# Computational Fluid Dynamics Model for Sensitivity Analysis and Design of Flow Conditioners

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Keywords: Computational Fluid Dynamics, Flow Conditioner, Swirling Flow, Flow Measurement, Flow Velocity Profile.

Abstract: Flow conditioners are used to measure flow rate more accurately. The sensitivity of flow measurement devices to swirling flows and not fully developed flows are subjects of concerns to flowmeter manufacturers as well as industries. Inaccurate flow measurement occurs in the presence of swirl flow and when the flow velocity profile is not fully developed. Distorted profiles occur when the piping configuration upstream of the flow measurement devices changes. Certain length of straight piping upstream of a flow meter is required to achieve acceptable flow velocity profile for expected flow meter accuracy. In some installations, it is not realistic to run lengths of piping to reach an acceptable flow velocity profile. Introducing flow conditioners into the system reduces piping needed to reach fully developed flow and significantly weaken swirling flows. In this study, a Computational Fluid Dynamics (CFD) model is developed and validated which is used to investigate systematically the sensitivity of various parameters for perforated flow conditioners. Published data and an experimental setup was used to verify the CFD model.

## 1 INTRODUCTION

Flow conditioners are used for homogenizing the velocity profile, as well as removing swirls, created by disturbances. Installations such as elbows and double elbows, create swirls in the flow that can result in inaccurate measurements by the flow meters. It is essential the use of a flow conditioner to remove disturbances in the flow, enabling proper performance of the flow meter. Most flowmeters are calibrated under conditions of fully developed flow. Typically, without a flow conditioner it can take approximately 30 L/D to obtain acceptable flow profile for the measurement devices. Adding long straight piping can be costly, and use up large amounts of space. Using a flow conditioner accelerates the development of flow profile as well while also fading swirls. There are certain standards, specifically ISO 5167, which define acceptable fully developed flow, free from swirls and pulsations. The standard states that, swirl-free conditions are presumed "to exist when the swirl angle at all points over the pipe cross-section is less than 2° (ISO, 2003)." The acceptable flow conditions exist when, "at each point across the pipe cross-section, the ratio of the local axial velocity to the maximum axial velocity at the cross-section agrees to within ±5% which would be achieved in swirl-free flow at the same radial position at a cross-section located at the end of a very long straight length L/D>100 of similar pipe (ISO, 2003)."

The purpose of this project was to investigate the performance of current perforated flow conditioners, and to design and build a CFD model as a test bench using academic COMSOL® Multiphysics software. The CFD model is used to further investigate the performance of the perforated flow conditioners and sensitivity of the design parameters.

## 2 FLOW CONDITIONERS

There are various types of flow conditioners such as those shown in Figure 1. However, for this study, two perforated flow conditioners shown in Figure 2 are examined. The perforated flow conditioner is chosen over the other types due to its most used in industry and ease of installation. Flow conditioners that require long lengths of piping such as the tube-type flow conditioner is effective in removing disturbances in flow, but it is not ideal for applications that are limited by space. In addition,



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maintenance is not as user-friendly for these types of flow conditioners. In order to compare CFD results with published data, the data from the study of comparison of velocity and turbulence profiles downstream of NEL and Mitsubishi perforated plate conditioner were used for CFD model verification and validation (Spearman, 1996).

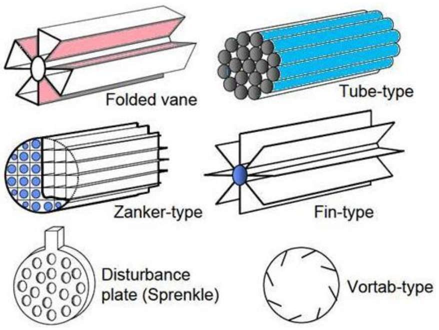


Figure 1: Different types of flow conditioners (Miller, 1996).

Figure 2: Perforated flow conditioners. Left: NEL Spearman, Right: Mitsubishi.

# 3 COMPUTATIONAL FLUID DYNAMICS MODEL

A CFD model was developed and compared with published experimental data. The same parameters used in previous works (Spearman, 1996) such as flow rate of 40 L/s and internal pipe diameter of 102.6 mm were used for the CFD model to study two types of upstream disturbances: i) a single 90° elbow, and ii) a double out of plane 90 ° elbows. Both disturbances had a bend radius to diameter ratio (R/D) of 1.5. Flow conditioners were placed 4 L/D downstream of flow disturbing installations. Measurements of velocity profiles were made at 3, 6, 11, 16, 21, 26, 31, 36 and 41 L/D downstream of each flow conditioner. These points correspond to 7, 10, 15, 20, 25, 30, 35, 40 and 45 L/D downstream of the disturbance. In addition, we used the Reynolds Averaged Navier-Stokes (RANS) turbulence using the standard k-$\varepsilon$ model available in the COMSOL® software. There are other RANS models such as k-$\omega$ model; there are of advantages and disadvantages when comparing two models (Drainy, 2009). The k-$\varepsilon$ model was used because of software and hardware limitations (Argyropoulos, 2015).

## 3.1 CFD Approach

Modelling the full configuration in 3D would require a lot of computing power, and will take extremely long time to run the simulation. Moreover, due to the limitations on academic version of COMSOL software, the model was broken up into two parts: a 2D axisymmetric model simulating the 77 L/D pipe upstream of the disturbance, and 3D model simulating the disturbance and the 48 L/D test section. The flat velocity profile as an inlet condition for 2D model eventually becomes fully developed at the end of the 2D model section. The outlet velocity profile of 2D model is then used as the inlet velocity for the 3D model. Turbulent kinetic energy, and turbulent dissipation rate is also derived from the straight section, which is used as part of the inlet condition.

The first step in verifying the results from CFD was to check the velocity profile at the end of the straight section of 2D model. If the velocity profile is fully developed, the velocity at the point $0.216r_o$ from the wall (where $r_o$ is the radius of the pipe), should be equal to the average velocity which in this case, the average velocity should equal the inlet velocity of 4.8381 m/s (Figure 3).

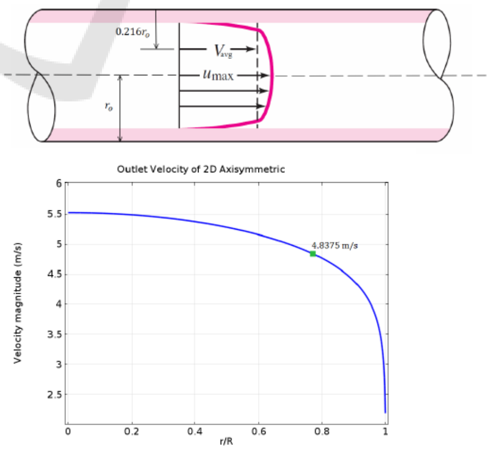


Figure 3: Velocity profile at outlet of 2D model ($V_{avg}$=4.8375 m/s).

The second step in verification is to compare the velocity profiles of the CFD model with both the Mitsubishi and NEL Spearman flow conditioner published data. The comparisons were made between the overall shape of the velocity profile, as well as percent error between similar points. Typically, the velocity profile data is plotted non-dimensionally with respect to the mean pipe velocity $U_{avg}$, to allow for comparison regardless of configuration inputs. An average percent error was taken between the points. These points were taken at five locations, at the centre, ±0.3 x/D, and ±0.4 x/D. Figure 4 and Figure 5 give a general comparison of the overall velocity profile shape, for both configurations without any flow conditioner. The overall shape from the CFD results follow the published data, with differences in magnitude closer to the wall. At the end of the pipe, the velocity profile closely matches each other. The peak is roughly 1.16 from the CFD model, versus 1.15 from the study.

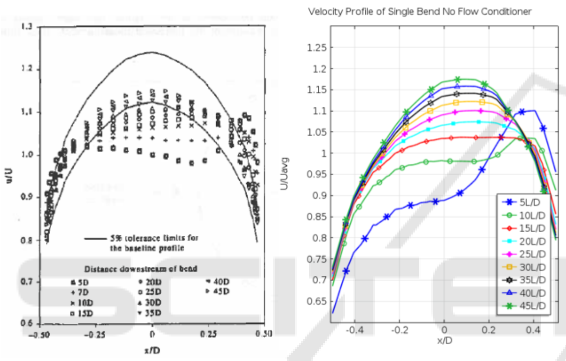


Figure 4: Velocity profile (single 90° elbow).

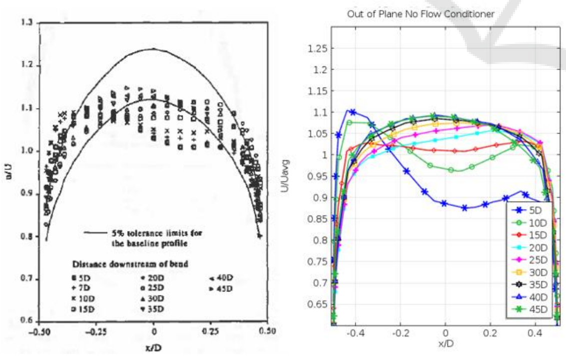


Figure 5: Velocity profile (double out of plane 90° elbows).

Figure 6 and Figure 7 show the individual comparison between the velocity profile from the CFD model and the study downstream of flow conditioners. The expectation was that, at the end of the test section the velocity profiles should be fairly similar to that of the study. Moving upstream from the end of the pipe, the accuracy and similarities should slightly decrease.

From Figure 6, the Mitsubishi flow conditioner was expected to have some asymmetry. There is some asymmetry from the CFD, but eventually becomes symmetric further downstream. The asymmetry is more prominent at lower L/D values, such as 11 L/D (see Appendix). The average error obtained from the single elbow Mitsubishi velocity profile plots was ±3.81%. Judging by the overall shape of the velocity profile, as well as the average error obtained, there is strong evidence that the CFD model can correctly predict the flow patterns. Similar to the elbow, the double elbow configuration flowing through the Mitsubishi should show some asymmetry. The error for this configuration running through the Mitsubishi flow conditioner was ±4.12%.

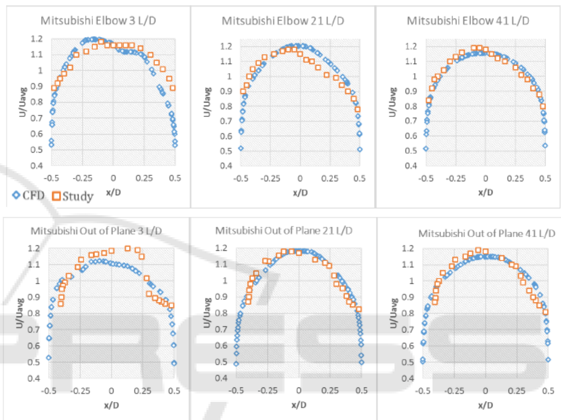


Figure 6: Velocity profile Mitsubishi: top: single 90° elbow, bottom: double out of plane 90° elbows.

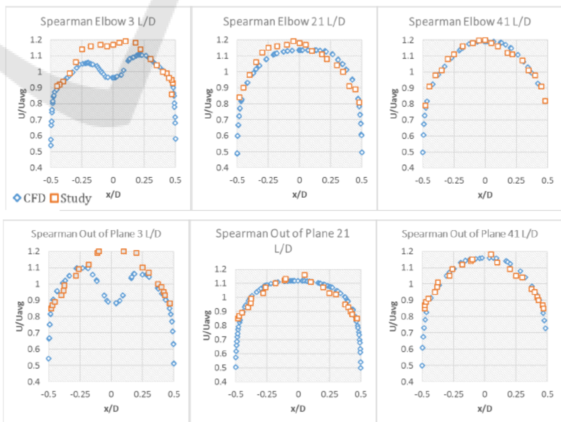


Figure 7: Velocity profile NEL Spearman: top: single 90° elbow, bottom: double out of plane 90° elbows.

# 4 PERFORMANCE ANALYSIS

The velocity profile and the swirl results for both Mitsubishi and Spearman flow conditioners CFD modelling using COMSOL® are presented in this section.

## 4.1 Velocity Profile

The Mitsubishi flow conditioner shows some asymmetry from 3 to 21 L/D (Figure 8 and Figure 9). Further, downstream the velocity profiles seems to become more symmetrical. While it may look as if the velocity profiles are within the acceptable tolerance of ISO 5167 (ISO, 2003), the study reports that even at 41 L/D the velocity profile does not meet the requirements.

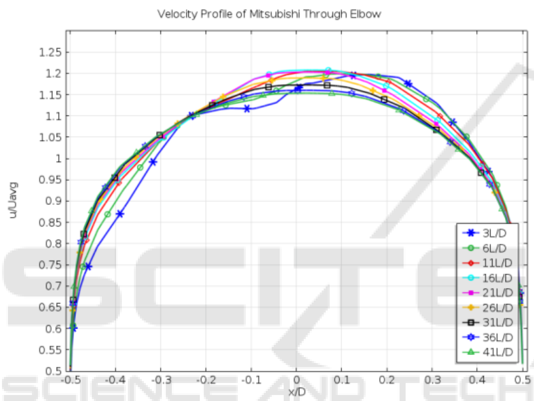


Figure 8: Velocity profiles downstream of Mitsubishi flow conditioner (single 90° elbow).

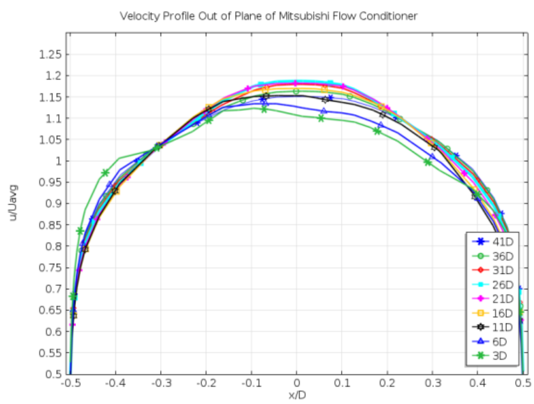


Figure 9: Velocity profiles downstream of Mitsubishi flow conditioner (double out of plane 90° elbows).

Figure 10 shows the profiles from the NEL Spearman flow conditioner through a double elbow. The results show that the performance of the NEL Spearman flow conditioner is comparable to that of the Mitsubishi.

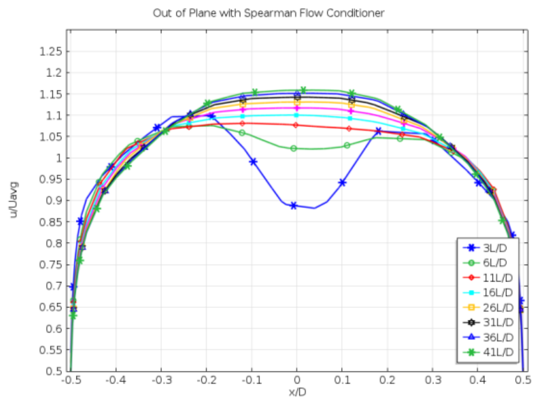


Figure 10: Velocity profiles downstream of NEL Spearman flow conditioner (double out of plane 90° elbows).

## 4.2 Swirls

For the accurate flow measurement, stable flow is required. The flow in any piping system is sensitive to upstream piping/fittings and devices that cause distortion not only on flow profile, but also may produce swirling flow that affects the accuracy of any flow measurement devices. By installing flow conditioners, the earlier mixing would take place resulting of fading the swirl and achieving the fully developed velocity profile in shorter L/D distance. Figure 11 and Figure 12 show the velocity filed (swirl) for a single and double out of plane 90° elbows.


Figure 11: Velocity field through 90° elbow (Re=1.5E6).

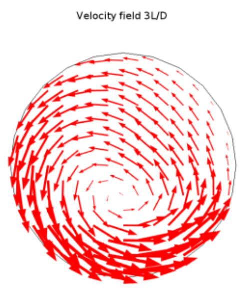


Figure 12: Velocity field through double out of plane 90° elbows (Re=1.5E6).

To compare the effectiveness in the removal of swirls, the analysis will include only the double elbow configuration. The comparison will be analysed at 1 L/D upstream, and 1 L/D downstream of the flow conditioner. Figure 13 shows that both flow conditioners are effective in removing swirls from the system. Upstream of the flow conditioner, the maximum velocity of the swirl was 1.26 m/s. After

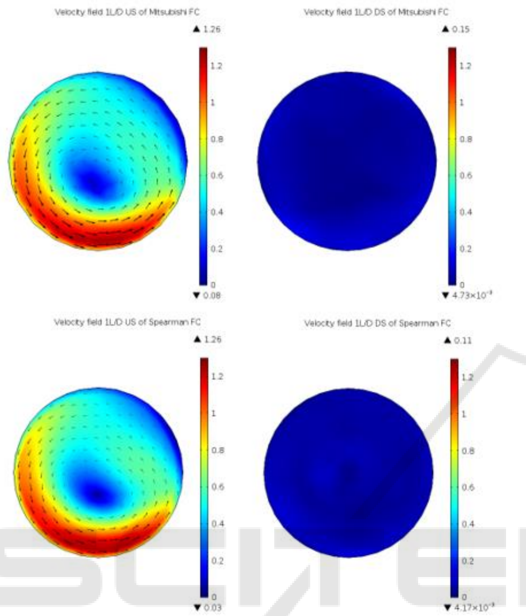


Figure 13: Velocity field upstream (US) and downstream (DS) of flow conditioners.

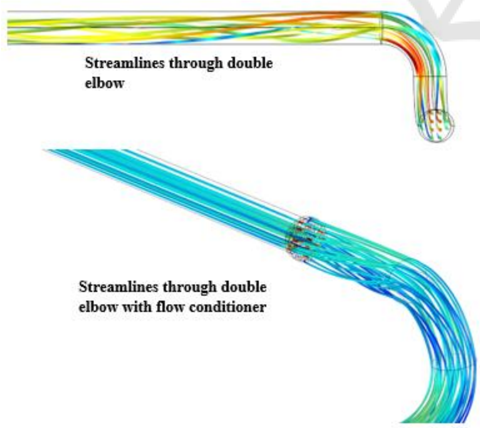


Figure 14: Velocity field US and DS of flow conditioners.

just 1 L/D downstream, the magnitude of the swirl significantly decreases, to a maximum velocity of 0.11 m/s. It is clear that, regardless of flow conditioner, the swirls are removed. The swirls can also be seen through streamlines in Figure 14, which die out relatively slowly. In contrast, the flow conditioner removes the swirls.

## 4.3 Flow Conditioner Modification and Results

Using the CFD model, a sensitivity analysis was performed on modified flow conditioner. The approach used in modifying the flow conditioner was to first select one flow conditioner, and change parameters such as the position of the holes, size, shape, and percentage porosity. The chosen flow conditioner to modify was the NEL Spearman, because there was room for improvement in terms of the geometry.

The corresponding velocity profiles for different modified NEL Spearman flow conditioner are shown in Figure 15-Figure 18. Design 1 configuration (Figure 15) produces a larger trough near the middle of the pipe.

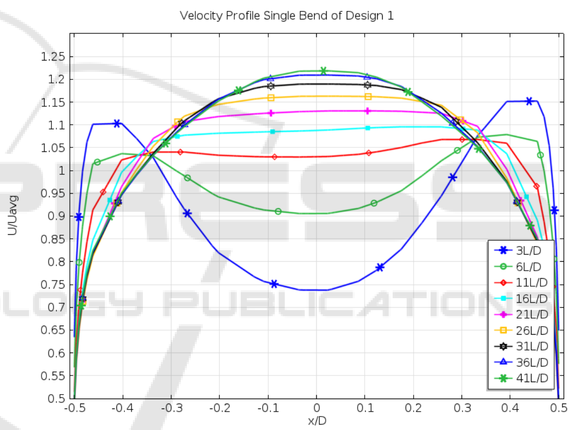


Figure 15: Design 1 velocity profile.

Due to the decreased hole size near the middle in design 1, more fluid flows through the outer portion, which is conveyed by the two crests near the wall. By decreasing the porosity, the pressure drop increased, which was expected. Moving away from the initial method of increasing the outer holes, while decreasing the inner ones, the next modification (design 2-4) was attempted to allow for more flow in the middle, rather than the outer. By this design change, the more turbulent flow is forced to mix with the less turbulent flow. As a result, the corresponding highest porosity is 56.7% for design 3, which is closer to the Mitsubishi porosity value. The dimensions and location of the holes for all four designs are presented in Appendix.

This iteration (design 3) has shown better performance than the first design, but both designs obtain fully developed flow at 21 L/D, which is higher than the benchmarked flow conditioners. However, this design has proved that increasing the flow through the centre, is more beneficial. There is slight asymmetry shown on the velocity profiles (Figure 17), which disappears after 21L/D. Table 1 shows the head loss coefficient for all four designs. The head loss coefficient for design 3 was lowest value, at a value of 1.9.

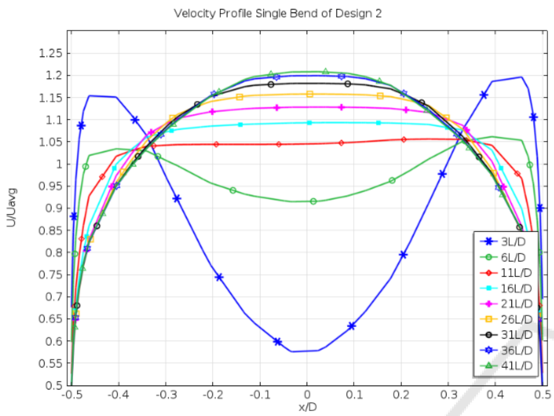


Figure 16: Design 2 velocity profile.

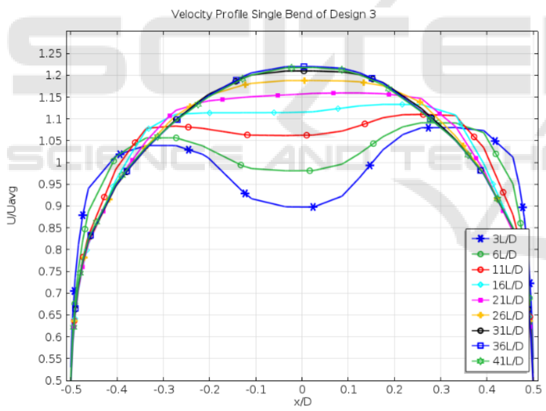


Figure 17: Design 3 velocity profile.

Table 1: Head loss coefficient comparison.

| Flow Conditioner | Head Loss Coefficient (K) CFD |
|---|---|
| NEL Spearman | 3.2 |
| Design 1 | 3.9 |
| Design 2 | 4.0 |
| Design 3 | 1.9 |
| Design 4 | 2.4 |

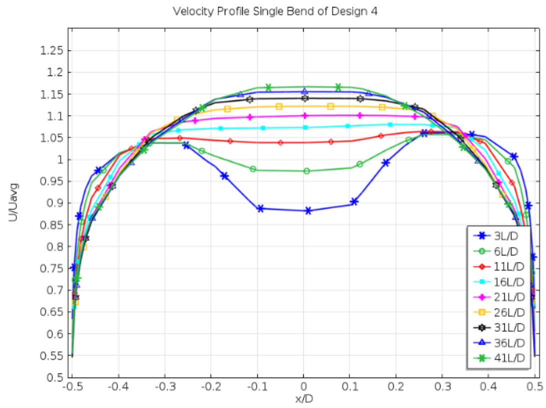


Figure 18: Design 4 velocity profile.

## 4.4 Experimental Setup

A mini pilot-scale model flow loop is used to test the flow conditioners. The experimental setup is one of the most important aspects of any computational fluid modelling verification and validation. A centrifugal pump and a turbine flow meter used to build the model. The same piping configurations as computational model with disturbances and flow conditioners used for experimental setup.

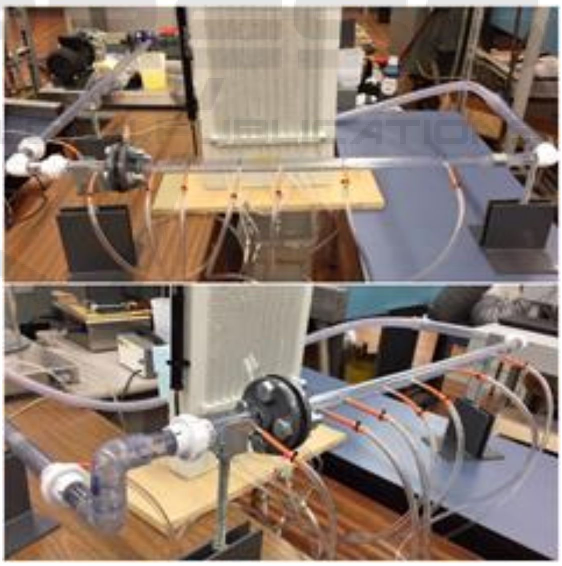

Figure 19: top: Flow loop with a single 90° elbow and bottom: double out of plane 90° elbows.

Figure 19 shows the two tested piping configurations with a flange for inserting the flow conditioner downstream of the disturbance. In addition, to find the effects of a flow conditioner, nine pressure taps were added on the piping (Figure 19) with the tap locations listed in Table 2.

For this experimental setup, the flow conditioners manufactured using the laser-cutting machine (Figure 20).

Figure 20: Manufactured flow conditioner.

Table 2: Location of pressure taps.

| Pressure Tap | Location |
|---|---|
| #1 | right before disturbance |
| #2 | 2D upstream of flow conditioner |
| #3 | 3D downstream of flow conditioner |
| #4 | 6D downstream of flow conditioner |
| #5 | 11D downstream of flow conditioner |
| #6 | 15D downstream of flow conditioner |
| #7 | 21D downstream of flow conditioner |
| #8 | 31D downstream of flow conditioner |
| #9 | 36D downstream of flow conditioner |

Along with verification through recreating past-published studies, COMSOL® models also were verified by comparing the differential pressures found through the experimental flow loop. The results show the same trend but a modified experimental setup is required to achieve a higher accuracy in comparison the results, which is a part of future activities.



## 5 CONCLUSION

COMSOL software is used to build a CFD model to investigate the performance of perforated flow conditioners with different designs. The model was verified and validated using published data for NEL Spearman and Mitsubishi flow conditioners. Using the developed model, the sensitivity on the performance of modifying parameters such as, thickness, size, position, and shape of the holes, were examined to develop a new perforated flow conditioner and to compare with NEL Spearman and Mitsubishi flow conditioners. The experimental flow loop was used to verify the COMSOL® models. The loop was designed to support testing for two upstream disturbances; i) an in-plane elbow disturbance, and ii) an out of plane elbow disturbance. Both setups emulate the two COMSOL® models. Needed improvements to the experimental flow loop will help in providing more accurate results and decreasing discrepancies due to physical limitations. The combination of computational model verified by experimental data can be considered as an efficient way for sensitivity analysis of flow conditioners and designing new flow conditioners.

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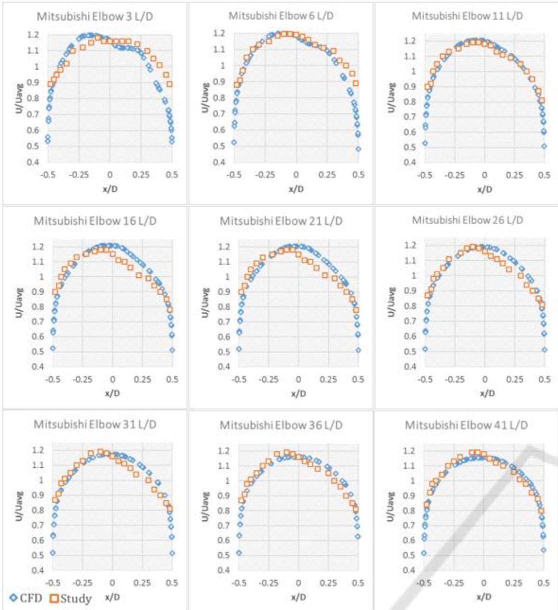
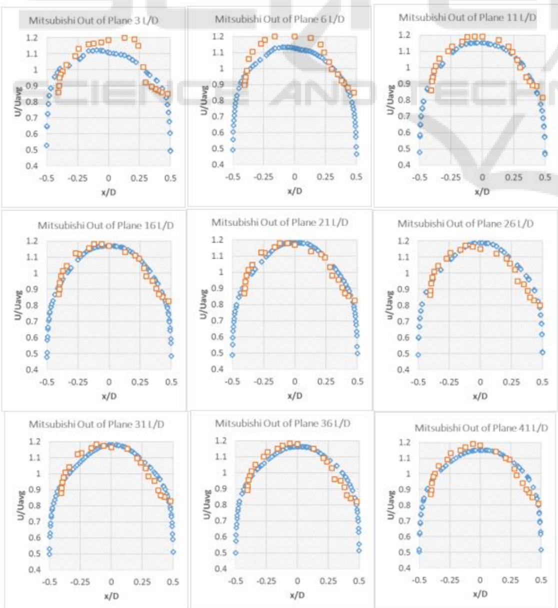
# APPENDIX

## Velocity Profile Comparison (Mitsubishi Flow Conditioner):

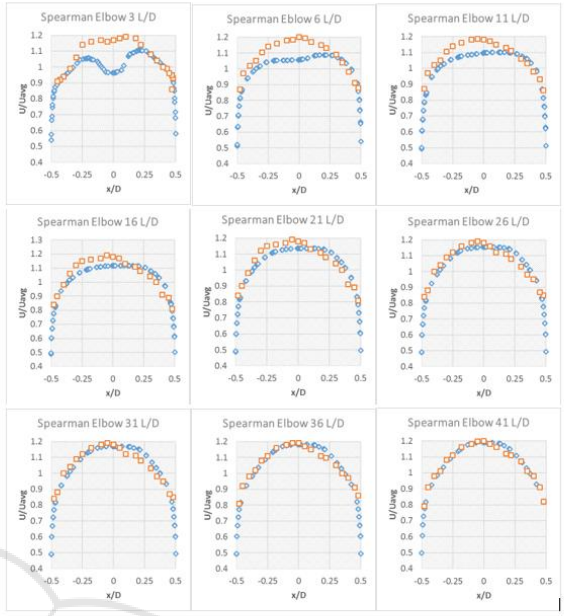



**Single 90° elbow (Mitsubishi)**

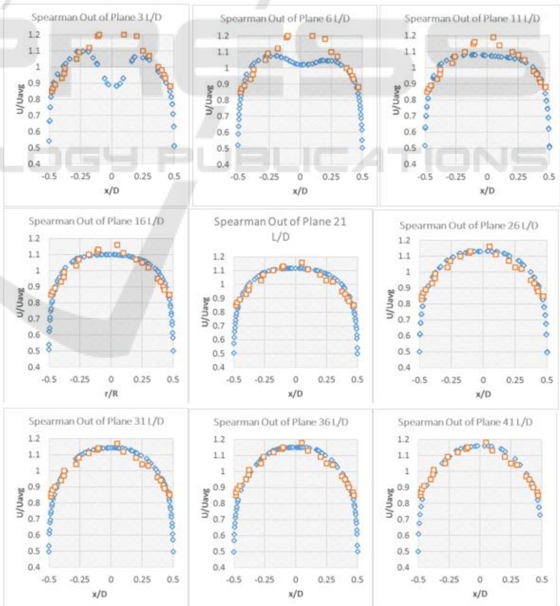



**Double out of plane 90° elbows (Mitsubishi)**

## Velocity Profile Comparison (NEL Spearman Flow Conditioner):

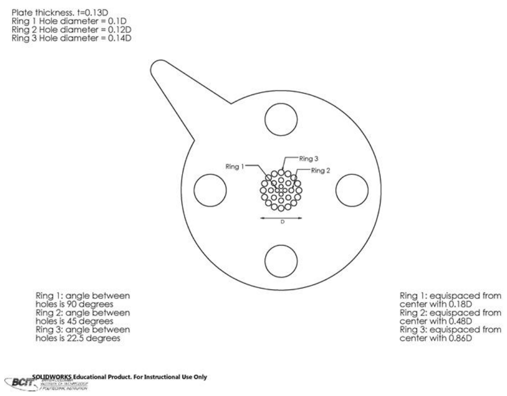


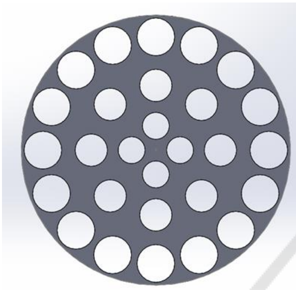

**Single 90° elbow (NEL Spearman)**



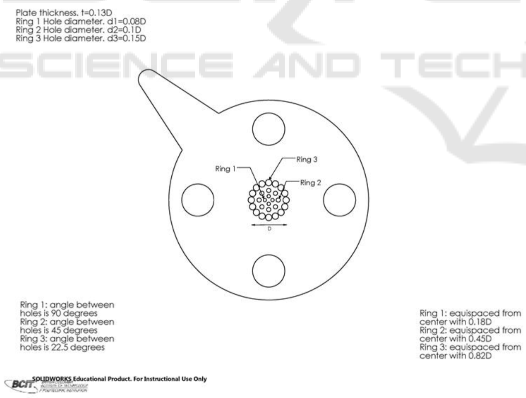

**Double out of plane 90° elbows (NEL Spearman)**

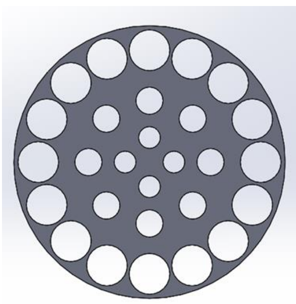
**<u>Flow Conditioner Design Drawings:</u>**



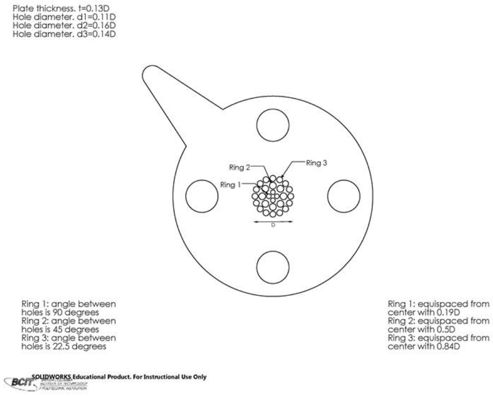



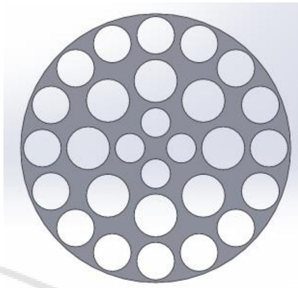
**Design 1 Configuration (46.9% Porosity)**



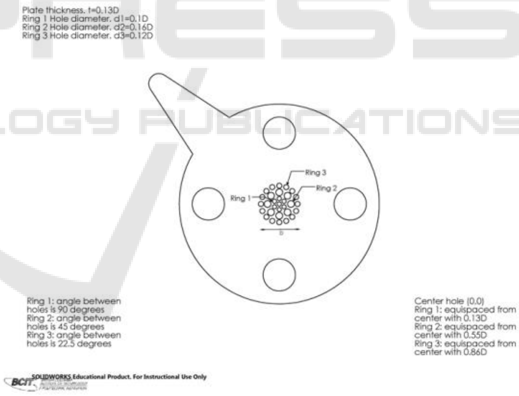



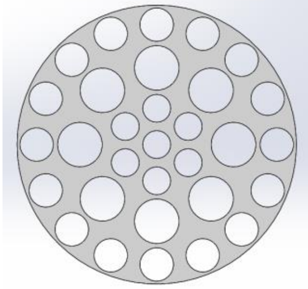
**Design 2 Configuration (46.6% Porosity)**



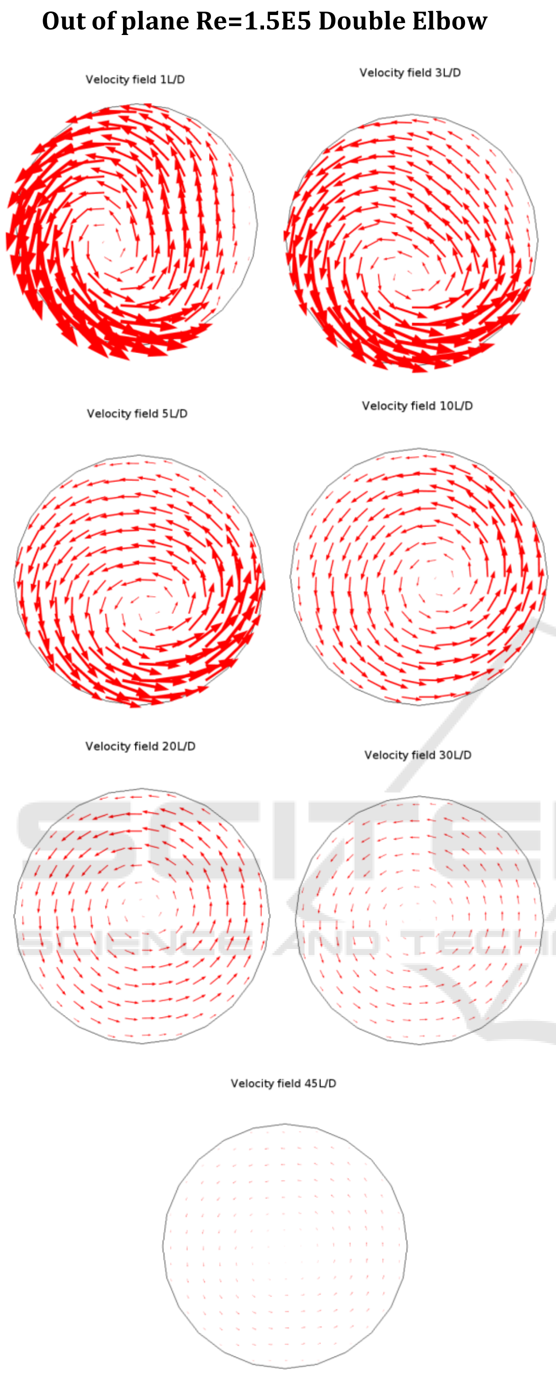



**Design 3 Configuration (56.7% Porosity)**

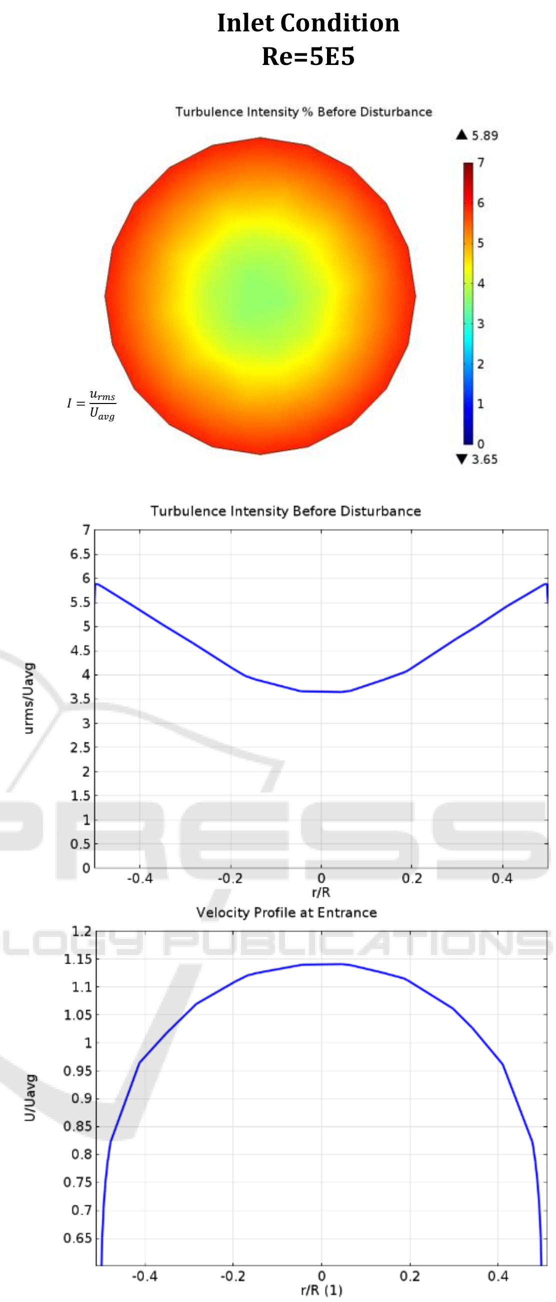


**Design 4 Configuration (50.5% Porosity)**

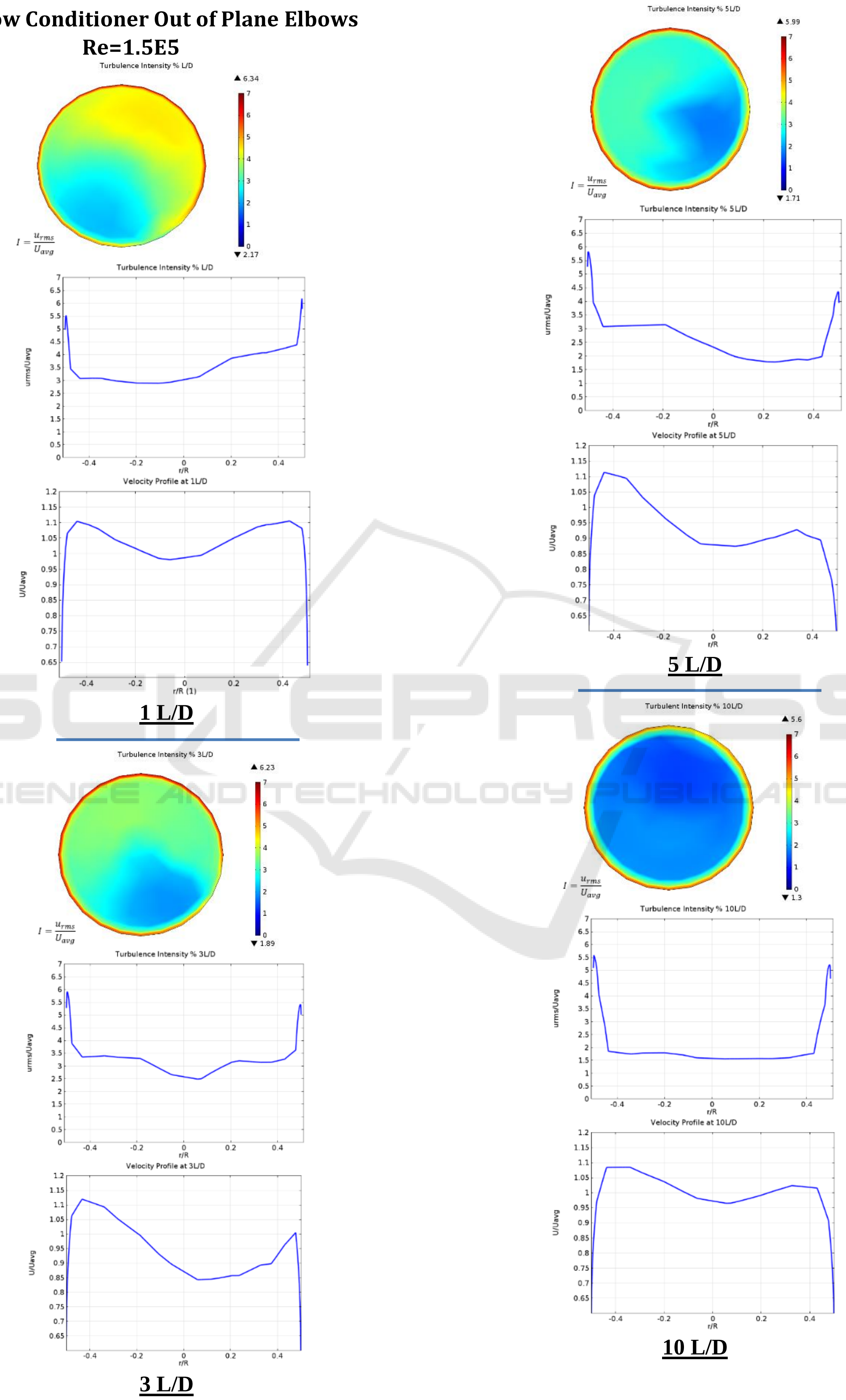


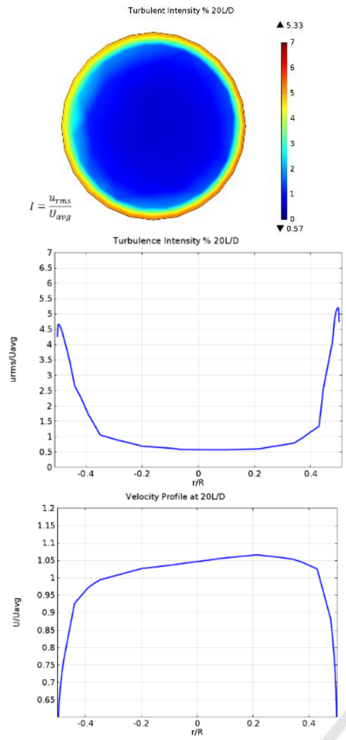

**Double out of plane 90° elbows (Without flow conditioner)**



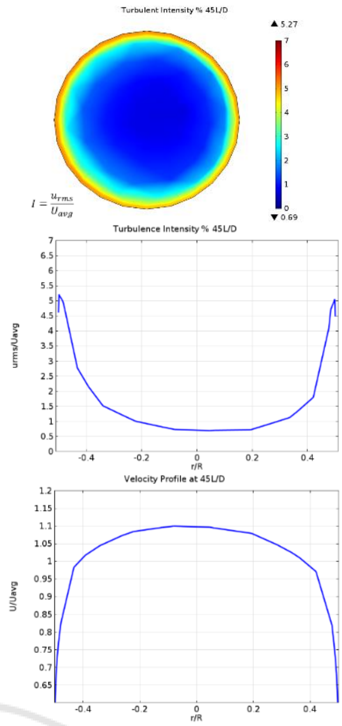

**Flow condition upstream of Disturbance**

**No Flow Conditioner Out of Plane Elbows**
**Re=1.5E5**

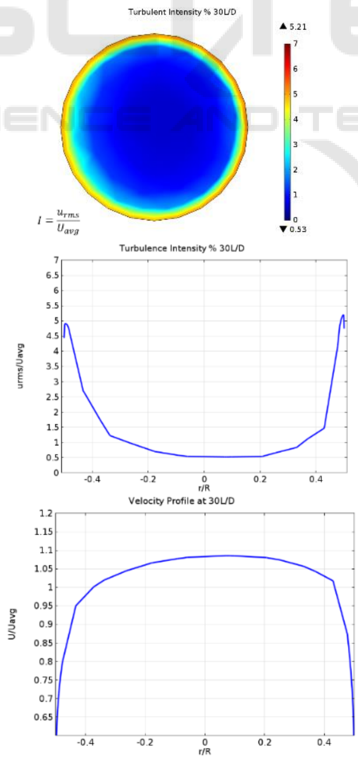





**20 L/D**




**45 L/D**




**30 L/D**

**Double out of plane 90° elbows Velocity Profile & Turbulence Intensity (Without flow conditioner)**