EXPERIMENTAL STUDY OF THE VALVE-BEND INTERACTION IN AN AIRCRAFT ECS SYSTEM

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ABSTRACT

Aircraft ventilation systems are crucial in maintaining a good air quality during flight. The aim is delivering both fresh and recirculated air to the cabin and cockpit of the plane. Typical components in a ventilation system are heat units, fans, filters and valves. The latter are usually electronically controlled butterfly valves which regulate the flow rate in the system. These devices have a significant impact and the flow field after the valve affects the working of every component downstream in the network. In this paper the flow fields before and after a butterfly valve are studied using hotwire and stereoscopic PIV measurements. Two configurations are tested: one configuration consisting of a single valve (single valve configuration) and one configuration consisting of a valve closely coupled after a 90° bend (valve + bend configuration). The velocity is measured in both a horizontal and vertical measurement plane to study the spatial structure of the flow. Both PIV and hotwire measurements show good agreement. In both configurations, the flow field is highly 3 dimensional. The bend has a large impact on the flow field after the valve. The central wake is significantly increased in length and the turbulence intensities increase from around 50% for the single valve configuration to more than 75% for the valve + bend configuration. This significant impact shows the importance of the interaction of different components in a ventilation network on the general characteristics such as pressure drop or noise propagation.

NOMENCLATURE

U	[m/s]	Axial velocity component
TI	[%]	Turbulence intensity
D	[mm]	Diameter
x	[m]	Cartesian axis direction, direction along pipe
y	[m]	Cartesian axis direction, horizontal direction
z	[m]	Cartesian axis direction, vertical direction

Subscripts

rms	Root mean square
x	Axial
0	Time averaged value

INTRODUCTION

Most studies related to the reduction of aircraft noise focus on externally propagated noise such as for instance noise during take-off and landing. However in aircrafts, the internal cooling and ventilation system (called Environmental Control System or ECS) also generates a significant amount of internal noise. This noise propagates through the piping system and a strong coupling with the internal flow may result in unwanted noise levels in the cockpit and cabin. The physical mechanisms responsible for this propagation are much more complex than for exterior noise propagation since the separation between flow and acoustic fields becomes much more arbitrary and more difficult to be described with classical modelling approaches. Therefore, most studies on ECS components just focus on one component in the system [1-5]. However, many interactions take place between different components in the network such as the blower units, control valves and bends. These interactions will influence the characteristics such as noise propagation and total pressure drop and need to be known to model accurately.

In this study, a first step is made in describing the interaction between two components in an ECS system, namely a 90° bend and an electronically controlled butterfly valve. The influence of the bend upstream of the valve on the flow field after the valve is studied. Particle Image Velocimetry (PIV) and Hot Wire Anemometry (HWA) are used to measure the flow field and the turbulence statistics. The result of this study helps in understanding the component interaction in an ECS system, which can serve as a base for understanding the flow/noise interaction.

EXPERIMENTAL SETUP AND METHODS

The ECS valve, measured in this study, is a butterfly valve which is installed in a piping network with inner diameter D=84,9mm. The valve opening is adjustable between 0° (closed) and 90° (open) and typical operating positions are situated between 10° and 30°. Under normal operating conditions in an aircraft ECS system, the inlet valve temperature is situated between 80°C and 110°C and a typical relative inlet pressure is between 1,25bar and 3,00bar, corresponding to typical mass flow rates of 0-1350g/s. In this paper two pipe networks are measured. One configuration is a single valve (further on called the valve configuration) and the other is the same valve with a 90° bend placed upstream (further on called valve + bend configuration). The curvature of the bend equals the internal diameter *D* of the casing. The length *L* between the bend and the valve is 1.5D in order to enable measurements in between the bend and valve. A schematic top view of the valve + bend configuration is shown in Figure 1. The valve and valve + bend configurations are both embedded in a network with 17D upstream tubing and 8D downstream tubing.

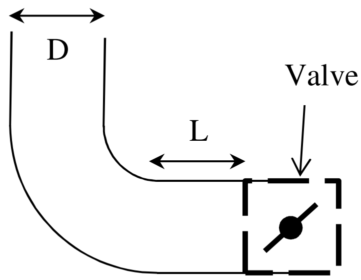

Figure 1 Schematic top view of the valve + bend configuration.

A uniform flow speed is generated using a parallel Roots' blower configuration. Due to the working principle of the blower, the maximum relative pressure at the outlet is limited to 1,1bar with a maximum volumetric flow rate equal to approximately 13m^3/min. Both compressors have three lobes to minimize both noise generation and small time-pulsations of the flow. On one of the Roots' blowers, a frequency regulator with PID controller is installed. The latter is used to couple the Roots' blower with a pressure sensor, located upstream of both configurations, in order to ensure identical inlet conditions between the different measurement campaigns and test configurations. Furthermore, a Schiltknecht MiniAir20 Turbine flow meter is installed at the downstream end of the test rig to measure the downstream centerline velocity and temperature. During all measurements, the outgoing flow velocity at the centerline is kept constant at 32 m/s. Also a heat exchanger coupled after the blower ensures a constant temperature of 31°C in all experiments.

The flow field is independently measured by both Particle Image Velocimetry (PIV) and Hot Wire Anemometry (HWA). In such way, the advantage of both methods can be combined and both can be used to validate each other. The cartesian measurement coordinate system has its x-axis along the pipe symmetry line, the y-axis along the horizontal direction and the z-axis along the vertical direction. For the PIV measurements, a laser sheet with a thickness of 0.5 mm is generated using a Dual Cavity Nd:YLF Pegasus- PIV laser with a wavelength of 527 nm and a pulse energy of 10 mJ @ 1,000 Hz. Two positions of the laser sheet are taken: one in the xy-plane (horizontal plane) and one in the xz-plane (vertical plane). Due to the finite thickness of the laser sheet in combination with the, relatively,

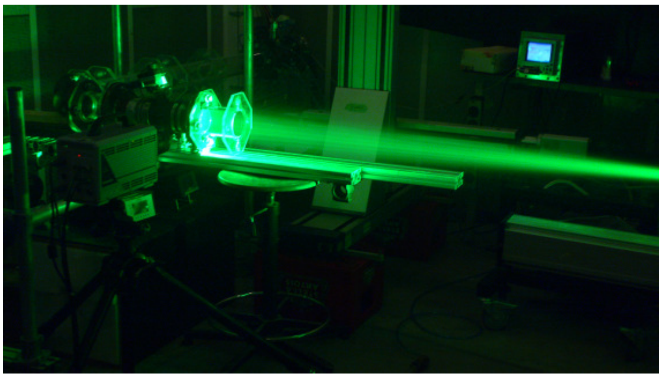

Figure 2 Direction of the laser sheet with respect to the piping network

small radius of the ducts, diffraction effects made it impossible to yield accurate results when inserting the laser shield through the tube wall along the y-axis. Therefore the laser is aligned with the symmetry axis (x-axis) of the pipe and enters the setup from the outlet, as shown in Figure 2. Hence, PIV upstream of the valve is not feasible. The images are recorded using a 'HighSpeedStar 5' CMOS camera with a resolution of 1,024 x 1,024 pixels. The camera is positioned, as shown in Figure 2, perpendicular to the laser sheet plane, in close vicinity of the plexi-glass measurement section, for both the horizontal and vertical laser sheet alignment. The calculation of the velocity vectors is done using the DaVis 7.2 software of LaVision GmbH. Due to refraction issues near the wall, the measurement plane is limited to, approximately, [-30mm, 30mm] in the flow x direction and [-35mm, 35mm] in the horizontal y and vertical z direction with a spatial resolution of 1.6579 mm between two adjacent vectors. In this framework, the HWA measurements provide more detailed information about the flow field in the vicinity of the wall as well as the 'high'-frequency content of the turbulent velocity field.

The hot wire measurements are carried out to obtain high frequency information on the aerodynamic field including data in close vicinity of the walls. The measurements are carried out on both a horizontal (*y*) and vertical (*z)* line. The raw data pre- and post-processing is carried out using Dantec Streamware Pro V10. For all hot-wire measurement an L-shaped probe (type: Dantec 55P14) is used. The probes are calibrated using a Dantec 90H02 Flow Unit. The calibration is carried out for a logarithmic distribution of 35 velocities ranging from 2m/s up to 70 m/s with a continuous monitoring of the flow temperature. In order to take into account the varying temperature of the measured flow, a temperature correction is added during acquisition to take into account the variation in the voltage of the hot-wire probe with varying temperature. For the unsteady flow measurements the data acquisition is carried out using a Dantec Streamline acquisition system and the voltages of the hot-wire sensors are sent to the processing software using a multifunctional I/O with correlated digital I/O for USB (NI USB-6229).

RESULTS AND DISCUSSION

Upstream HWA measurements

Figure 3 shows the axial velocity profiles upstream of the valve, obtained with HWA, for both the horizontal and vertical

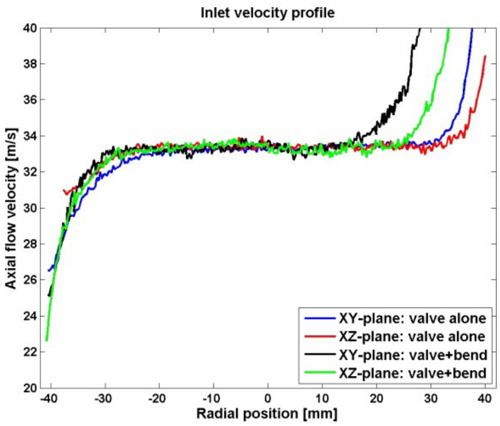

Figure 3 Hot wire measurements of the inlet axial velocity profile 5D upstream of the valve and valve + bend configuration.

axis. Due to refraction/reflection PIV can't be used in this region of the flow. A sudden increase in velocity is observed at large (positive) values of the radial position. This is caused by leakage effects of the insertion of the hot-wire probe. These holes are sealed as much as possible. However due to the relatively high pressures in the upstream section of the valve and the traversing of the probe, leakage is unavoidable. For the valve + bend configuration, this leakage is higher due to the increased pressure in the upstream tubing. As such the HWA measurements near the insertion can be discarded. Figure 3 shows that the inlet velocity profiles are axisymmetric and similar for both configurations. The turbulent intensity profiles (not shown here) indicate values of around 12% in the boundary layer and 6% near the pipe center. These medium turbulence levels are caused by the fact that inside the duct system no turbulence decreasing measures, such as e.g. expansion chambers, turbulent screens or honeycomb structures, are present. This to ensure the setup is representative for real ECS systems.

HWA measurements between bend and valve

The axial velocity profile along a horizontal measurement line at the outlet of the bend is shown in Figure 4. The profile is asymmetric with higher velocities near the outer radius of the bend. Note that due to leakage of the probe, the velocities below y = -30 mm can be discarded. The asymmetry in the flow is only in the symmetry plane of the bend as the profiles along a vertical symmetry plane (not shown here) are symmetric. The profile shown in Figure 4 is typical for a 90° bend as the centrifugal forces move fluid towards the outer wall, creating a zone of low velocity near the inner radius. As a result, due to the imbalance between the centrifugal force and radial pressure gradient, secondary flow structures, called Dean vortices, are created [6-8]. These vortices move fluid from the inner side of the pipe towards the outer side and as such significantly change the wake of the valve as shown later.

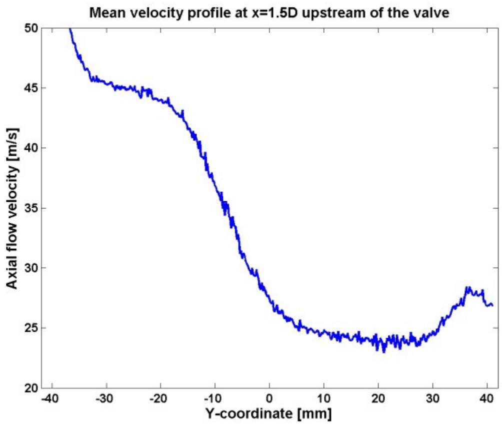

Figure 4 Hot wire measurements of the axial velocity 1.5D upstream of the valve + bend configuration. The horizontal measurement line is located at the outlet of the bend.

Downstream HWA measurements

The mean axial velocity profiles at a distance of 1.5D downstream of the valve are shown in Figures 5 and 6 for both the valve alone and the valve + bend configuration. As the pressure after the valve is atmospheric, no leakage is present near the probes' insertion. The velocity profiles are asymmetric and wake-like in both horizontal and vertical directions. The asymmetry is induced by the asymmetric wake behind the valve

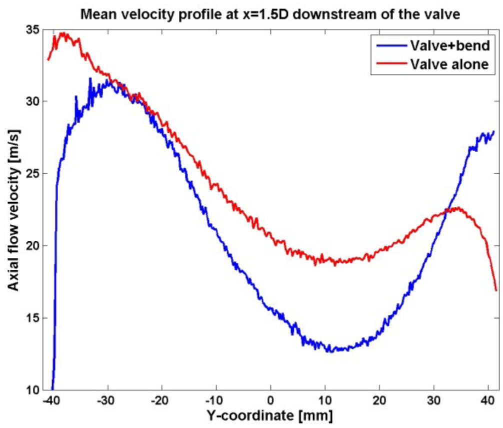

Figure 5 Axial velocity profile along the central horizontal axis at x/D=1.5 after the valve.

disc [9]. As the valve is opened (Figure 1), more fluid is flowing through the upper section, creating an asymmetric wake. If a bend is placed upstream of the valve, this uneven distribution of flow along the valve is compensated by the extra fluid near the outer radius of the valve (Figure 4). As such, the profiles tend to be more symmetric. Comparing the minimal axial velocity near the center between the valve alone and the valve + bend configuration shows that the value for the configuration with valve is significantly lower. As such, the length of the wake behind the valve increases if a bend is placed upstream. The turbulence intensity levels of the axial velocity component, defined as

$$TI\left(\%\right)=\frac{\left(u_x^{'}\right)_{rms}}{U_{x0}}, \qquad (1)$$

are shown in Figures 7 and 8. The maximum values are situated near the central pipe axis as is typical for wake flows behind a disc [10]. The intensities are in the order of 55% for the valve alone and 75% for the valve + bend configuration. Figures 5 to 8 show the significant impact of the bend on the valve 's wake and therefore the characteristic for a single valve, like for instance the flow coefficient or pressure drop, should not be extrapolated to a valve + bend configuration.

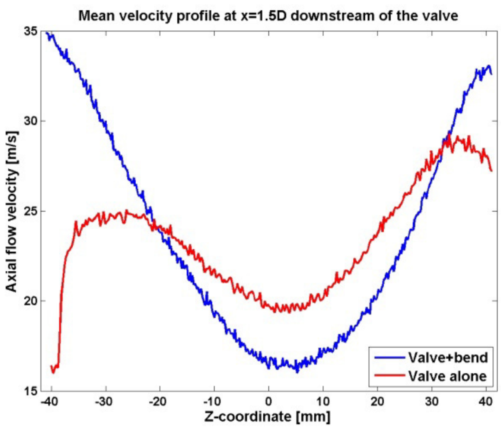

Figure 6 Axial velocity profile along the central vertical axis at x/D=1.5

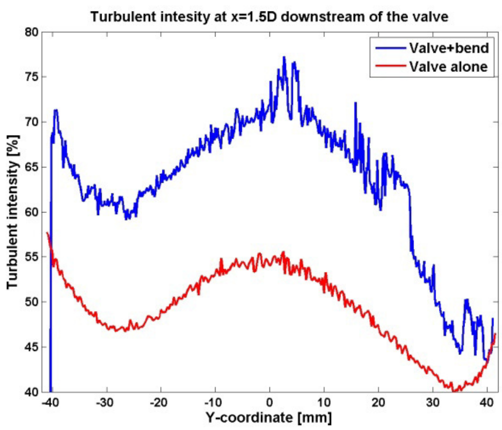

Figure 7 Turbulence intensities profile along the central horizontal axis at x/D=1.5 after the valve.

Downstream PIV measurements

In order to identify the global flow structure behind the valve, PIV measurements are taken downstream of the valve. The measurements were validated with the HWA data and comparison showed good agreement within measurement accuracy. The results for the valve alone configuration are shown in Figure 9. The other configurations (not shown here) showed very similar results.

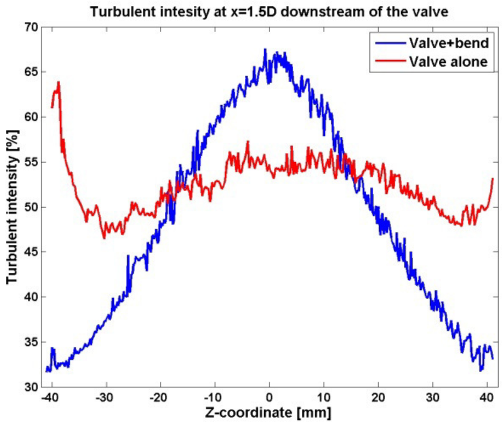

Figure 8 Turbulence intensities along the central vertical axis at x/D=1.5 after the valve.

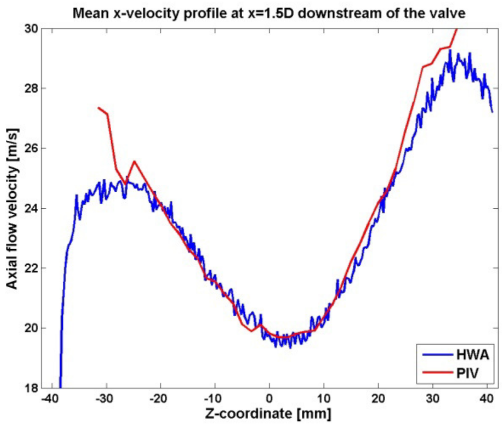

Figure 9 Comparison of PIV and HWA measurements at x/D=1.5 after the valve (valve alone configuration).

The time averaged flow fields of the axial velocity are shown in Figures 10 and 11. Note that the figures have different scaling to enlighten more details of both flow fields. For the valve alone configuration, the velocity field is wake-like. There is asymmetry with larger velocities near the upper side of the pipe. Also, the axial velocity near the centreline is positive, meaning the measurements are taken downstream of the stagnation point behind the disc. Comparison with the hotwire measurements in Figure 6 confirms these conclusions. The flow field of the valve + bend configuration is quite different. The velocity field is still wake-like and asymmetric. However, in this configuration, the maximum axial velocities are situated near the bottom of the pipe, as is also confirmed by the HWA measurements in Figure 6. Also, the axial velocities near the centreline are also smaller meaning the bend increases the length of the wake behind the valve.

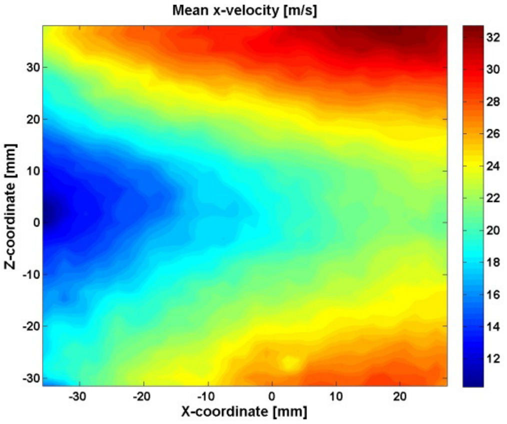

Figure 10 Time averaged PIV measurements for the valve alone configuration. Velocity vectors in m/s.

The instantaneous PIV velocity fields of the valve alone and valve + bend configuration are shown in Figures 12 and 13. Both flow fields are very turbulent with small eddies shed from the disc edges [10]. Due to the high turbulent flow field after the valve, measuring second order statistics with PIV would require too much samples to be practically feasible. However, since the maximum velocities are almost two times higher than the maximal mean velocity, the PIV measurements confirm the highly turbulent nature of the flow as also confirmed by Figures 7 and 8.

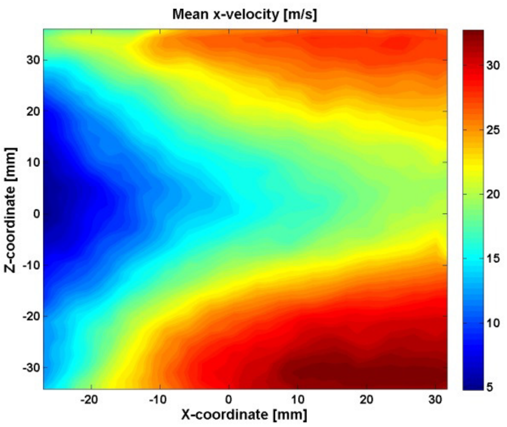

Figure 11 Time averaged PIV measurements for the valve + bend configuration. Velocity vectors in m/s.

CONCLUSION

In this paper the interaction between a bend and a butterfly valve is studied using HWA and PIV. Two configurations are tested: one configuration consisting of a single valve (single valve configuration) and one configuration consisting of a valve closely coupled after a 90° bend (valve + bend configuration). Velocity measurements are taken at locations before, in between the bend and valve and after the valve. Both PIV and HWA measurements show good agreement. In both configurations, despite the axisymmetric inlet conditions, the flow field becomes highly 3 dimensional and asymmetric. The bend has a large impact on the flow field after the valve. The central wake is increased in length and the turbulence intensities increase from around 50% behind the valve to more than 75% if a bend is placed upstream. This significant impact shows the importance of taking into account the interaction of different components in a HVAC network on the general characteristics such as pressure drop or noise propagation.

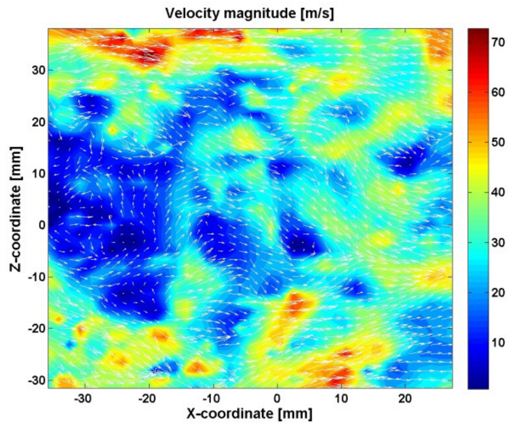

Figure 12 Instantaneous PIV measurements for the valve alone configuration. Velocity vectors in m/s.

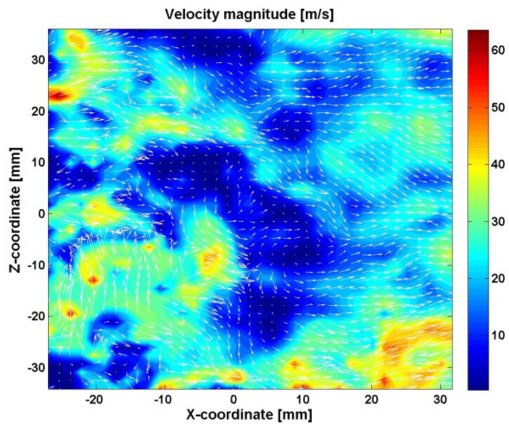

Figure 13 Instantaneous PIV measurements of the valve + bend configuration. Velocity vectors in m/s.

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REFERENCES

[1] Modi PP., and Jayanti S., Pressure losses and flow maldistribution in ducts with sharp bends, *Chemical Engineering Research and Design*, Vol. 82(A3), 2004, pp. 321-331

[2] Manglik RM., and Bergles AE., Heat transfer and pressure drop correlations for rectangular offset strip fin compact heat exchanger, *Experimental Thermal and Fluid Science*, Vol. 10, 1995, pp. 171-181

[3] Carolus T., Schneider M., and Reese H., Axial flow fan broad-band noise and prediction, *Journal of Sound and Vibration*, Vol. 300, 2007

[4] Sengissen A., Caruelle B., Souchotte P., Jondeau E., and Poinsot T., LES of noise induced by flow through a double diaphragm system, *Proceedings of the 15th AIAA/CEAS Aeroacoustics Conference,* AIAA Paper 2009-3357, Miami, May 2009

[5] Hekmati A., Ricot D., and Druault P., Aeroacoustic analysis of the automotive ventilation outlets using Extended Proper Orthogonal Decomposition, *Proceedings of the 15th AIAA/CEAS Aeroacoustics Conference,* AIAA Paper 2009-3357, Miami, May 2009

[6] Hellström LHO., Zlatinov MB., Cao G. and Smits AJ., Turbulent pipe flow downstream of a 90° bend, *Journal of Fluid Mechanics*, Vol. 735, R7, 2013, doi:10.1017/jfm.2013.534

[7] Dean WR, The streamline motion of fluid in a curved pipe, *Phil. Mag.*, Vol. 30, 1928, pp. 673-693

[8] Sakakibara J., and Machida N., Measurement of turbulent flow upstream and downstream of a circular pipe bend, *Physic of Fluids*, Vol. 24, 2012, 041702

[9] Huang C., and Kim RH., Three-Dimensional Analysis of Partially Open Butterfly Valve Flows, *Journal of Fluids Engineering*, Vol. 118(3), 1996

[10] Rind E., and Castro I.P., On the effects of free-stream turbulence on axisymmetric disc wakes, *Experiments in Fluids*, Vol. 53, 2012, pp. 301-318