2018

CFD Case Study: Heat Exchanger Inlet Air Velocity Distribution for Ducted Tests in a Psychrometric Chamber (ASHRAE RP-1785)

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ABSTRACT

This paper presents the airside analysis of coil duct configurations using Computational Fluid Dynamics (CFD) to determine which configuration best mitigates airside maldistribution for ASHRAE RP-1785. RP-1785 has a global objective of providing accurate refrigerant charge and oil retention data for residential coils, collected in a controlled experiment. The final test matrix of the study includes several representative residential indoor and outdoor coils to be tested at various refrigerant and airside inlet conditions. The coil performance, charge, and oil retention behavior is strongly influenced by the airflow; therefore the uniform airflow distribution to coils is critical to RP-1785 to maintain a well-controlled experiment. Analysis of four 3D CFD cases are presented with the largest coil of the initial test matrix (105.6 in (268.2 cm) length, 40 in (101.6 cm) height, 5 in (12.7 cm) depth) installed in the Oklahoma State University psychrometric chambers. The simulation domain was extended to include the airflow characteristics within the psychrometric chamber to determine the effect of the asymmetric air inlet boundary condition. The analysis concluded the three significant factors affecting the airflow uniformity: the distance between the duct and wall, the distance between the duct and chamber floor, and the upward incoming airflow area of the floor. The CFD study results are used to inform the design of the duct to be used for coil testing in RP-1785 and the final duct design is presented.

1. INTRODUCTION

This study is a subpart of ASHRAE RP-1785 that has a global objective of obtaining refrigerant charge and oil retention data of round-tube plate-fin heat exchangers for a variety of condensing and evaporating mode operating conditions. The project subpart presented addresses the design of airside ducts and the duct design objective to provide uniform heat exchanger operating conditions. A test coil, placed in a specially designed air duct, uses a psychrometric chamber to provide uniform inlet air temperature and relative humidity. At the same time, refrigerant and oil pass through the heat exchanger at a controlled saturation and inlet temperature. Once the target steady state is reached, the weight of the refrigerant and oil can be individually measured by a specially designed differential mass measurement scale. The influence of airflow distribution on the resulting refrigerant and oil charge measurements are outside of the scope of RP-1785. Therefore, the design objective of the airside duct is to mitigate the amount of airside maldistribution to ensure confidence in the resulting test data.

Airflow and condition uniformity is critical to heat exchanger performance measurements. Wile (1947) has shown that non-uniform temperature distribution along with non-uniform velocity distribution lead to problems with heat exchanger capacity measurements. Wile suggested the use of air mixers (horizontal/vertical) which consist of a series of vanes arranged to divide the airflow into a number of small streams and then divert these streams across each other. ASHRAE Standard 41.1 (1986) pointed out non-uniform velocity as a cause of failure to obtain heat balance and recommends several mixers for non-uniform airflow. ASHRAE Standard 41.2 (1987) shows airflow measurement procedures and additionally suggests straighteners as an effective tool to produce a virtually uniform flow.

Payne *et al*. (2003) observed that the airside non-uniformity can result in a large reduction in heat exchanger capacity, as much as 30 % in extreme cases. Similarly, Blecich (2015) found that severe non-uniform airflow can deteriorate the effectiveness of the fin and tube heat exchangers up to 30%. Both studies highlight the importance of uniform airflow for fin and tube heat exchanger tests.

The suggestions in ASHRAE Standards 41.1 and 41.2 unfortunately cannot be applied if coils are folded into 3 or 4-sided configuration or have a length that is approximately 40% of the available room width. The psychrometric rooms to be used for this study do not qualify as a result of the latter qualification from these standards. Therefore, the present study uses CFD to investigate how ducts should be designed in order to have uniform airflow within a limited psychrometric chamber space.

In the CFD analysis, a test coil (OC*) with a tube length of 105.6 in (268.2 cm), typical for high efficiency residential outdoor units, was used as the worst case. It is expected that the air passing through the large coil may be uneven due to the fact that the coil size is relatively large compared to the flow measurement infrastructure and the psychrometric chambers. It should be noted, that the test plan was later changed to include a shorter outdoor coil, OC3, to replace this large coil, as shown in Table 1. While the coil dimensions analyzed it is expected that the results are relevant to duct design for the final duct designs selected. The final section of this study uses the results of the CFD analysis for the duct design of IC1, the first coil to be tested in this project.

Table 1: Selected coil matrix for ASHRAE RP-1785

Coil Name	IC1	IC2	OC1	OC2	OC3	OC*
Tube Length, in (cm)	17.5 (44.5)	17.5 (44.5)	48.0 (121.9)	48.0 (121.9)	72.0 (182.9)	105.6 (268.2)
Coil Height, in (cm)	16 (40.6)	28 (71.1)	30 (76.2)	34 (86.4)	48 (121.9)	40 (101.6)
No. Tube Rows	3 row	3 row	2 row	2 row	2 row	N.A.

2. MODELING

A CFD simulation tool was developed for analyzing airflow and designing ducts installed in a pair of existing psychrometric chambers. This model covers a computational domain including the psychrometric room(s), a coil, and ducts. First, chamber's air circulation and its details are described; and then various duct inlet airflow configurations are explored using this tool with the computational details presented. In the real chamber, air moves through the chamber ceiling, but in this simulation, all air is assumed to pass through the duct without going through the ceiling. While this is the limitation of this simulation, the analysis can suggest the flow characteristics in the psychrometric chamber with the test duct in place and inform design decisions.

2.1 The computational domain (the psychrometric chamber)

These series of experiments will be performed in the existing psychrometric chambers at Oklahoma State. These chambers are a pair of fully-controlled psychrometric chambers which are adjacent to one another (one indoor and one outdoor) and can be operated independently or in parallel depending on needs. The outdoor room and its flow measurement bay (code tester) will be leveraged for these series of experiments. The airflow for the coil testing facility is generated using the flow measurement bay of the psychrometric chambers. Typically the flow measurement bay is used to measure unit airflow and create specific static pressure for a unit that is under test in the psychrometric chamber. The flow measurement bay will be used to measure airflow across a coil as well as generate the required airflow by connecting a custom ducting system to the code tester. The psychromteric chamber's top view are illustrated in Figure 1 that highlights the major components in the room including the conditioning loops and the flow measurement bay. Air flows from the conditioning bays into the room where it is directed toward the coil under test and into the flow measurement bay. The coil[1] and duct are placed in the middle of the room to accept the conditioned airflow.

[1] Coil tube length initially determined by ASHRAE RP-1785 Research Project Management Subcommittee

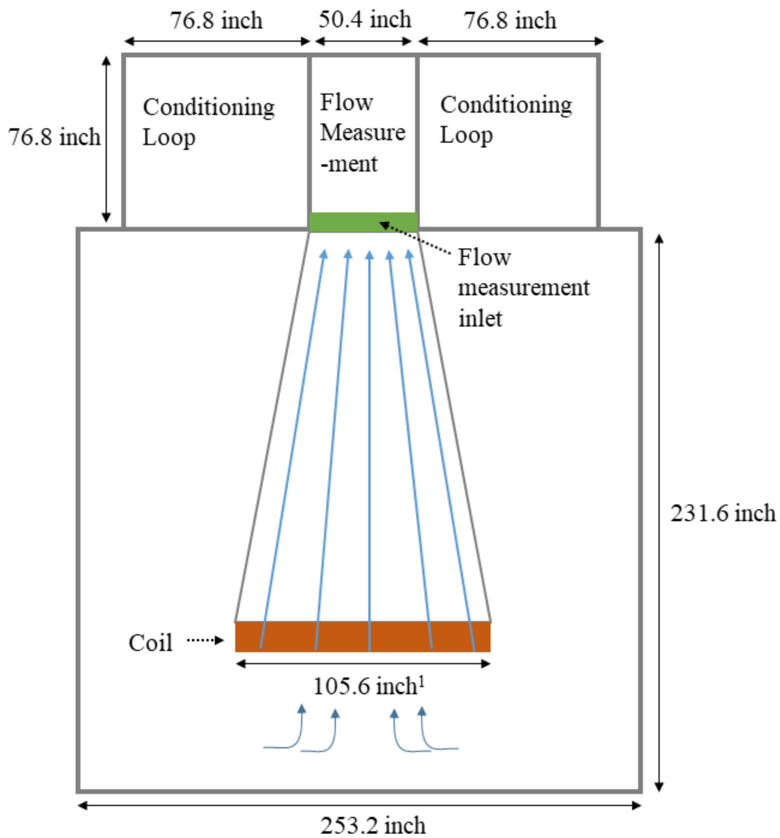


Figure 1: The psychrometric chamber's top view

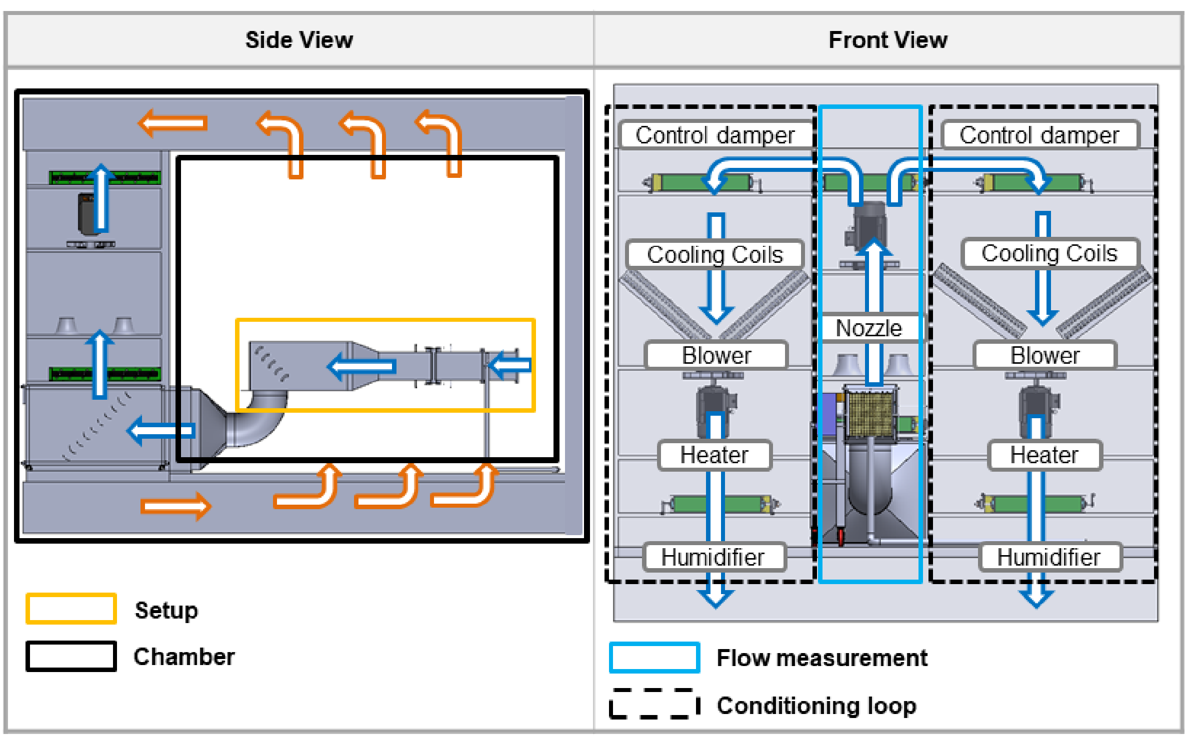


Figure 2: Air circulation within the chamber

The air circulation of the psychrometric chamber is detailed in Figure 2. Once air enters the setup through the inlet duct, it passes by test coils and the flow measurement bay. The flow measurement bay is located in between the two conditioning loops. The air that goes through the flow measurement bay and is then divided to flow through two conditioning bays. The conditioned air is then returned to the room through a perforated floor of the chamber. Some of the air re-enters the test duct/coil, the remainder rise to the ceiling and is brought back to the conditioning bays through the ceiling plenum. The air that goes through the ceiling is merged with the air that goes through the flow measurement bay, and the air circulation process mentioned above is repeated during the psychrometric chamber operation.

2.2 CFD simulation

The domain previously described including the psychrometric chamber, the coil, and the duct are included CFD simulation. This study uses Ansys CFX 18.2 Academic version and generated a total of 485,000 meshing elements for this simulation. Steady state full 3D simulations are performed with air at 25℃ and 1atm. This simulation is an isothermal flow analysis. K-Epsilon turbulence model is used. The duct outlet is the domain outlet boundary condition having forced flow (3,000 cfm). The floor incoming airflow is the domain inlet boundary condition with zero relative pressure. The coil and settling means (steel mesh) are approximated as isotropic porous medium, with increased mesh resolution within the medium. A standard fluid-porous interface type is used as a boundary condition between regular fluid domain and the isotropic medium. Additional information about the computational domain is shown in Figure 3.

To explore various duct design options a series of four duct design configurations were explored and the mal-distribution quantified for each case. The detailed descriptions about four CFD cases are shown in Figure 3 and 4. Case A1 was designed to represent the most ideal configuration possible and has the longest duct length, so the air flow is expected to be the most uniform in these cases; hence A1 is used as a reference case. It should be noted that case A1 is a hypothetical scenario where the duct is not constrained by the length of just the outdoor psychrometric chamber but allowed to extend into the adjacent sister chamber. While there was not an intention to do this, this allows a basis of comparison against a more preferred orientation.

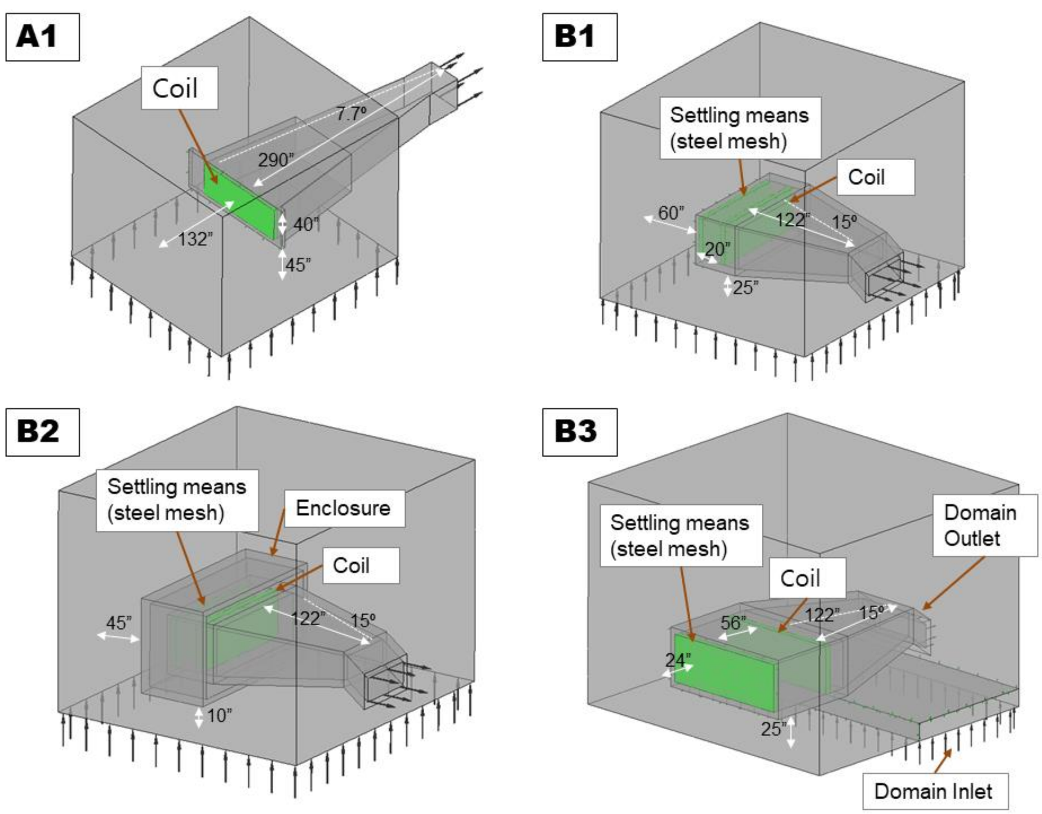


Figure 3: The CFD domain of the four cases highlighting the CFD domain and inlet and outlets of the domain

Case B1 is the base case for using one chamber, the outdoor chamber. It has a smaller stream-wise duct length than that of case A1. Cases B2 and B3 are the modifications of case of B1. Case B2 added an enclosure to the duct inlet of case B1 in order to reduce interference from external air and to obtain uniform airflow. Case B3 is made to control duct inlet flow by adjusting the distance between the chamber wall and the duct inlet, and the opening area of the floor to generate more uniform flow. This is attempted by blocking the half of the floor and the other half of the floor is opened. Additionally, case B3 ducting is extended toward the chamber wall.

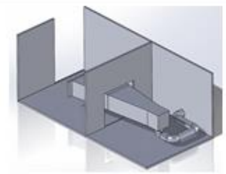
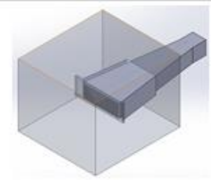
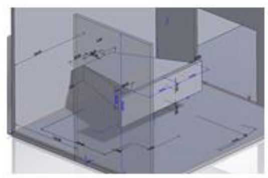
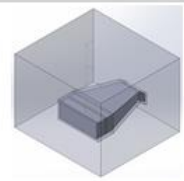
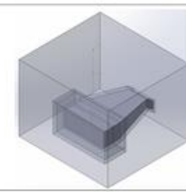
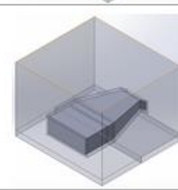
Name	Description	A vs B type	CFD Modeling	Note
A1	• The longest duct • Using outdoor and indoor chambers			The reference
B1	• Using only the outdoor chamber			B-type's base model
B2	• Using only the outdoor chamber • Adding enclosure to the duct inlet	↑		B1's modification
B3	• Using only the outdoor chamber • Extending the duct length • Adjusting floor inlet air flow	↑		B1's modification

Figure 4: Four CFD cases analyzed in this study.

3. RESULTS

For each case, the flow characteristics in the ducts and chamber were analyzed as velocity vectors and velocity contours. In addition, a numerical value of the uniformity of the airflow was introduced to quantitatively determine the amount of maldistribution of airflow. The four cases are compared and analyzed using this metric based on the CFD results.

3.1 Air flow velocity vectors and velocity contours

The air flow velocity vectors for each of the cases presented previously are compared in Figure 5. Subjective observation of case A1 in Figures 5 and 6 compared to the other cases suggests it does have the least amount of maldistribution. Comparing cases A1 and B1 in Figures 5 and 6, the air coming from the floor is directly entrained from the floor and passes into the inlet duct in A1 and B1 with minor mixing in the room. Case B1's top view and views in Figure 5 shows that centered air flow and the dead-zone in the edge of the duct. It is seen that there is an upward incoming flow from the psychrometric chamber floor to the inlet duct as well in case B1. In case B2, the air passing through the narrow enclosure is reflected and centered on the coil as shown in Figure 5 and Figure 6. These velocity vectors and contours suggest a high velocity concentration at the center of the coil with large dead-zones near the edge. Although case B2 has a subjectively maldistributed airflow in these results, it is possible that this configuration could be used for controlling airflow with the enclosure with the inlet duct; hence adjusting the shape of the enclosure shows the possibility of obtaining uniform airflow.

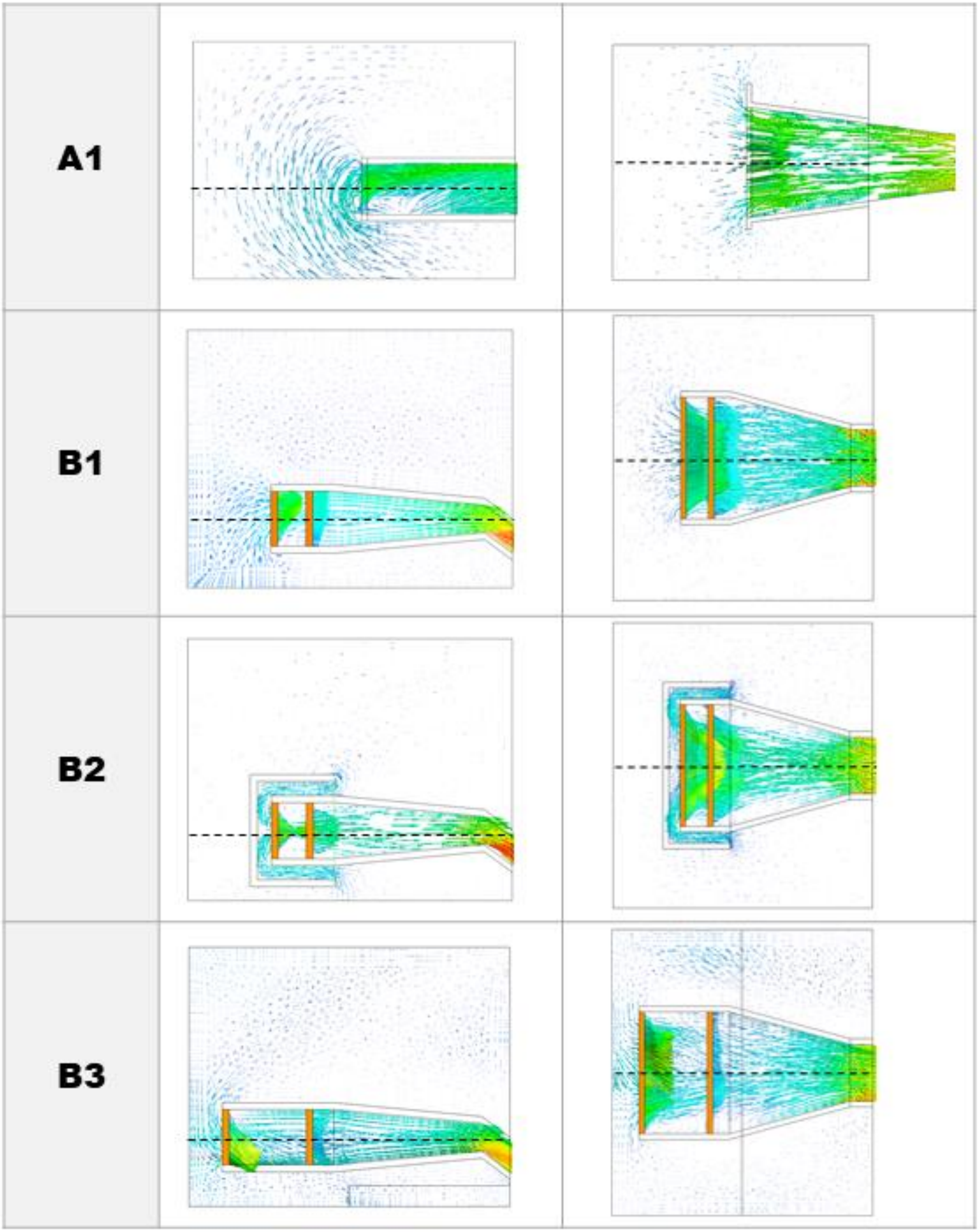


Figure 5: Vector contours, (Left) Side view at the center of the coils, (Right) Top view at the center of the coils
The dotted line represents the positions of the cross-sectional areas of each other

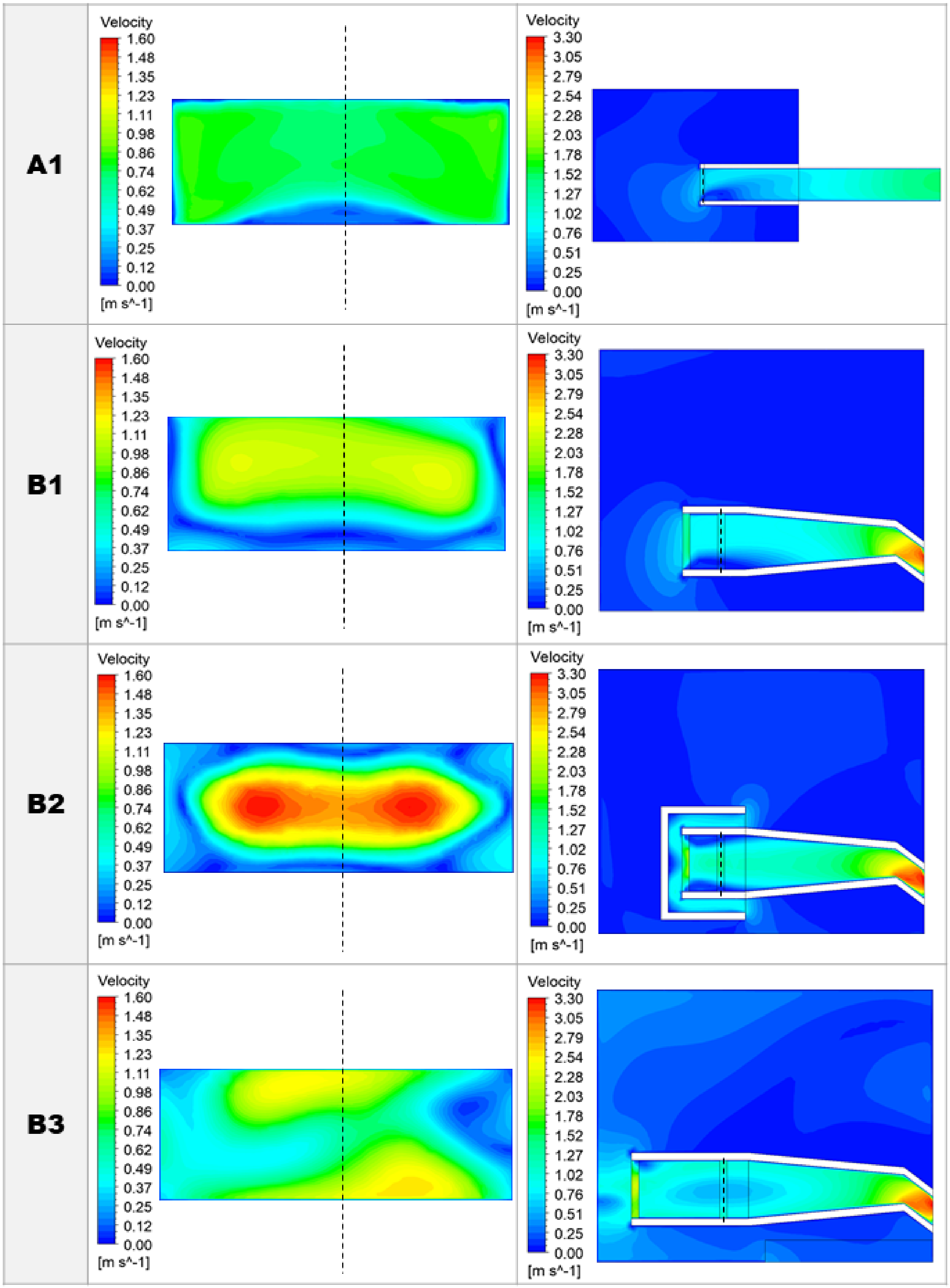


Figure 6: Velocity contour, (Left) Front view on the coils, (Right) Side view at the center of the coils
The dotted line represents the positions of the cross-sectional areas of each other

From Figure 5, Case B3 illustrates downward airflow near the duct inlet due to the blockage of the floor circulating airflow around chamber. Case B3 was designed to achieve uniform airflow by adjusting the airflow coming from the floor and the distance between the wall and duct. As a result, it can be seen that by adjusting the floor inlet area, the airflow directly entrained from the floor disappears. In addition, although the flow is not uniform, such as case A1, it can be seen that the flow is dispersed unlike the cases B1 and B2 where the flow was centralized; hence, this shows the possibility of the control of the inlet duct air flow by adjusting the airflow coming from the floor and the distance between the chamber wall and inlet duct.

3.2 Numerical airflow uniformity evaluation

To qualify the subjective findings from the previous section a numerical value of the uniformity of the airflow is developed and measured using results from the CFD simulation. One hundred sampling points are randomly distributed on each coil with similar manner as shown in Figure 7. The standard deviation of the velocity on the coils are calculated resulting in the values shown in Figure 8. A lower standard deviation can be interpreted as having greater airflow uniformity and can be useful metric to determine how uniform the airflow is. In combination with the previously presented visual analysis this metric appears representative of airflow uniformity.

In addition, Figure 8 shows the standard deviation results normalized against case A1. Case A1 has the most uniform airflow on the coil among four CFD cases thanks to the long duct length. Although case A1 has the smallest standard deviation value among four cases, case B3 could be a good compromise in terms of the standard deviation of the velocity on the coils when using short length duct: case B3 has 41% more the value than the baseline case A1. This also means the possibility of having the value less than 141% of A1 in terms of the standard deviation if the duct geometry and position are optimized when using short length duct.

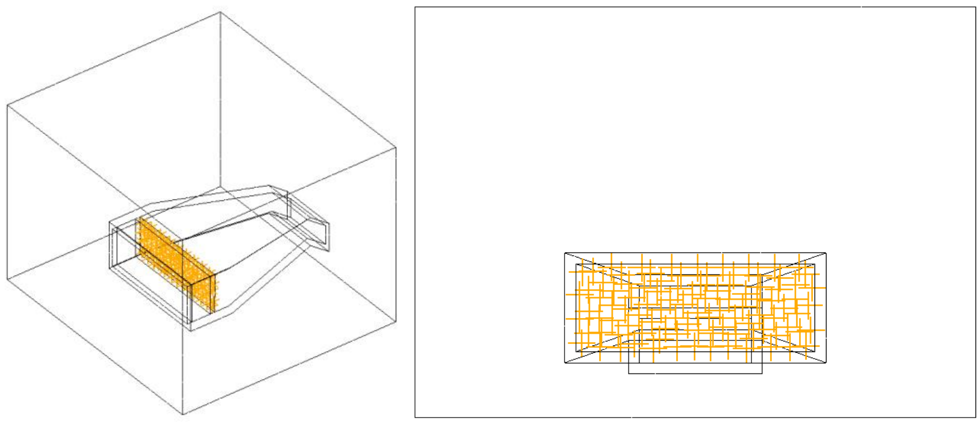
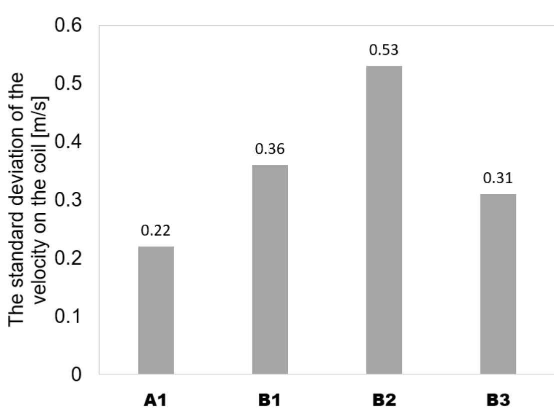
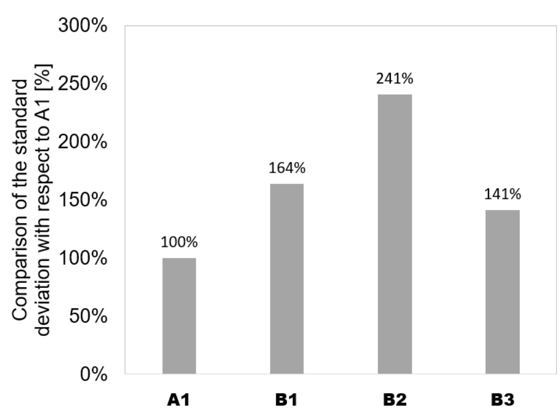


Figure 7 : Randomly distributed one hundred sampling points on the coil of case B1



a) The standard deviations (m/s)



b) Comparison of the standard deviations of the velocity on the coils with A1 as the baseline (%)

Figure 8: The standard deviations of the velocity on the coils of each cases

3.3 Duct design

A duct is designed for a test coil, IC1 (17.5 in (44.45 cm) tube length, 16 in (40.64 cm) coil height). The design is informed by the CFD analysis and shown in Figure 9. Since it was observed that the distances between the inlet duct and chamber wall, the distance between the duct and perforated floor play a role, the flexible tube and the turning vane are applied to the duct in order to allow moving the setup after it is installed, relative to the chamber walls to obtain more uniform airflow; the design has the same the distance between the duct and the wall as the case B3 shown previously.

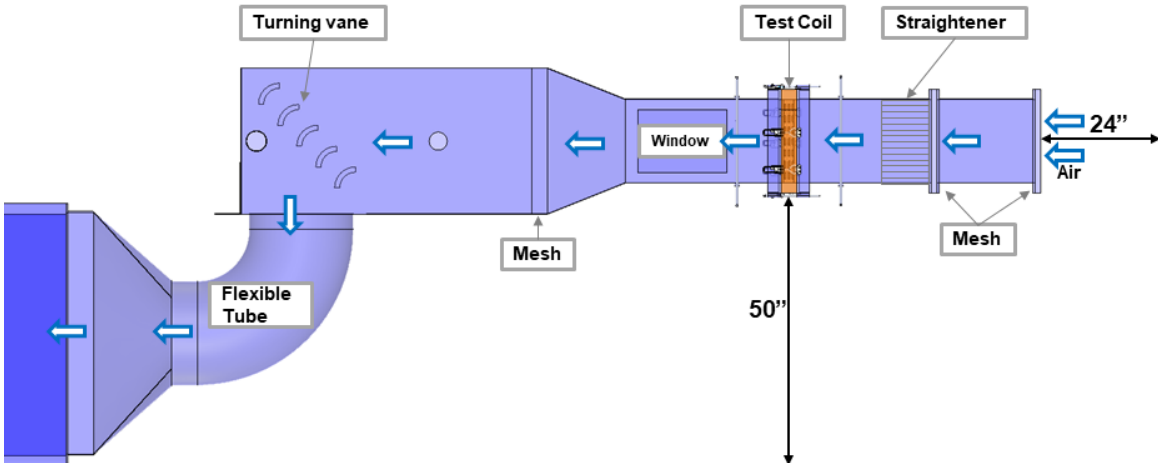


Figure 9: Duct design for IC1

6. CONCLUSIONS AND FUTURE WORK

As a preliminary study for ASHRAE RP-1785, CFD was used to investigate how to obtain comparatively uniform airflow on the large to be tested outdoor coils. The analysis presented became a reference to duct designs; hence, based on the CFD analysis the IC1 duct was designed. The conclusions of this study can be summarized as follows:

(1) From the CFD results, it appears that the distance between the duct and the wall can affect the airflow uniformity; thus, the duct design included a flexible tube between the duct and the nozzle bay that allows the distance between the duct and the wall to be adjusted.
(2) The chamber floor opening area has also been found to affect the airflow uniformity; therefore, experiments will be conducted by adjusting the floor area in order to have a uniform airflow
(3) To avoid direct entrainment of the airflow from the floor, IC1 duct was designed to be at least 50 in (127 cm) from the floor. The duct height is adjustable as well.

Following this study, the duct design presented will be constructed. This duct is equipped with additional straighteners and meshes to provide more uniform air flow. Additionally air uniformity tests for the ducts will be conducted to verify acceptable airside velocity uniformity. Custom ducts for the remaining four coils will then be designed and constructed using this simulation to inform them.

NOMENCLATURE

IC	indoor coils
OC	outdoor coils

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ACKNOWLEDGEMENT

This study has been funded by ASHRAE under project number RP-1785. We would like to thank PMS for valuable comments and support, Kishan Padakannaya (JCI) for his patience and support in selecting and manufacturing the coils, and Damon D. McClure(Harrison-Orr) for the manufacturing of ducts. We also appreciate the help of Gary Don Thacker, Gerry Battles, Omer Sarfraz, and Saad Saleem.