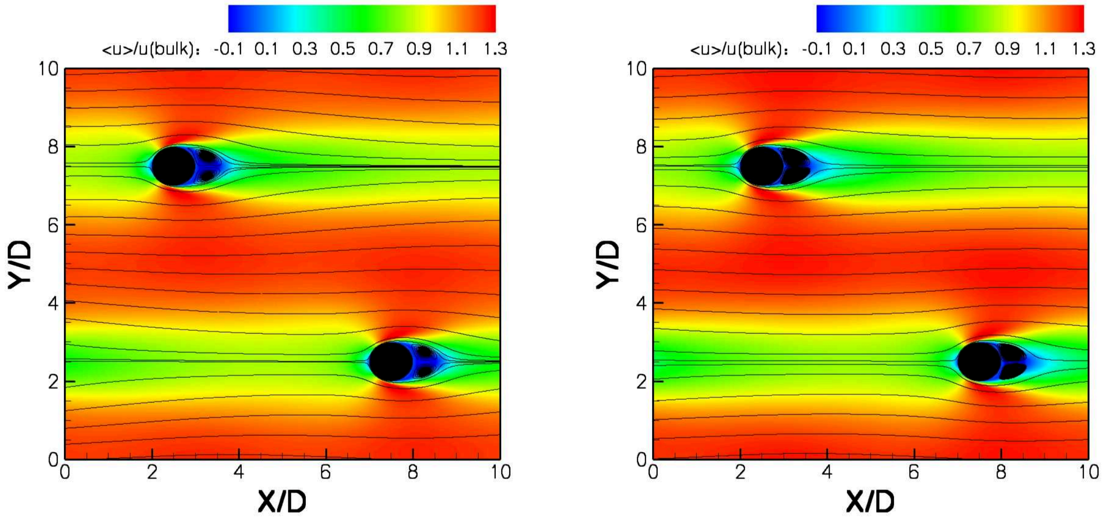

Figure 4: Distribution of time-averaged streamwise velocities together with streamlines in selected horizontal planes at two heights. Left: Z=0.5D; Right:Z=5D

In Figure 5 time-averaged wall-normal velocities together in selected horizontal planes at two different heights (i.e. Z/D=0.5 and Z/D=5) are shown. Near the bed (i.e. at Z/D=0.5) the region of strong upflow is apparent with vertical velocities greater than 15% of the bulk velocity. The wake region near the channel bed is characterized by general upward movement, whereas in the region between the cylinders there is downwards-movement of fluid. At about half channel depth (Z/D=5) above discussed movements are still present however much weaker.

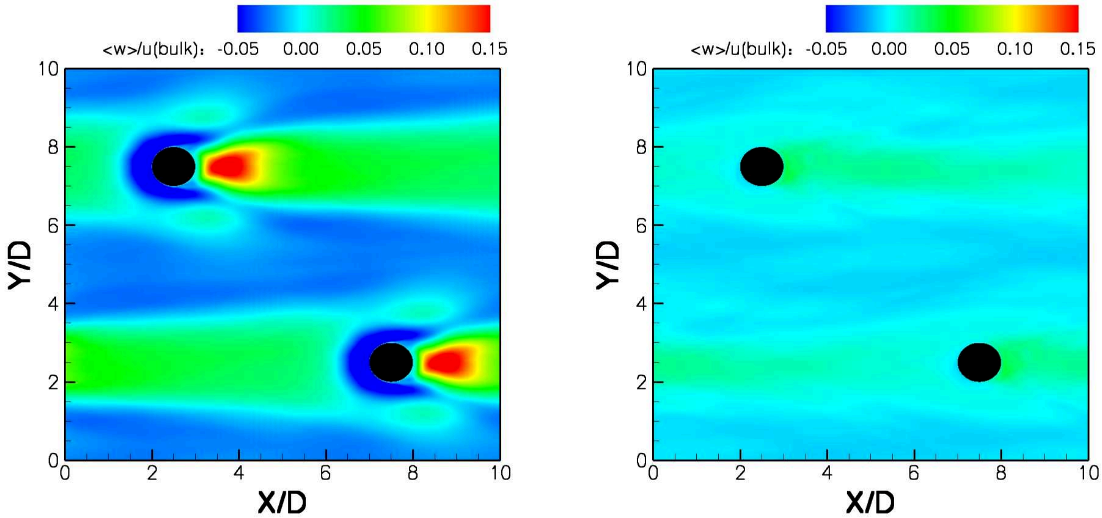

Figure 5: Distribution of time-averaged wall-normal velocities together with streamlines in selected horizontal planes at two heights. Left: Z=0.5D; Right:Z=5D

Figure 6 presents streamwise velocity contours together with streamlines of the secondary flow in two selected cross-sections (position is indicated in the sketch in the upper left corner). Behind the cylinders a near bed counter-rotating vortex pair is formed which transports high-momentum fluid near the bed from the area between the cylinders into the wake, where it is lifted upwards. This vortex pair weakens further downstream before the flow encounters the next cylinder.

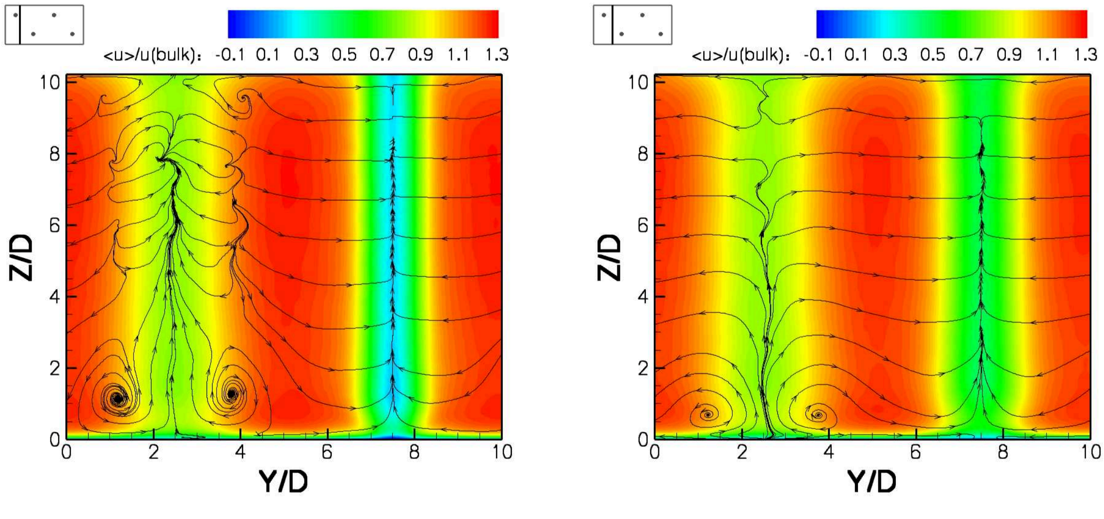

Figure 6: Distribution of time-averaged streamwise velocities together with streamlines of the secondary flow in selected cross-sections at two heights.

Figure 7 presents isosurfaces of the pressure fluctuation p' at an instant in time. The fluid-vegetation interaction is clearly visible in the form of vortex shedding. As in the case infinitely long cylinders a von Karman vortex street develops in the rear of the cylinders, however the vortices are broken up when the flow encounters the downstream cylinder. Further work is underway to quantify the flow structures.

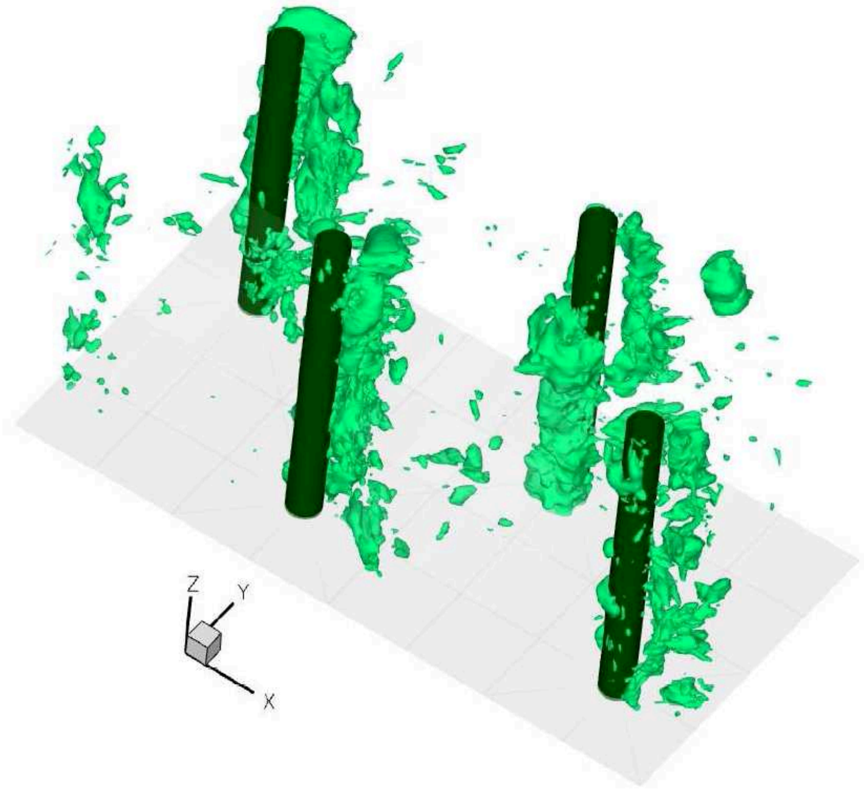

Figure 7: Von Karman-type vortex shedding behind each cylinder visualized by isosurfaces of the pressure fluctuation p'.

5. CONCLUSIONS

In this paper we have presented the results of a Large Eddy Simulation of open channel flow through a matrix of cylinders. The time averaged velocities were discussed and it was found that the flow exhibits fairly large lateral gradients, with lower flow velocities in the wake of the cylinders and higher velocities between the cylinders. An area of strong upflow behind the cylinder was identified that prevails until 2/3 of the water depth. A counter-rotating vortex pair forms in the lee of the cylinder which transports high-momentum fluid from the region between the cylinders into the wake behind the cylinders. Von Karman type vortex shedding was visualized and it was observed that previously shed vortices break up when interacting with the downstream cylinder.

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