The Effects of Geometry on Flexible Duct CFD Simulations

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ABSTRACT

Flexible ducts have been widely used in the building industry due to low cost and ease of installation. These ducts can be installed in a wide range of configurations, which creates a challenge for pressure loss calculations. Computational fluid dynamics (CFD) simulations allow variable configurations and are emerging as an alternative to laboratory measurements. Issues with the CFD simulations of flexible ducts have been modeling the complex geometry and the computational requirements to complete a simulation. In this study, five 8" diameter 15% compressed duct geometries were modeled including: periodic-triangular (PT), helix-triangular (HT), periodic-circular (PC), helix-circular (HC), and periodic-double-triangular (P2T). These modeled duct shapes were compared to determine the complexity of modeling and computational requirements. The performance of each model was determined based on the agreement with the measured data. The difference of static pressure differentials between PT and HT geometries was within 3%. Similarly, static pressure differentials between PC and HC, geometries were also within 3%. These results suggested that simulating the helix, which is the actual geometry of flexible ducts, had negligible effect on the results. In addition, simulation results of the models with triangular wall geometry were within 50% closer agreement to measured data than the circular wall geometry. The results suggested that periodic-double-triangular (P2T) geometries, which are also more computationally efficient, can be used in 8" diameter 15% compressed flexible duct simulations. The calibrated CFD model can then be used for various duct configurations.

INTRODUCTION

Flexible ducts have two major advantages over metallic ducts. These ducts are faster, less costly, and more flexible to install when compared with metallic ducts. The internal structure of flexible ducts, which produces these advantages, is also the source of higher pressure losses than metallic ducts. Weaver and Culp (2007) studied 6", 8" and 10" diameter flexible ducts for various compression factors and sag conditions. They showed that sags as small as 2.5" per 5' long duct significantly increase duct pressure losses. In reality, flexible ducts are installed in various degrees of sag, bend, compression conditions. Existing resources, which are limited to few configurations, include ASHRAE Handbook of Fundamentals (ASHRAE, 2005), the Air Conditioning Contractors of America's (ACCA) Manual D, and Air Diffusion Council's (ADC) *Flexible Duct Performance and Installation Standards*. Properly designing flexible duct systems requires determining pressure losses in a wide variety of conditions. Improperly designed or installed flexible ducts increases energy consumption and comfort problems while decreasing equipment life (Taghavi et al, 2007).

CFD, which is a numerical analysis of fluid flow, is emerging as an alternative to laboratory measurements in determining pressure losses in flexible ducts. A well-designed CFD model allows accurate airflow simulations and is a faster and less costly method when compared to laboratory testing. Shao and Riffat (1995a, 1995b) calculated the k-factors and pressure losses at duct fittings, including the elbows, using the standard k-ε turbulence model. Koskela (2004) also utilized the k-ε model to simulate air distribution at duct nozzles. In more recent studies the k-ε model was used by Rechia et al (2007) to simulate rectangular straight duct airflow and by Taghavi et al (2007) to simulate airflow in flexible ducts. Uğursal and Culp (2006, 2007) showed that the standard k-ε CFD model was able to predict pressure differentials in some configurations of flexible ducts within 5% of the measured data. In other configurations predictions ranged from 20% to 50% higher than the measured data.

In this study, the standard k-ε model was also used for the CFD simulations. The details of the k-ε model are explained in Fluent Inc. software documentation (Fluent 2005). The study addresses the discrepancies between the simulated and measured data. Early efforts of the 3-D modeling showed that wall geometry has a dominating effect on the pressure loss calculations. A parametric study of flexible duct geometry has been conducted and presented in this study.

METHODOLOGY AND 3-D MODELS

The presented study is a comparative analysis of simulated and measured data. The accuracy of the simulated data was determined based on the agreement with the measured data at which closer agreement indicates better performance of the simulation. Uğursal and Culp (2006, 2007) modeled an idealized blow-through condition of flexible duct with fully rounded wall geometries. The helix-circular (HC) model was compared to three other geometries including: helix-triangular (HT), periodic-circular (PC) and periodic-triangular (PT). In the last part of the analysis a fifth model, the periodic-double-triangular (P2T), was presented.

Simulations were conducted for five volumetric airflows ranging from 140 cfm to 300 cfm. Pressure differentials from three regions of different lengths were calculated and projected to fit to the in-H_2O/100' standard (Figure 1). Results from a 3' long section, which were free of end effects, showed closer agreement with the measured data. Therefore, a 3' section was used in the analysis.

The CFD models in this study used an 8" diameter, 15% compressed flexible duct, which was composed of one 5' long flexible duct section and two 2' long straight end sections (Figure 1). End sections were added to the model to emulate the laboratory setting. Fluent software required the inlet and boundary conditions (each end face perpendicular to the longitudinal axis) to be placed in a turbulence-free region. Gambit (Fluent, 2004a, 2004b) and Fluent (Fluent 2004c, 2005), two commercially available software packages were used in this study. The flexible duct geometries and the associated meshes were created using Gambit 2.2.30. CFD simulations were conducted using Fluent 6.2.16.

Flexible ducts were constructed with a polyester inner layer molded around a steel helix wire, an outer fiberglass insulation layer and vapor barrier. The helix core and polyester layers were modeled in the study to simulate the air flow. The helix core extended a distance of 1.5" along the central axis for each 360° full turn. The compression factors were determined based on the contraction from the fully stretched condition.

This study focuses on pressure loss comparisons between the helix-circular (HC), the helix-triangular (HT), the periodic-circular (PC) and the periodic-triangular (PT) structures. A total of five geometries were created for the study (Figure 2). Figure 2a shows the idealized blow-through fully rounded HC structure. The idealized condition was used to reduce the geometric complexity of the flexible duct. In physical ducts, the flexible duct wall geometry is characterized by irregularities. The HT structure (Figure 2b) more closely represents real inner layer conditions than the HC structure. Figure 2c and 2d show PC and PT structures which allow a simpler geometric formation by eliminating the helix geometry. Periodic structures also have the potential to be simulated in 2-D due to the axis-symmetric geometry. Figure 2e presents the P2T structure which has two periodic elements between each modeled periodic wire.

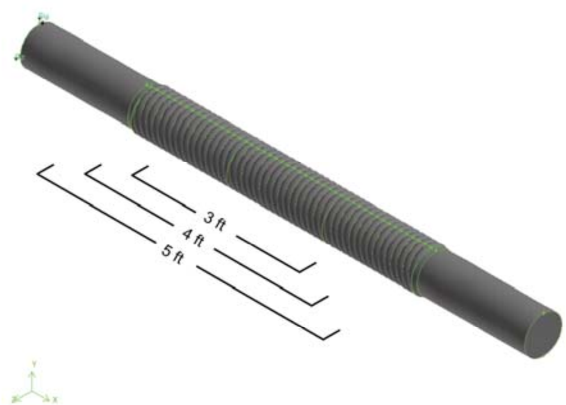

Figure 1. 3-D model of 9' long simulation domain.

RESULTS

Static pressure values were extracted from the data points which were placed on the central axis. The location of the data points corresponded with each 360º turn of the helix core for HC and HT. One data point was placed at each segment for PC and PT. Figure 3 shows the static pressure at each data point on the central axis. The static pressure increased when the duct profile changed from flexible to straight duct. The flexible section has a smaller effective diameter than the straight section due to the near-wall turbulence. The sudden increase in the effective diameter resulted in a drop in the air velocity which increased the static pressure. This situation does not affect the pressure loss calculations in the flexible section. Figure 4 shows the change in the static pressure values at each data point, which was calculated by taking the static pressure difference between the two preceding points. Figure 4 illustrates that pressure losses settled down to a repetitive value after 1.5' into the flexible duct which also indicates well-developed flow. Static pressure losses from the well-developed flow regime were used in the analysis.

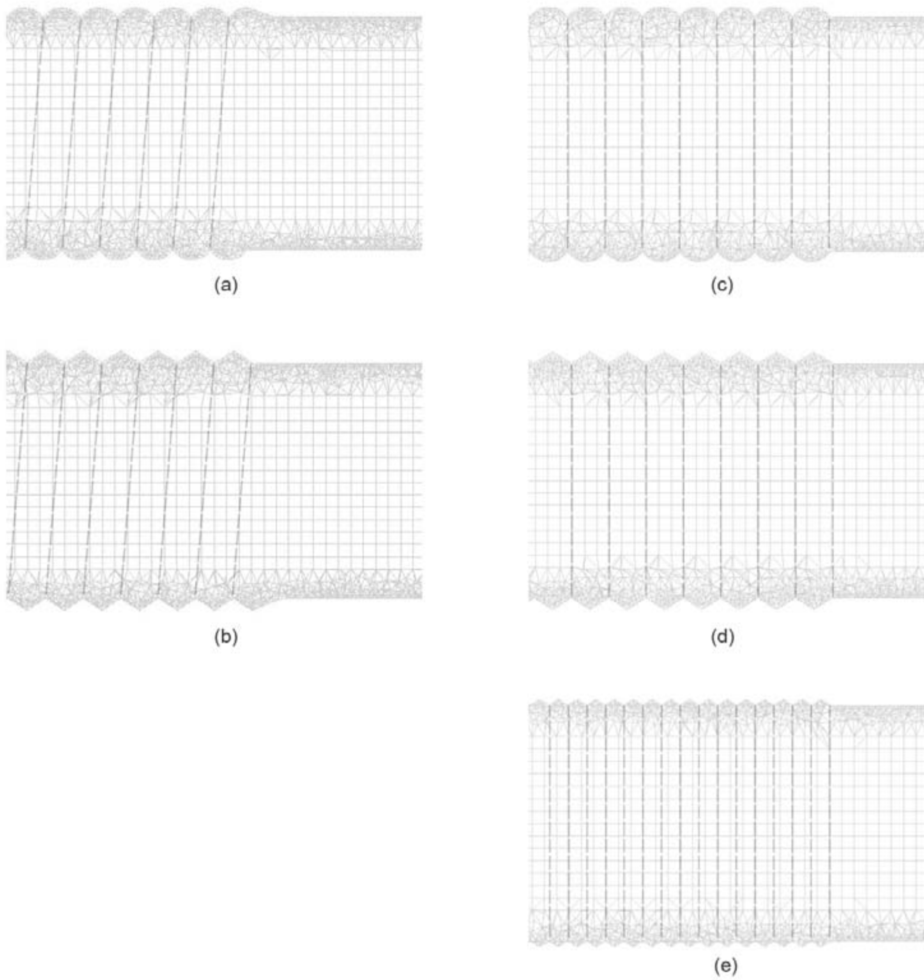

Figure 2. Wall geometries (a) Helix-circular (HC), (b) Helix-triangular (HT), (c) Periodic-circular (PC), (d) Periodic-triangular (PT), (e) Periodic-double-triangular (P2T)).

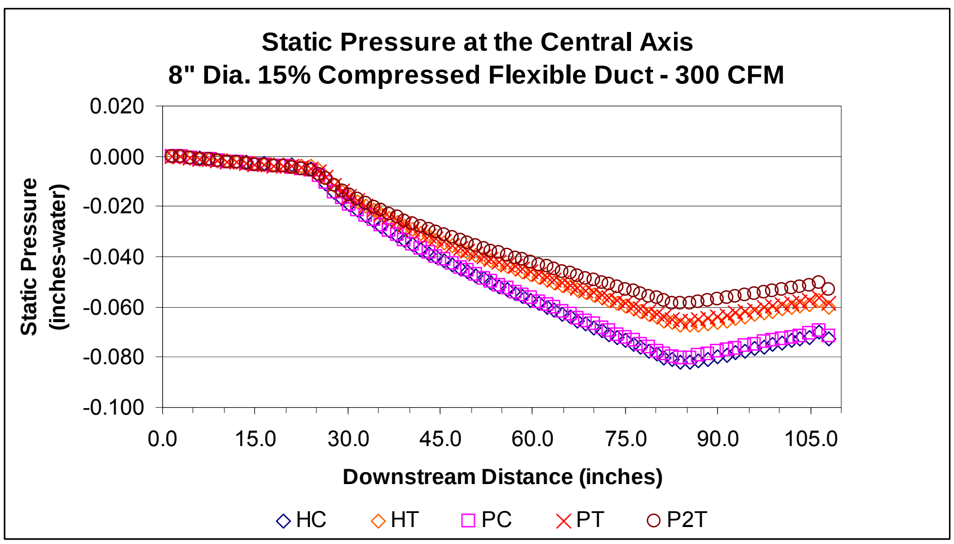

Figure 3. Static pressure at the central axis

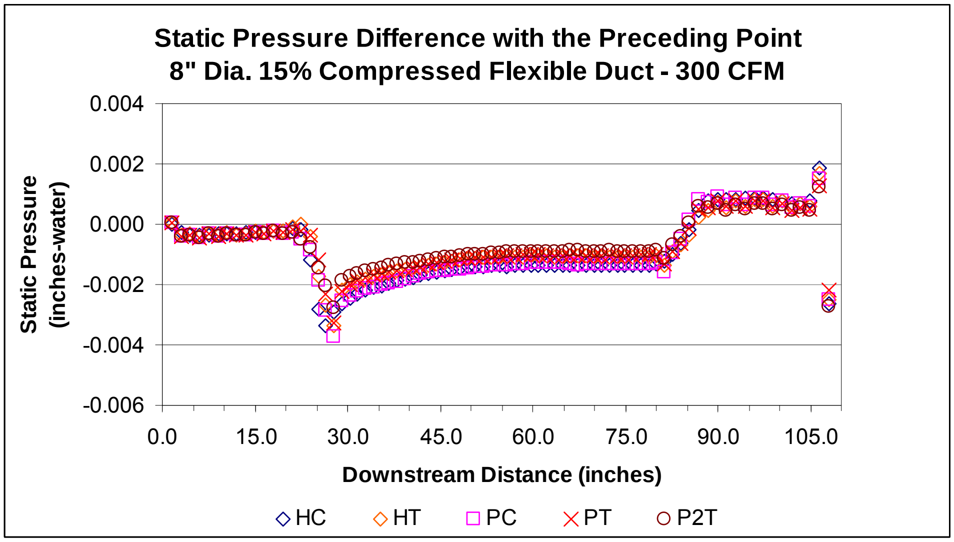

Figure 4. Static pressure difference with the preceding point at the central axis.

The measured and simulated static pressure losses (ΔP) at different volumetric airflows were calculated and presented in Table 1 and Figure 5. In the analysis, the first comparison was between the helical and periodic geometries. The difference between the HC and PC geometries was an average of 2%. Similarly, the difference between HT and PT was an average of 3%. Both values were within the margin of expected laboratory measurement error and therefore were negligible. The helical structure was similar to real-life conditions, however, the structure had minimal effect on the simulation results. The study showed that periodic structures can replace helical geometries. The advantage of periodic walls is that they are geometrically less complex and they allow 2-D CFD simulations due to their axis-symmetric character. The second comparison was between the circular and triangular walls. Figure 5 illustrates that triangular wall geometries yielded closer results to the measured data. The average improvement of PT over PC was 52%. The study was then extended to model a fifth flexible duct which was named P2T, where each segment had an extra cusp in the middle. The resulting geometry had double triangles in each segment. As shown in Figure 5, the average improvement by using P2T was 55% over PT. The main reason was that triangular geometries emulate flexible ducts which can be characterized with apices (Weaver and Culp 2007). The P2T structure emulated the irregularites of the inner liner of flexible ducts better than the PT structure.

A detailed analysis of air velocity, velocity pressure, and static pressure for HT and PT is presented in Figure 6. Pressure and air velocity values from cross sections at 0.255 in. intervals (five sections at each segment) were taken. Air velocity components on the x-coordinate (parallel to the central axis) were normalized based on the number of cells at each section, whereas static and velocity pressures were averaged. The air velocity fluctuates at each segment of the PT structure, as shown in Figure 6. There were minimal deviations within the helix core of the HT, indicating a smoother flow regime. Velocity pressure values clearly corresponded with the air-velocity profiles demonstrating fluctuation within the PT structure. Although minimal, static pressure was also affected by the air velocity. The study concluded from this analysis that although periodic geometry had certain effects on the flow character, the static pressure values were not affected. The resulting static pressure differentials were the same for both PT and HT.

Table 1
The measured and the simulated static pressure losses (ΔP) (inH$_2$O/100')

cfm	140	180	220	260	300
Lab Data	0.1845	0.3073	0.4620	0.6496	0.8661
HC	0.3383	0.5404	0.7779	1.0516	1.3641
HT	0.2674	0.4312	0.6229	0.8594	1.0933
PC	0.3290	0.5305	0.7584	1.0324	1.3368
PT	0.2587	0.4213	0.6041	0.8213	1.0686
P2T	0.2258	0.3617	0.5272	0.7215	0.9395

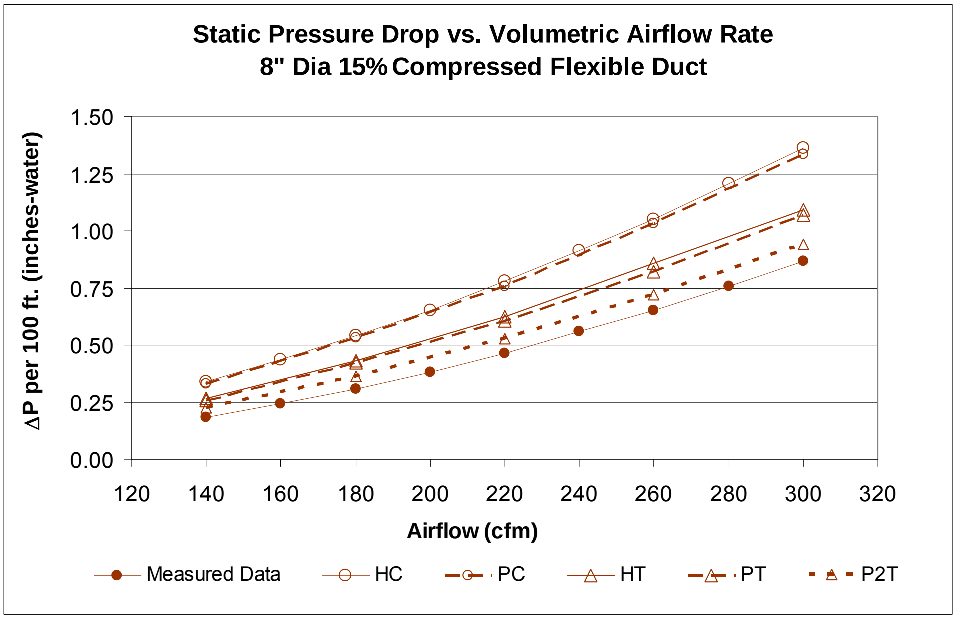

Figure 5. Static pressure differentials based on volumetric airflow.

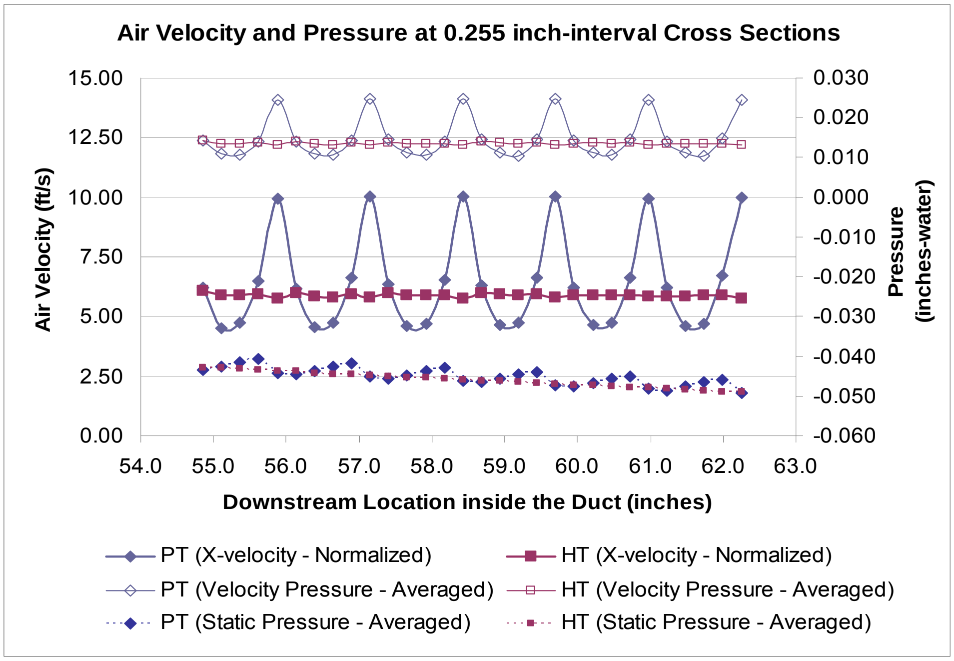

Figure 6. Air velocity, static pressure and velocity pressure at the cross sections of the flexible duct.

CONCLUSION

Flexible ducts have complex structures with irregular wall shapes. Due to the complex geometry, the 3-D model of the simulation domain had significant effect on the CFD results. Five combinations of wall and core geometries were simulated for five volumetric airflows in order to determine the optimum geometric domain for these complex flexible duct structures. Double triangular wall with periodic core structure (P2T) demonstrated the closest agreement with the measured data. The periodic wall geometry has the potential to be simulated in 2-D which is computationally more efficient than the 3-D simulations. Further study will use 2-D models as well as the P2T structure for 4% and 30% compressed flexible ducts. In conclusion, the P2T structure has been shown to be useful to simulate 8" diameter 15% compressed flexible ducts.

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