COMPUTATIONAL FLOW MODEL OF

WESTFALL'S LEADING TAB FLOW CONDITIONER

AGM-09-R-08 Rev. B

By

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WESTFALL MANUFACTURING COMPANY

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INTRODUCTION

Alden Research Laboratory Inc. (Alden) was contracted by Westfall Manufacturing Inc. (Westfall) to aid in the development of a novel leading tab flow conditioner.

The objective of a flow conditioner is to reduce flow meter measurement error by: eliminating swirl, quickly impose a fully-developed velocity profile within the pipe, and minimize turbulence regardless of the flow conditions upstream. A successful flow conditioner will accomplish this with minimal pressure loss, and with the shortest pipe length possible.

The leading tab concept, when coupled with anti-swirl plates, has been proven to be quite effective at reducing swirl and improving the flow distribution at short distances downstream of the conditioner. Turbulence levels are also maintained at fairly low levels, which helps improve measurement accuracy. The principle by which the conditioner operates is that the primary tabs create vortices that mix the flow by turning it "inside-out", and then quickly dissipate at the pipe wall. The secondary tabs then leave a fully developed, non-swirling flow in their wake.

COMPUTATIONAL MODEL DESCRIPTION

The model geometry was developed using the commercially available three-dimensional CAD and mesh generation software, GAMBIT V2.4.6. The computational domain generated for the model consisted of approximately 2 million hexahedral and tetrahedral cells.

Numerical simulations were performed using the CFD software package FLUENT V6.3.26, a state-of-the-art, finite volume-based fluid flow simulation package including program modules for boundary condition specification, problem setup, and solution phases of a flow analysis. Advanced turbulence modeling techniques, improved solution convergence rates and special techniques for simulating species transport makes FLUENT particularly well suited for this study.

Alden used FLUENT to calculate the three-dimensional, incompressible, turbulent flow through the pipe and around the flow conditioner. A stochastic, anisotropic, two-equation k-ε model was used to simulate the turbulence. The anisotropic model was required to properly resolve the secondary flows that developed as a result of changes in geometry. Detailed descriptions of the physical models employed in each of the Fluent modules are available from Fluent, Inc., the developer of Fluent V6.3.26.

MODEL BOUNDARY CONDITIONS

The tests were conducted in 6" sch. 40 steel pipe, and the test section consisted of two 90° bends in perpendicular planes separated by 2 pipe diameters. This configuration provides both non-uniform velocity profiles and swirling flow. As noted by the ASME *Measurement of Fluid Flow in Pipes Using Orifice, Nozzle and Venturi* guidelines: "This is not a good upstream installation; a flow conditioner should be used where possible".

The upstream end of the flow conditioner was placed 4 pipe diameters downstream from the second bend, and is used as the datum for comparison. It has been determined through previous testing that the flow conditioner performs similarly at different flow rates, provided the flow is turbulent, so only one air flow rate was tested: 1000-cfm at ambient pressure and temperature. A uniform velocity inlet was imposed at the model inlet, which was placed 10 pipe diameters upstream of the first bend. A uniform static pressure boundary condition was imposed at the model outlet, which was placed 20 pipe diameters downstream of the mixing device's leading edge so that the impact of the flow conditioner could be documented as a function of downstream distance. On all surfaces, no-slip impermeable adiabatic wall boundary conditions were applied with roughness heights set to 0.00015-ft as appropriate for steel pipe.
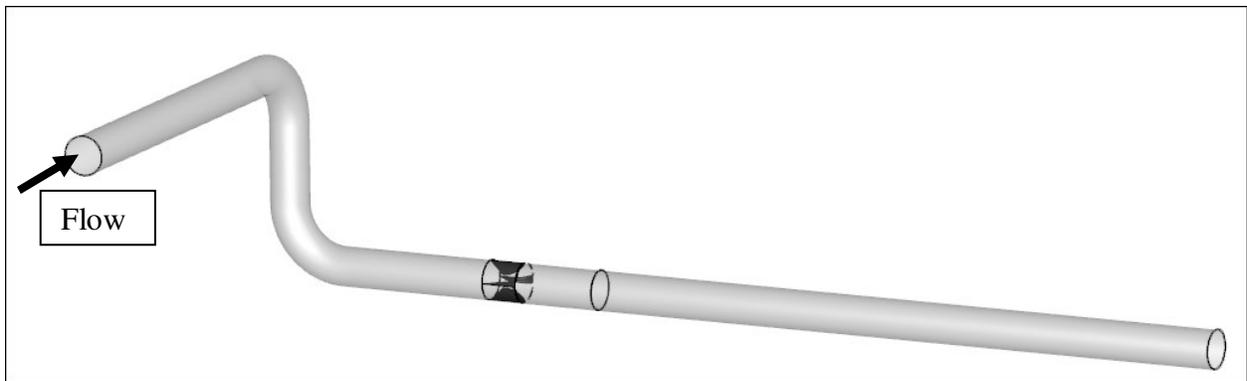
Air flow in a 6-in Sch40. steel pipe, after two out-of-plane 90° bends.
The flow conditioner is installed 4D downstream of the second bend.

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A baseline case was evaluated at the tested flow rate without a flow conditioner for comparison of pressure loss, deviation from fully-developed flow profile, swirl, and turbulence.

A fully developed velocity profile was estimated using the empirical power-law equation:

$$\frac{v}{V_{max}} = \left(\frac{y}{R}\right)^{1/n} \qquad \text{where:} \quad n = -1.7 + 1.8 \, \log Re_U$$

Deviation from fully developed flow was determined by the coefficient of variance (CoV) of the velocity in each cell from the ideal fully developed profile. The power-law equation is only an approximation of a fully developed flow profile, and was found to deviate from an actual fully developed profile by approximately 0.89%.

Dimensioned drawings of the conditioner used are included at the end of this report.

RESULTS AND DISCUSSION

The goal of the flow conditioner is to develop a fully developed profile quickly. To do this, swirl needs to be eliminated, and a fully developed profile needs to be established where the velocity and turbulence profiles no longer change as the fluid travels downstream.

Flow Characteristics:

The basic beneficial flow characteristics that the leading tab flow conditioner creates are:

- Two strong counter rotating vortices that are generated at the edges of the primary tabs in the bulk flow (away from the wall). These vortices very quickly exchange momentum between the flow at the center of the pipe with the flow at the wall.

- The vortices quickly migrate to the wall in the wake of the primary tabs due to the tab angle, and the vortex pair's close proximity to each other. Once attached to the wall, the vortices quickly decrease in intensity due to high shear stress at the pipe wall, through which rotational momentum is lost, and excessive turbulence is dissipated.

- Radial fins that effectively eliminate swirl near the pipe walls, where the rotational inertia is greatest.

- Relatively low pressure loss associated with this device (0.94 inwg with ambient air at 1000 acfm in a 6" pipe, or a k-value of 0.57).

- Tapered leading edges and other geometric features that prevent fouling.

- Secondary tabs located downstream of the primary tabs that eliminate the trailing vortices and quickly establish a radially symmetric fully developed velocity profile.

Pressure Loss:

Pressure loss was measured across the flow conditioner by comparing pressure at the test section inlet with and without the conditioner installed. From the results, a k-value of 0.574 was calculated using the pressure loss, and a gas density of 0.076-lbm/ft3. The addition of the secondary tabs increases the pressure loss by 1.6% compared to the conditioner without the secondary tabs. The k-value may be used to extrapolate to find pressure losses at other

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conditions as long as the flow remains incompressible. A plot of pressure loss vs. flow rate is included at the end of this report.

There are three main sources of measurement error in flow meters, and each will be addressed separately: swirl, flow mal-distribution, and turbulence.

Swirl:

Swirl can be induced by consecutive out-of-plane bends, as is the case studied, and takes many pipe diameters to die out due to friction. Swirl causes measurement error especially in orifice flow meters by influencing the pressure measured at the pressure taps.

The radial vanes in this flow conditioner are very effective at eliminating swirl near the pipe walls where the angular momentum is highest. A small amount of swirl remains untreated in the center of the flow, however this represents a very small fraction of the flow energy, and should not contribute to significant measurement error.

Swirl is measured as the average tangential velocity divided by the average axial velocity. The swirl decay rates remain the same for all flow conditions, and will remain the same as long as the flow is turbulent. The swirl with the secondary tabs is similar to the swirl without the secondary tabs at distances of 7D or greater. The extension of the radial fin above the transverse surface on the secondary tabs was found to considerably reduce swirl that would otherwise be aggravated by the slight expansion of the spanwise surfaces on the secondary tabs. A plot of the decay of swirling flow for the 1000-cfm case, as well as color contour plots, are included at the end of this report.

Flow Distribution:

Poor flow distribution naturally occurs after any pipe bend or change in cross section. This causes measurement error in orifice meters as the high and low velocities are not evenly distributed radially, so the pressure measured at the tap is not necessarily an accurate indication of the average pressure at that location.

The leading tab flow conditioner addresses mal-distribution by inducing a small amount of pressure loss, and turning the flow "inside-out" so that momentum is fully exchanged across the flow stream.

Flow distribution is measured as the CoV of the flow from fully developed. Although deviation from fully-developed flow is a useful measure of what distance downstream a flow meter can be placed, it does not directly translate to a quantifiable level of measurement error. Due to the flow disturbance caused by the flow conditioner, the initial deviation from a fully developed profile is greater with the conditioner than without, but by less than 4D downstream, the conditioner creates a more developed profile. The addition of the secondary tabs to the flow conditioner help to develop a fully developed profile more quickly by completely eliminating the swirl from primary tabs. Additionally, the spanwise surface of the secondary tab is tapered towards the wall to further reduce any momentum transfer from the center to the wall (and vice versa) while providing a diffuser section to reduce the peak centerline velocity to that of a fully developed flow. With these flow features, the velocity profile is essentially fully developed by 8D downstream of the conditioner inlet.

In order to achieve the shortest duct run possible, the flow conditioner was also tested with the flow conditioner inlet placed at the outlet of the second bend. The conditioner was tested with the primary fins oriented at 0° to the axis of the bend, and also at 45° to the bend axis. The deviation from fully developed flow was measured as a function of downstream distance from the bend outlet, and compared to the results with the inlet to the conditioner placed 4D downstream of the bend outlet.

It was found that the flow conditioner's performance is insensitive to orientation, as the 0° and 45° orientations had nearly identical flow deviations at all points downstream of the conditioner. It was also found that the flow conditioner performs slightly better 4D downstream of the bend than 0D downstream of the bend, but until the measurement error of the conditioner is tested, it is unknown if this slight difference in flow deviation will result in significant differences in

measuring error. In any case, placing the flow conditioner directly at the bend outlet yields a better flow profile within 10D of the bend outlet, and further than 10D downstream the flow conditioner performs better 4D downstream of the bend. A plot of the deviation from fully developed flow for the 1000-cfm case, as well as color contour plots, are included at the end of this report.

Turbulence:

Excessive levels of turbulence can be a cause for measurement error, especially in ultrasonic flow meters. The flow conditioner reduces turbulence downstream much more quickly than a trailing tab or perforated plate flow conditioner by forcing the turbulence to the walls, where it dissipates quickly due to the increased shear stress.

Turbulence is measured as turbulent intensity, or the ratio of the root mean square of the velocity fluctuations to the mean flow. The decay of turbulent intensity downstream of the flow conditioner remains constant across all flow rates tested, and will be constant for all turbulent flow conditions. The turbulent intensity by 10D was 6% with the flow conditioner, compared to 5% without. At 20D, the average turbulent intensities were equal with and without a flow conditioner, although the distributions across the pipe cross section were different, owing to the different flow patterns. The turbulent intensity with the secondary tabs is very similar to the turbulence without. A plot of turbulent intensity for the 1000-cfm case, as well as color contour plots, are included at the end of this report.

Mixing:

Although mixing was not tested in this case, it is likely that mixing rates are decreased somewhat with the secondary tabs due to the suppression of circulation downstream of the flow conditioner.

CONCLUSIONS

This flow conditioner design generally works very well. It is effective at mitigating any swirling flow that is created upstream. The sweeping curve of the tabs has reduced pressure loss below that of previous designs, and is effective at conditioning the flow. The tapered shape of the tabs has also allowed the radial vanes to be extended farther into the flow to further reduce swirl from previous designs, without reducing the high velocity core that is helpful for quickly re-establishing a fully developed profile. The secondary tabs improve performance as a flow conditioner in all aspects save a slight increase in pressure loss. No further development is proposed at this time.

NOTES:

ALDEN Research Laboratory Inc.

Solving Flow Problems Since 1894

Westfall Leading Tab Flow Conditioner

Rev. C with Primary & Secondary Tabs

Drawn By: KHM	Paper Size: LETTER	Project Number: 409509	Drawing Number: ARL-409509-Rev.C-1	Rev. C
Plot Date: 9/14/2009	Scale Factor:—		Last Saved: 9/14/2009	SHEET 01 OF 2

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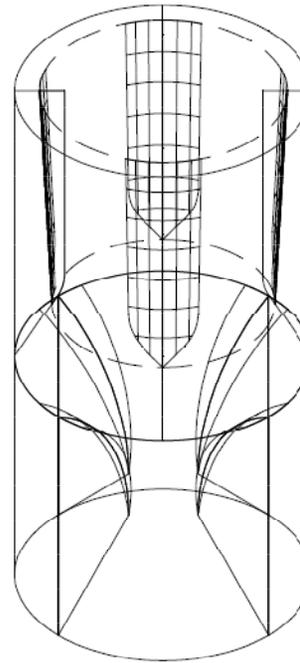
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Flow Conditioner Pressure Loss vs. Flow

◆ 6" Flow Conditioner RevC

—— k-Value = 0.574

Pressure Loss (inwg) vs *Flow Rate (cfm)*

Air flow in a 6-in Sch40. steel pipe, after two out-of-plane 90° bends.

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The flow conditioner is installed 4D downstream of the second bend.

Swirl Suppression - 1000cfm

1000-cfm air flow in a 6-in Sch40. steel pipe, after two out-of-plane 90° bends.

The flow conditioner is installed 4D downstream of the second bend.

westfall_revA_1000cfm_control
Contours of Tangential Velocity (ft/s)

Jul 28, 2009
FLUENT 6.3 (3d, pbns, rke)

westfall_revC_02b_1000cfm
Contours of Tangential Velocity (ft/s)

Sep 08, 2009
FLUENT 6.3 (3d, pbns, rke)
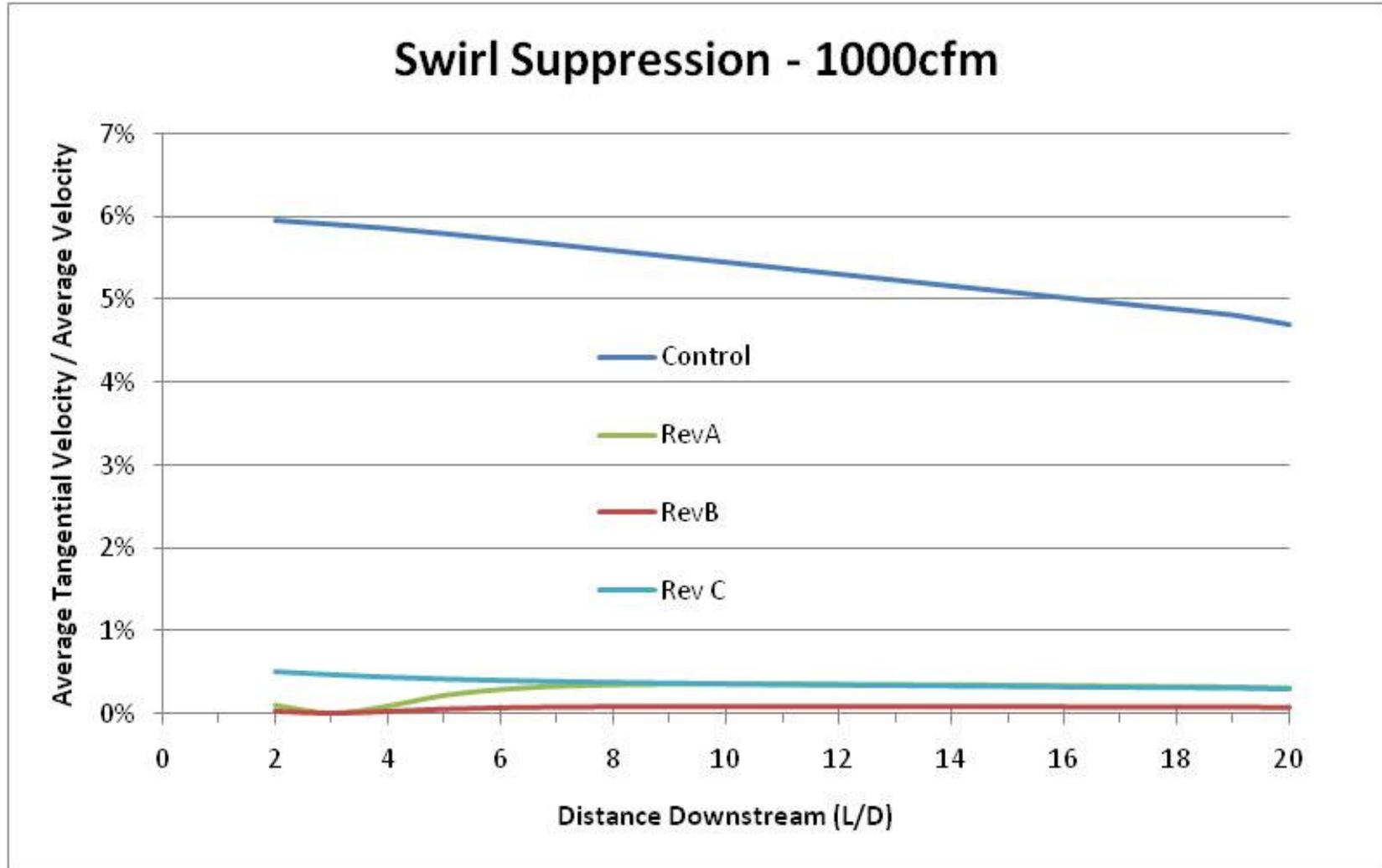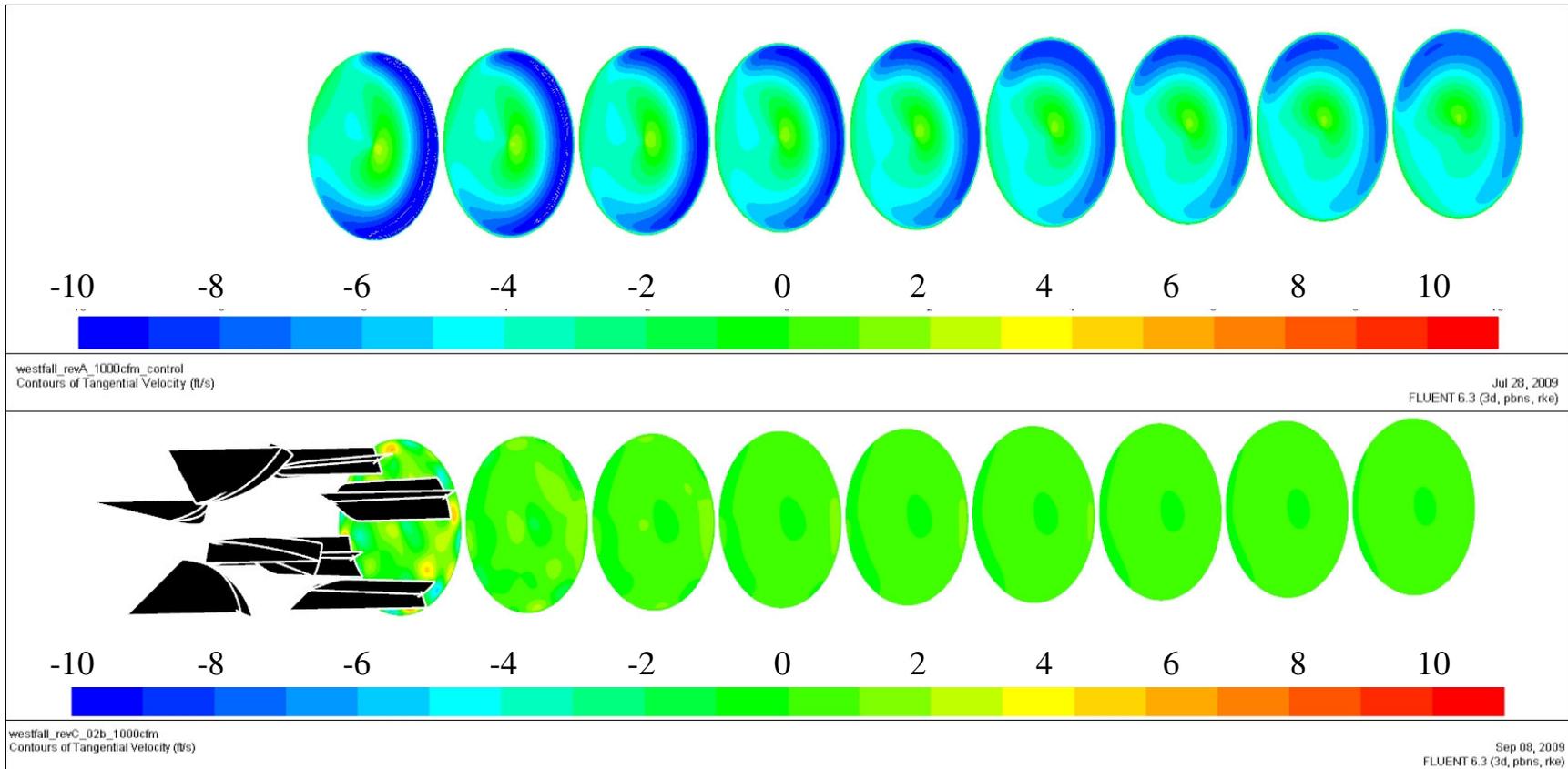
1000-cfm air flow in a 6-in Sch40. steel pipe, after two out-of-plane 90° bends.
The flow conditioner is installed 4D downstream of the second bend.
Contours of Tangential Velocity (ft/s) for distances 2-10 D downstream of the flow conditioner inlet:
With (lower) and without (upper) the flow conditioner installed.

409509 / AGM-09-R-05 RevC.

Deviation from Fully Developed Flow

1000-cfm air flow in a 6-in Sch40. steel pipe, after two out-of-plane 90° bends.
The flow conditioner is installed 4D downstream of the second bend.

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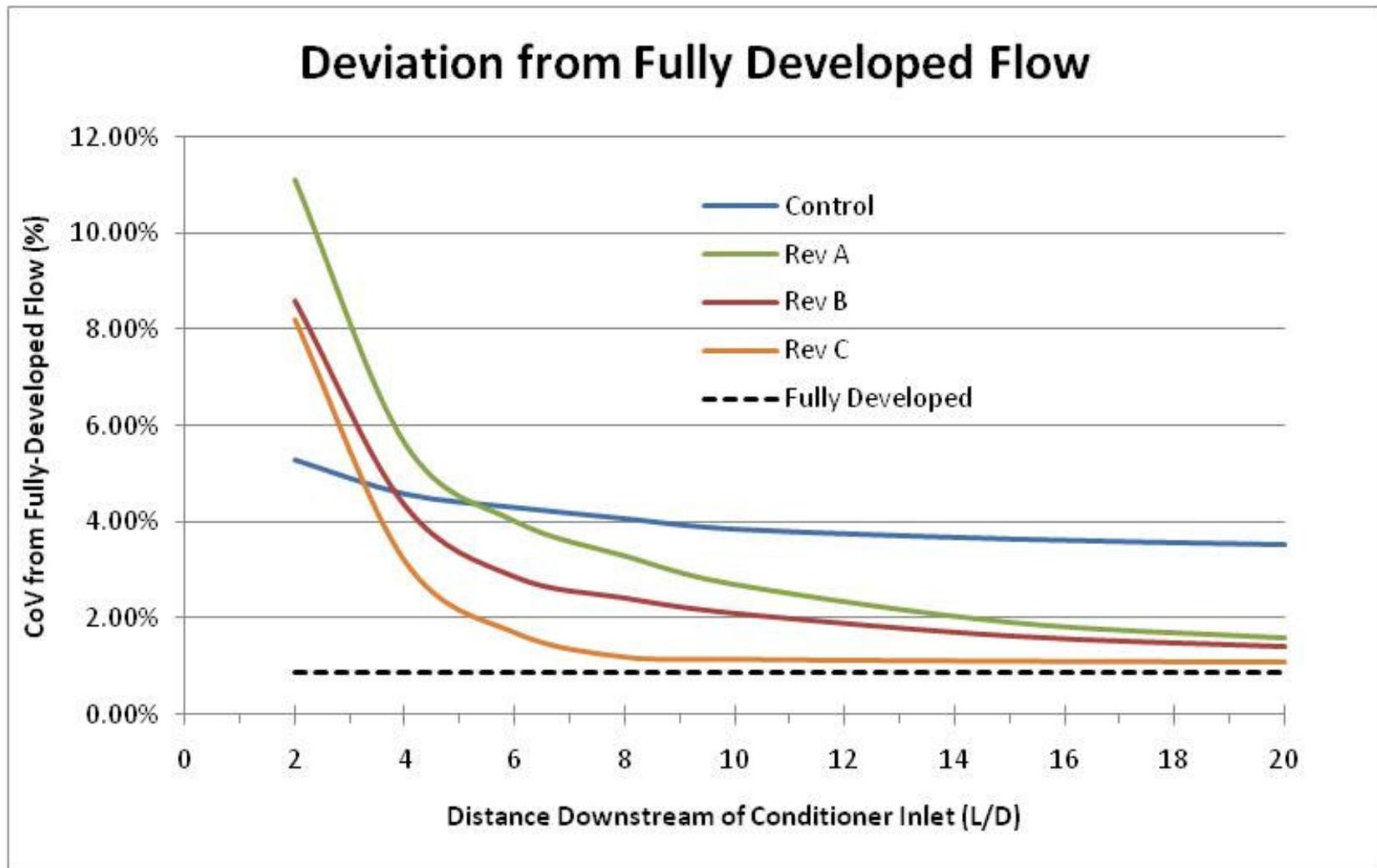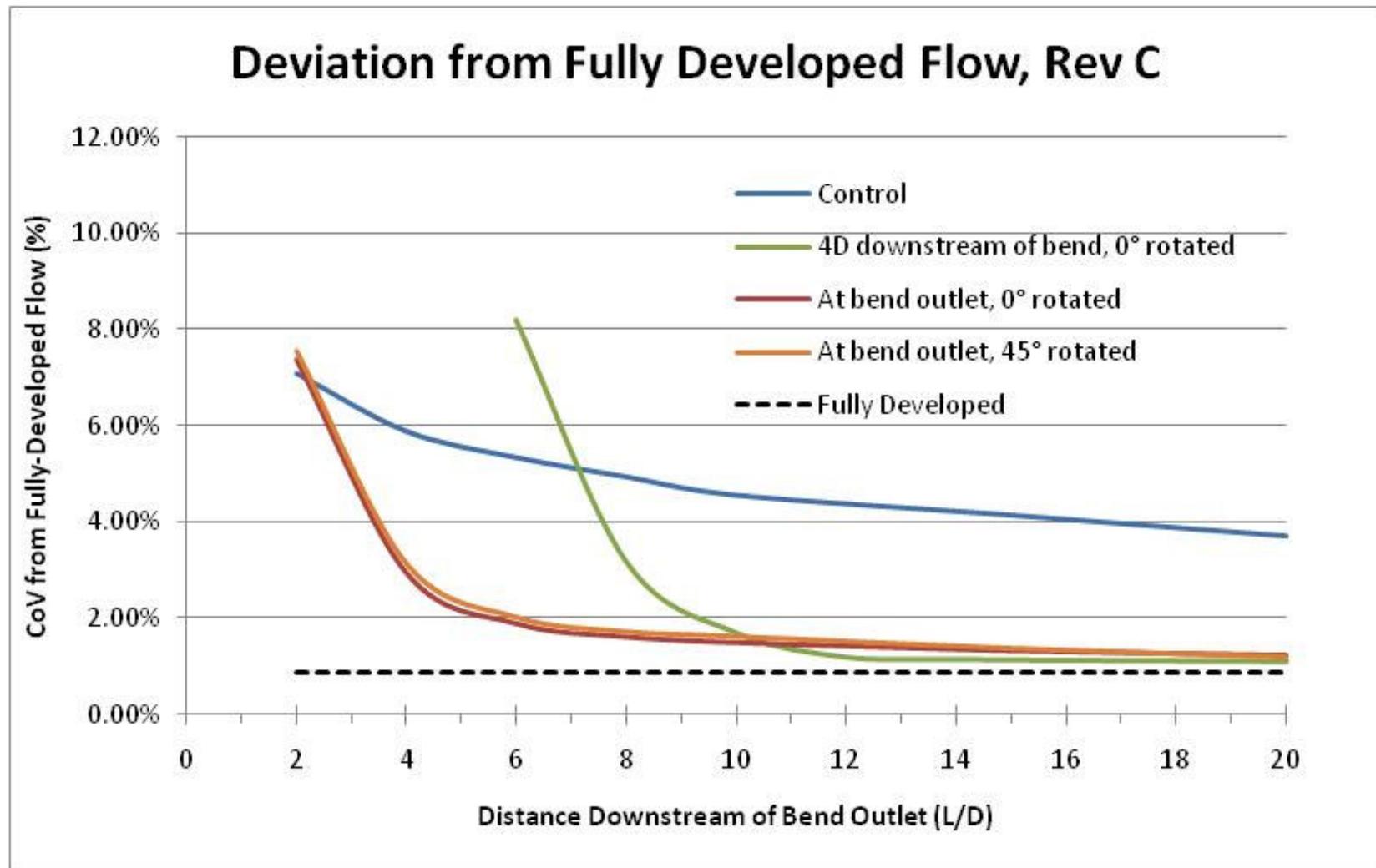
1000-cfm air flow in a 6-in Sch40. steel pipe, after two out-of-plane 90° bends.
The flow conditioner is installed either 0D or 4D downstream of the second bend.
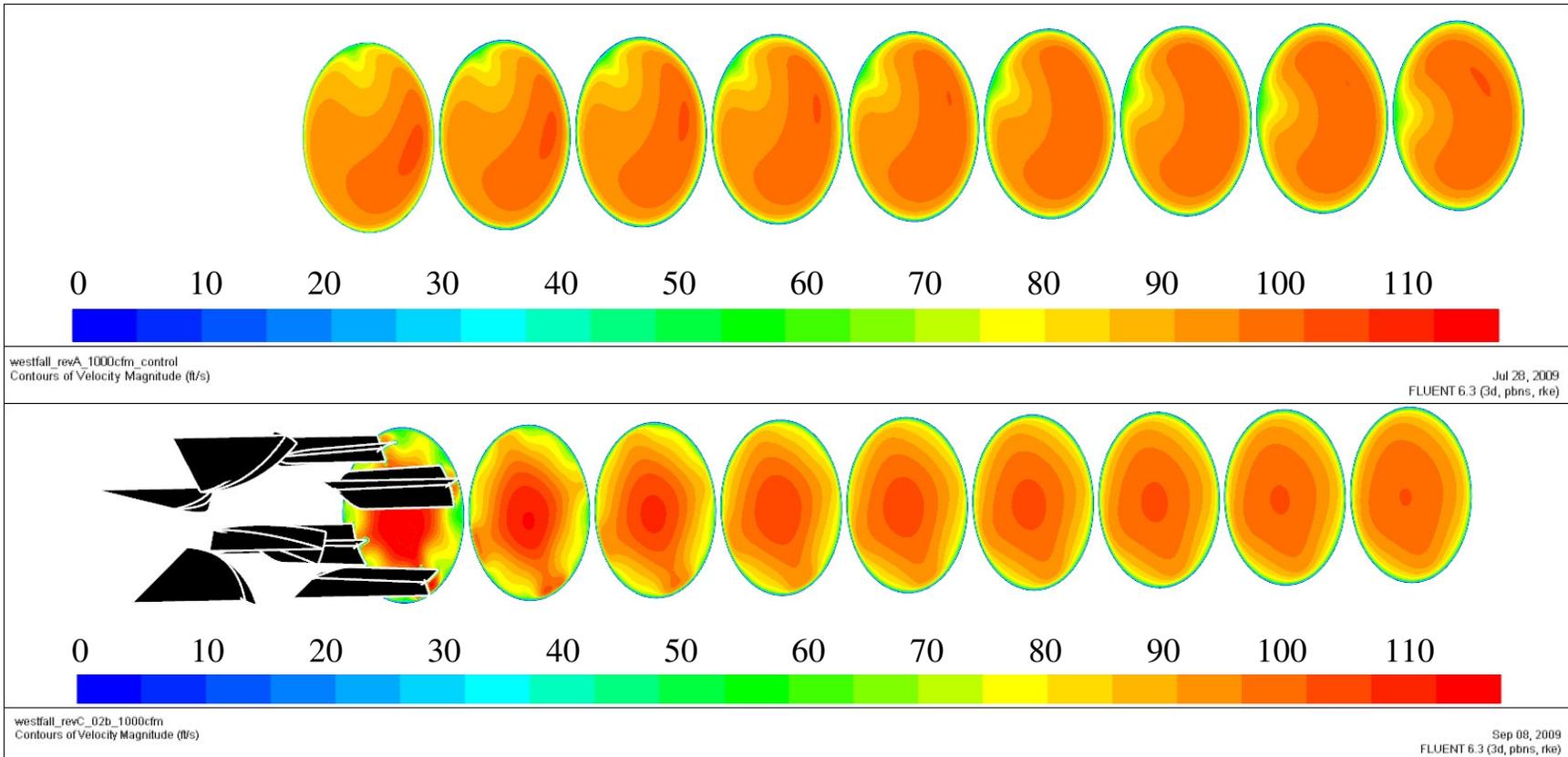
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1000-cfm air flow in a 6-in Sch40. steel pipe, after two out-of-plane 90° bends.
The flow conditioner is installed 4D downstream of the second bend.
Contours of Velocity Magnitude (ft/s) for distances 2-10 D downstream of the flow conditioner inlet:
With (lower) and without (upper) the flow conditioner installed.

Average Turbulent Intensity

1000-cfm air flow in a 6-in Sch40. steel pipe, after two out-of-plane 90° bends.
The flow conditioner is installed 4D downstream of the second bend.

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Contours of Turbulent Intensity (%)

westfall_revA_1000cfm_control
Contours of Turbulent Intensity (%)

Jul 28, 2009
FLUENT 6.3 (3d, pbns, rke)

westfall_revC_02b_1000cfm
Contours of Turbulent Intensity (%)

Sep 08, 2009
FLUENT 6.3 (3d, pbns, rke)
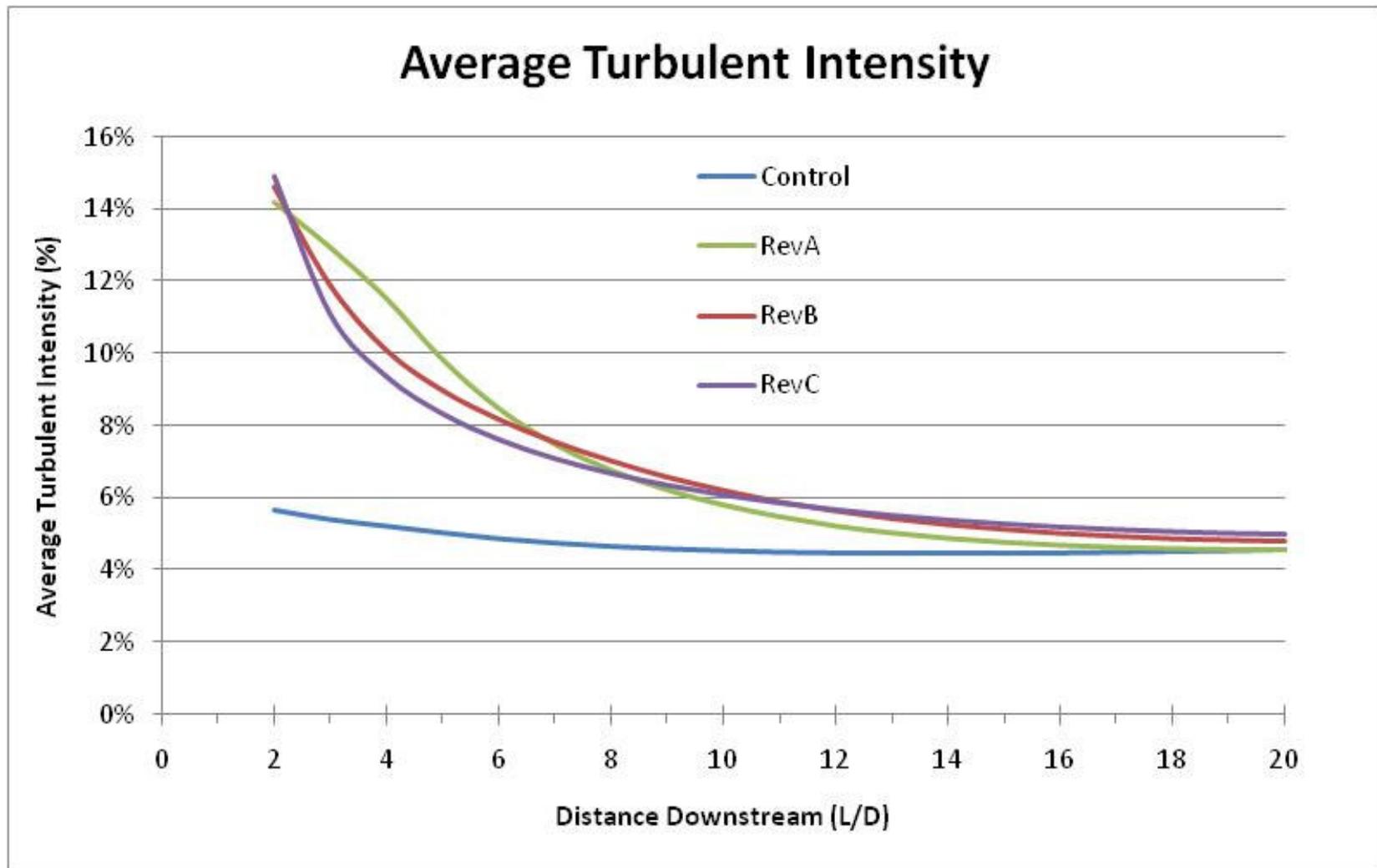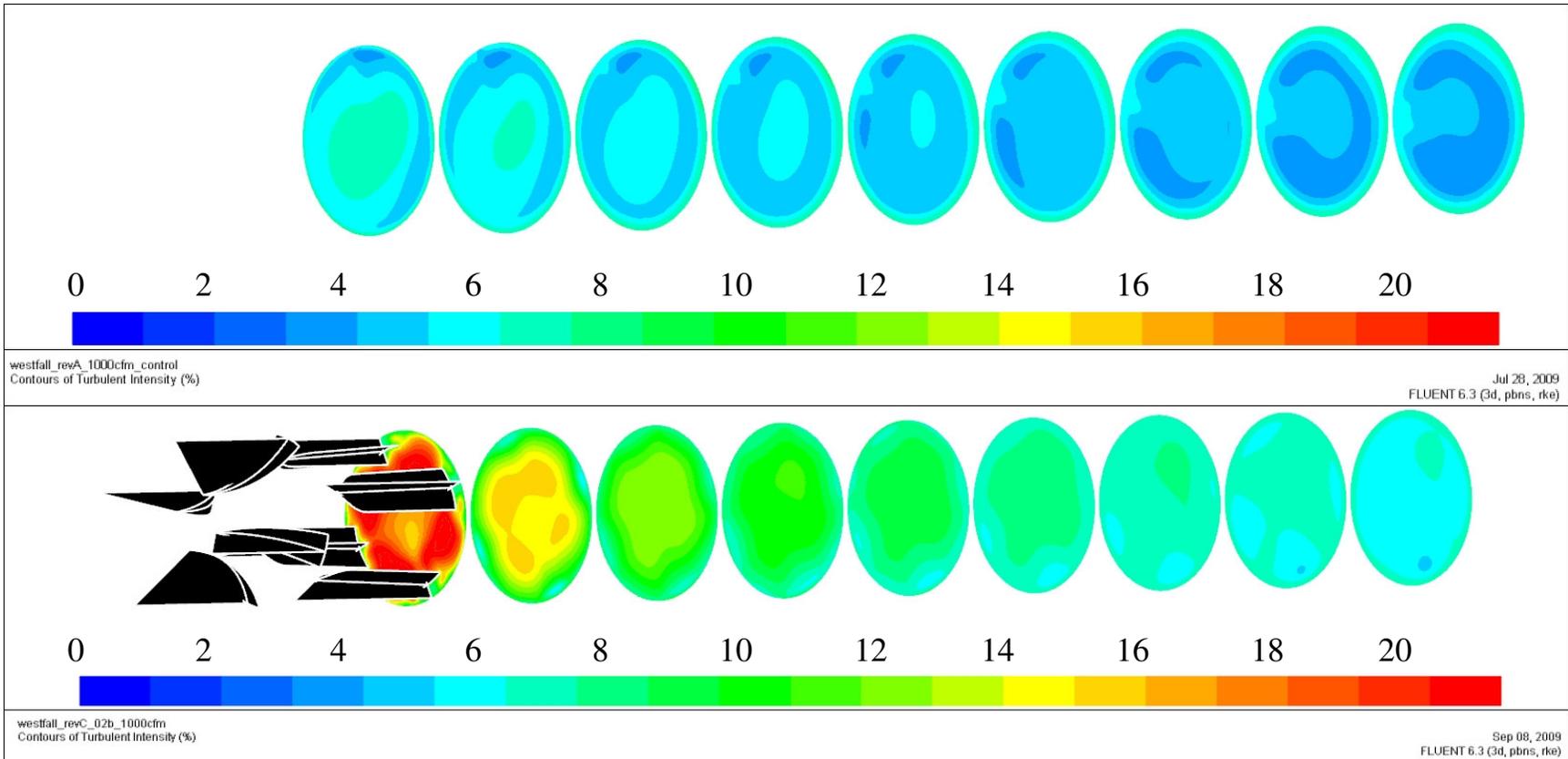
1000-cfm air flow in a 6-in Sch40. steel pipe, after two out-of-plane 90° bends.
The flow conditioner is installed 4D downstream of the second bend.
Contours of Turbulent Intensity (%) for distances 2-10 D downstream of the flow conditioner inlet:
With (lower) and without (upper) the flow conditioner installed.

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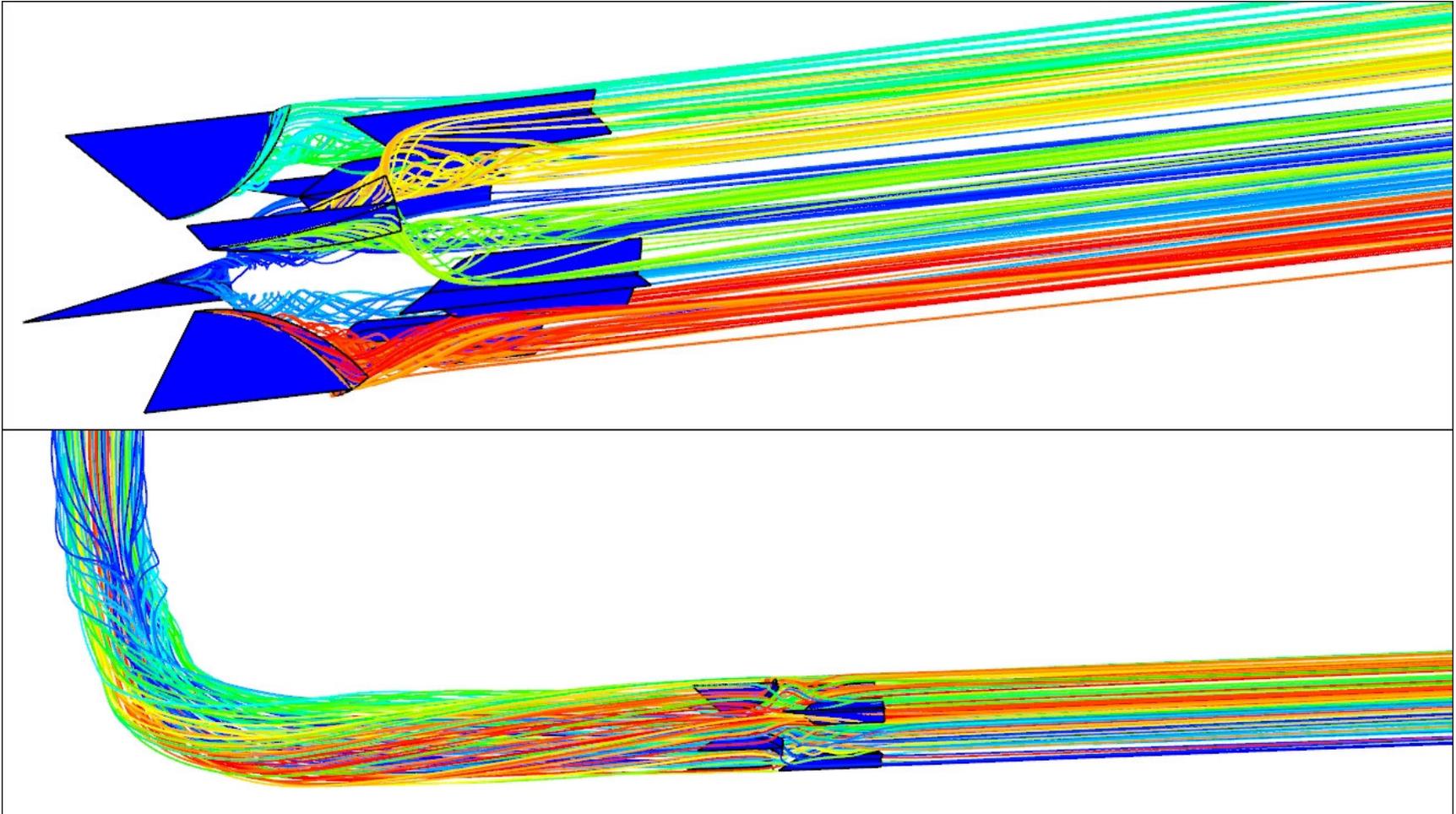
1000-cfm air flow in a 6-in Sch40. steel pipe, after two out-of-plane 90° bends.
The flow conditioner is installed 4D downstream of the second bend.
Pathlines with the flow conditioner installed.

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