

Comparative CFD Analysis of Extended Plenum and Reducing Trunk Ductwork Systems in Heating, Ventilation, and Air Conditioning (HVAC)

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Abstract - Among the core components of a Heating, Ventilation, and Air Conditioning HVAC system, the ductwork systems convey conditioned air from central equipment to various required spaces within a building. Efficient duct design is crucial for minimizing pressure losses, reducing energy consumption, maintaining balanced airflow, ensuring adequate ventilation and enhancing the overall system performance. This comparative analysis employs computational fluid dynamics (CFD) to analyze and compare two widely used HVAC supply systems; the reducing trunk ductwork and the extended plenum ductwork. Identical airflow (1000 CFM) conditions and standard air properties for the real-life HVAC project were taken in the study. Both systems are modelled in 3D; steady-state, isothermal flow and viscous, $K-\omega$ Shear Stress Transport (SST) models are used to capture realistic duct flow behaviour in a simulation environment. Key performance metrics like airflow distribution, velocity and pressure contours, flow uniformity, and turbulence levels have been analysed. The analysis shows that the reducing trunk configuration provides more uniform airflow, even mass distribution, maintains a balance of pressure and velocity, and has lower pressure and energy losses compared to an extended plenum ductwork system. In contrast, the extended plenum ductwork system is simpler to fabricate and easy to design but suffers from an imbalance of mass flow and velocities at the outlets, and pressure accumulated at the end cap, resulting in comparatively more pressure and energy losses, while reducing trunk ductwork system provides balanced branch flows.

Key Words: HVAC, duct design, ductwork systems, airflow distribution, pressure distribution, CFD analysis.

1. INTRODUCTION

HVAC duct design mainly focuses on developing an efficient and cost-effective air distribution system that ensures proper indoor air quality, thermal comfort, and energy efficiency within a building. This involves optimizing duct size and ductwork systems to minimize pressure losses and energy consumption by ensuring uniform air distribution across all occupied zones and reducing noise and vibration levels within ASHRAE standards acceptable limits. The ductwork systems plays a critical role in the overall performance, like ensures optimal airflow distribution, minimizes pressure and energy losses, space optimization, cost-effectiveness and ease of maintenance and enhances energy efficiency an HVAC system. The two most common HVAC ductwork systems, the extended plenum system (a constant size trunk) and the reducing trunk system (trunk cross-section decreases after each branch), are used for duct layout. The extended plenum is popular for its simplicity and easy to install. However, if the trunk main duct is too long (generally >24 ft. for single end plenum and >48 ft. for double end plenum), airflow tends to accumulate pressure at the end, causing the farthest branches to get more flow. The reducing trunk system mitigates this by decreasing the trunk area after each takeoff, maintaining a more uniform velocity and pressure along the length. The analysis aims to quantitatively compare these two ductwork systems on a real-life project using the CFD method and examine airflow patterns, pressure losses, and turbulence etc.

The analysis is limited to steady; incompressible, isothermal airflow, heat transfer and time-varying effects are neglected. HVAC duct designers aim for energy-efficient systems; lower pressure drop means less fan power, with balanced uniform flow at low cost. The study incorporates both theoretical and simulation-based approaches to evaluate duct design configurations under realistic conditions, offering practical recommendations for improved HVAC system design. Recent advancements in modelling and simulation tools, such as Computational Fluid Dynamics (CFD), have enabled more accurate prediction and analysis of airflow characteristics within duct networks. These tools provide engineers and designers with a deeper understanding of pressure distribution, velocity profiles, turbulence effects, and system behaviour under varying operating conditions [10].

2. LITERATURE REVIEW

HVAC engineers are challenged to design air distribution systems with optimal performance while satisfying a long list of requirements, including maintaining the desired indoor air quality, thermal and acoustical comfort, minimizing energy usage, and life-cycle cost. One major part of the air distribution system is the ductwork system. The pressure drops in the ductwork system are vital to consider while designing it. In this regard, fittings generate substantial pressure losses in the ductwork system. Therefore, having the appropriate fitting design in the system is important to achieve a superior ventilation system. Pressure drop in the ductwork system can be reduced to optimize the shape of the fittings [1] and many numbers of fittings cause more pressure head loss, so try to be avoid the minimum number of fittings to be used in duct design [8]. Regional and national differences in construction cost and energy supply result in different costs for HVAC solutions. Due to the large field of possibilities and continuous price changes, many studies analyse a small set of variables to reduce calculation time. A few of these studies have examined the effect of heating and ventilation system parameters on life cycle cost (LCC) and energy use in detail [2]. An automated duct routing method which is able to connect air diffusers across space with the consideration of duct pressure balance, construction obstacles, air resistance reduction and minimizing construction costs. Treating air diffusers as nodal connections of a graph, the method uses a rule-based traversal algorithm (RBTA) and a fast resistance calculation model (FRCM) to generate the duct network [3]. Traditional manual duct design can result in fan energy waste due to duct network imbalance and human design error. Computer-aided methods are used to completely automate the HVAC duct system design process [3], [4]. The initial installation cost of each duct design using lower pressure ducts over a 15-year life cycle lower pressure ductwork system generally yield life cycle costs for savings, particularly in homes [5]. The selection of optimal air duct materials based on ASHRAE standards requires the construction of air ductwork from galvanized iron steel sheets, which is the conventional material. However, this material is expensive, and the cost is uncertain, difficult to install, and increases energy consumption, which makes the total project costly. Advancements in material science development have led to alternative materials for air ductwork that offer superior air diffusion characteristics. Alternative materials are more worthwhile than conventional materials due to the various benefits and cost reduction [6]. This research leveraged Dynamo to develop the Automatic Ductwork BIM Model Generation System to analyse HVAC system conflicts. This program can read CAD drawings to rapidly generate ducts with the appropriate size and elevation according to CAD drawings and constructs suitable duct fittings. It not only shortens the time and cost of BIM modelling but also minimizes manual errors [7]. In HVAC duct design, the main focus is on reducing head loss pressure by optimizing the duct design. External static pressure head loss depends upon the conditioned air flow rate, duct material, duct shape & size, duct fittings, duct takeoffs, ductwork system etc. The circular duct has low pressure head loss in comparison to the rectangular duct, but it has height and cost limitation [9]. In rectangular duct conditioned air conveyed from the main branch to supply branches at that time, most of the pressure lead loss occurs due to a 90-degree corner with a sharp bend, but it can be minimized by the use of y-shaped bend. For proper distribution of air guides, vanes may be used at corners, but it increases the costing of the system [10]. Many researchers have calculated the air (CFM) supply in an office building system using the McQuay Duct Sizer software [8], [14] to characterize the velocity and head loss in a round and rectangular HVAC ducting at various duct thicknesses and to optimize the thickness of the duct in an HVAC system according to ASHRAE standard [12]. Theoretical and software enabled tools to provide a detailed comparative analysis of the costs and benefits involved in selecting a particular shape (rectangular or circular) of duct for a prescribed situation [13]. Air distribution system performance can have a big impact on overall HVAC system efficiency. Therefore, air distribution systems face a number of mandatory measures and prescriptive requirements. Duct efficiency is affected by different parameters like aspect ratio, location, insulation, leakages etc. [14]. In a rectangular duct, there is more turbulence as compared to a circular duct [15].

Although the above-mentioned studies realize the importance of ductwork systems, they will also affect the velocity and total pressure head loss in HVAC duct design. Duct design can be further optimized through the selection of the most appropriate ductwork system for the specific application.

3. OBJECTIVES

The main objective is to comparative analysis (CFD) of an Extended plenum and a Reducing trunk ductwork system on a real-life HVAC project to investigate the key parameters affecting HVAC duct design and performance. It aims to evaluate the differences in the mass flow rates at all outlets and pressure accumulation at the end cap for both the duct systems and evaluate the pressure and velocity at all major points on the mid-plane along the streamline throughout the duct length as the basis of comparison for the duct systems under study.

4. METHODOLOGY

4.1 Geometry creation

The 2D and 3D geometry of both the ductwork systems are created in SpaceClaim geometry, according to the data provided by the HVAC consultant. In both the ductwork systems, air is passed from the AHU to the mouthpiece and then distributed in two opposite directional main ducts as shown in the geometry.

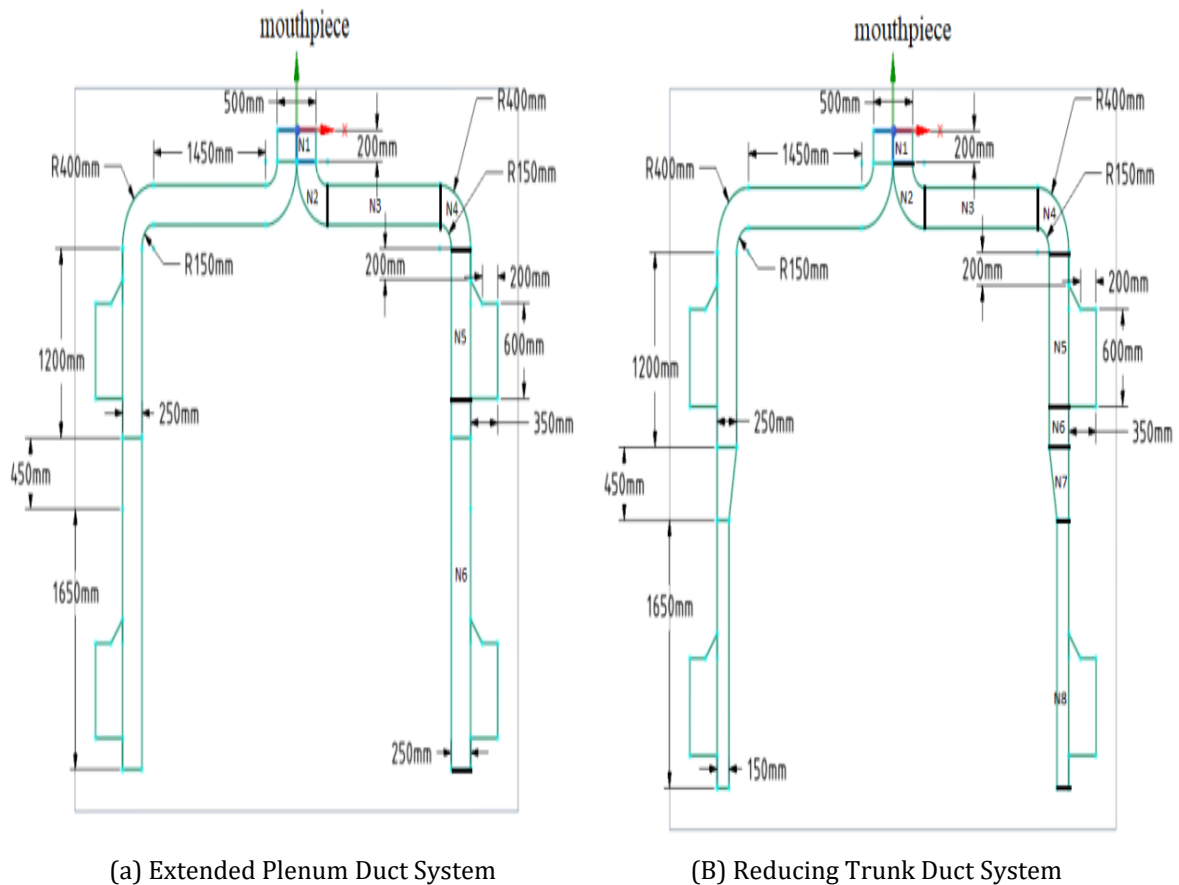
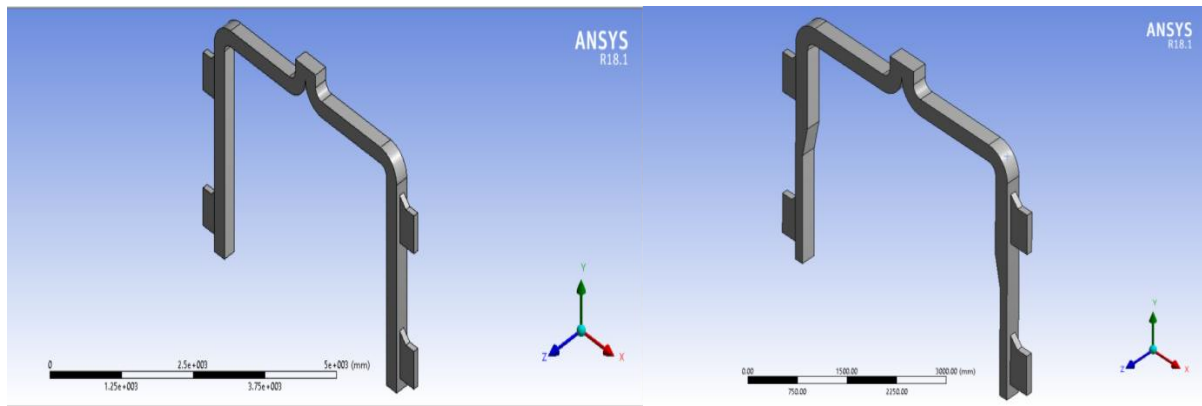


Fig- 1: 2D Geometry



(a) Extended Plenum Duct System

(B) Reducing Trunk Duct System

Fig- 2: 3D Geometry

4.2 Mesh generation

Meshing is a critical pre-processing step in CFD that defines how the fluid domain is discretized for numerical simulation. The accuracy, convergence, and computational cost of an ANSYS Fluent simulation heavily depend on the quality of the mesh. **Tetrahedral** mesh generated with 15 mm element size, is fairly uniform throughout the model, with finer meshing near bends and narrow regions, which is appropriate to capture flow gradients and structural variations.

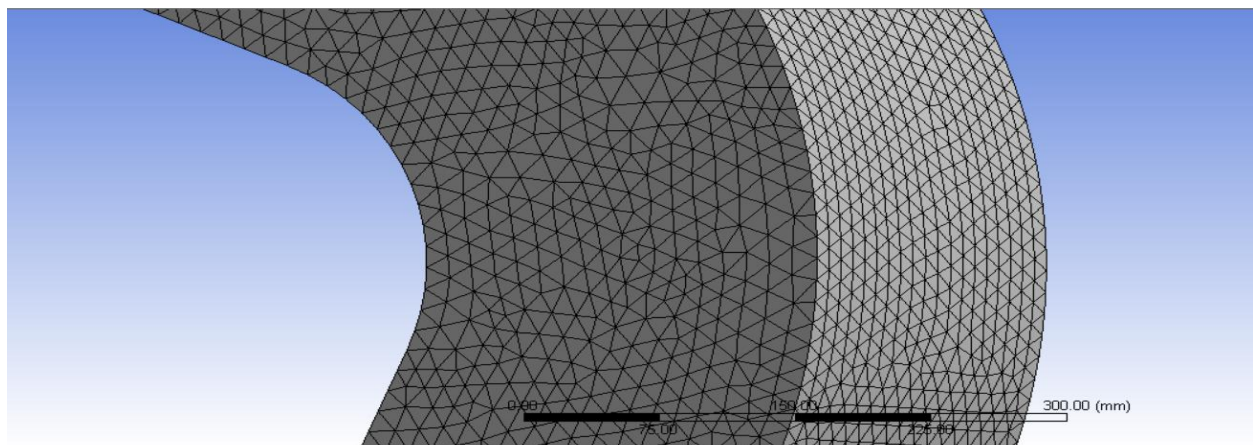
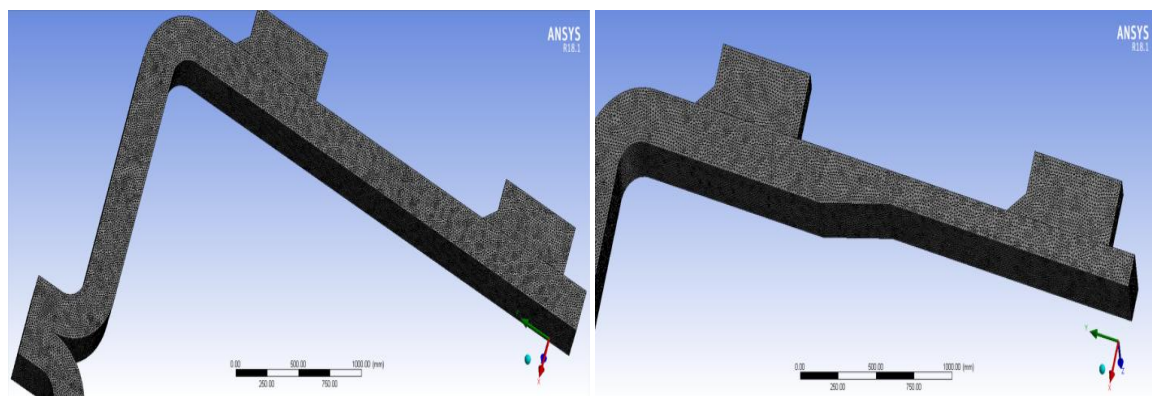


Fig- 3: Mesh Structure

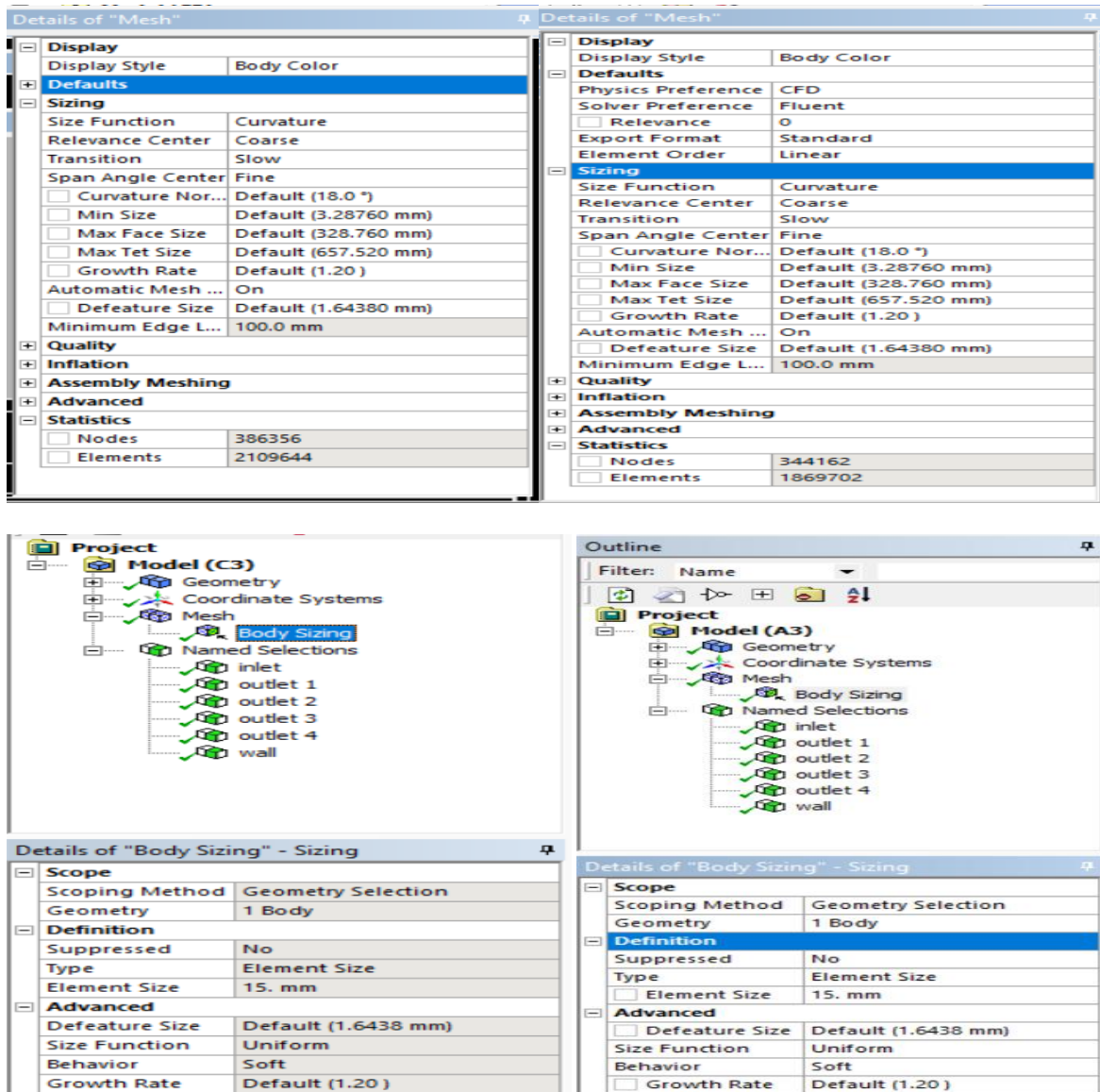


(a) Extended Plenum Duct System

(B) Reducing Trunk Duct System

Fig- 4: Mesh Model of both Duct Systems

4.2.1 Mesh Details



(a) Extended Plenum Duct System

(B) Reducing Trunk Duct System

Fig- 5: Mesh Details of both Duct Systems

4.3 Physics Setup

ANSYS Fluent pressure-based, steady was used. The flow was modelled as incompressible air (density $\sim 1.2 \text{ kg/m}^3$, viscosity $1.8 \times 10^{-5} \text{ Pa s}$) at 22 °C, neglecting buoyancy. The energy equation is on and applied viscous model, the $k-\omega$ SST model was enabled.

4.4 Materials

In the fluid domain, Air was used as an incompressible ideal gas with specified operating conditions and in the solid domain Galvanized Iron metal sheet is mostly used for HVAC duct systems.

4.5 Boundary Conditions

The input parameters and boundary conditions provided by the HVAC consultant are used. The selected AHU fan supplies **1000 CFM (0.472 m³/s)** of conditioned air at **70 pa** (external static pressure) corresponding to a uniform velocity of **4.8 m/s** at the inlet face of ductwork system. All four branch outlets were set at **0 (zero) Pa** gauge pressure, representing the diffusers exhausting to ambient conditions. Branches were sized by an equal friction method (**0.1 inch WC/ 100 feet**) to ensure even flow distribution; with each branch outlet designed to carry **250 CFM**. A dynamic mesh method was applied. The duct walls were modelled as no-slip and adiabatic. Key assumptions included no heat transfer (isothermal conditions), neglecting particulate or humidity effects, steady flow, and symmetrical branch flows. These assumptions simplify the analysis, enabling a focused comparison of duct layout effects.

4.6 Solution

A simple algorithm was adopted for Pressure-Velocity coupling, with the PRESTO! Scheme was applied for pressure in spatial discretization. Second-order pressure, second-order upwind momentum and Second-order upwind energy condition were employed.

4.6.1 Residual curve

This plot displays the residuals for each governing equation as a function of iteration number (0–700). The residuals indicate the extent of change in the solution from one iteration to the next. The simulation is nearly converged with residuals approaching constant values [10].

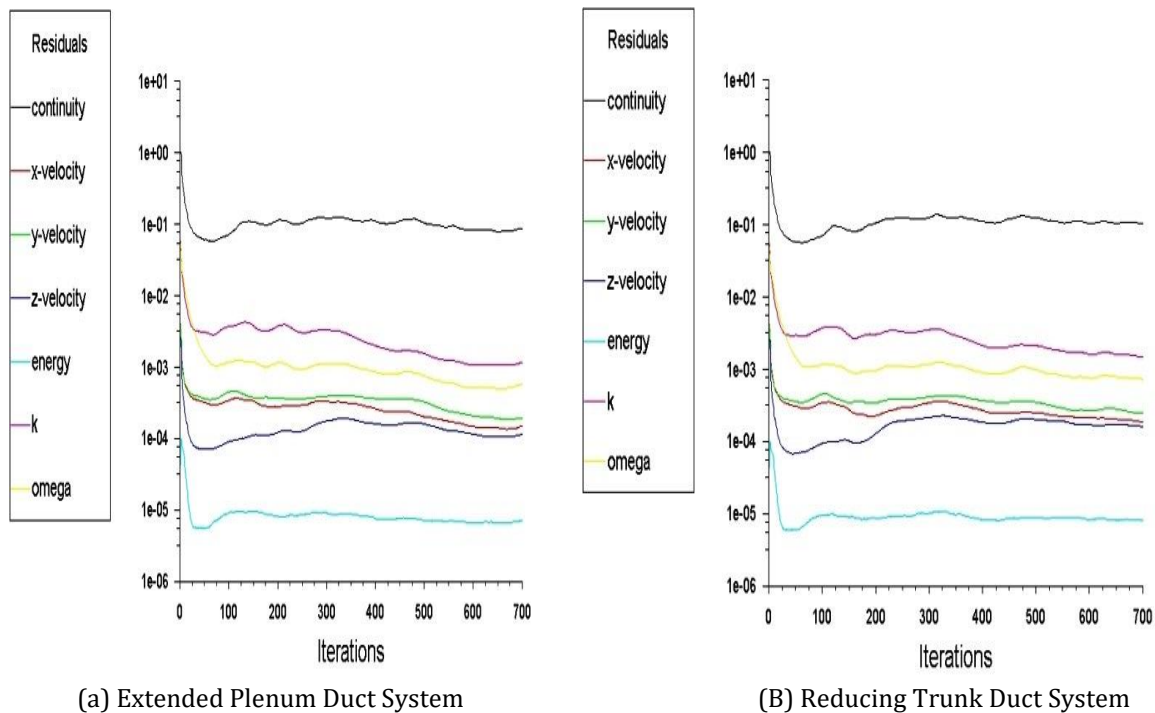
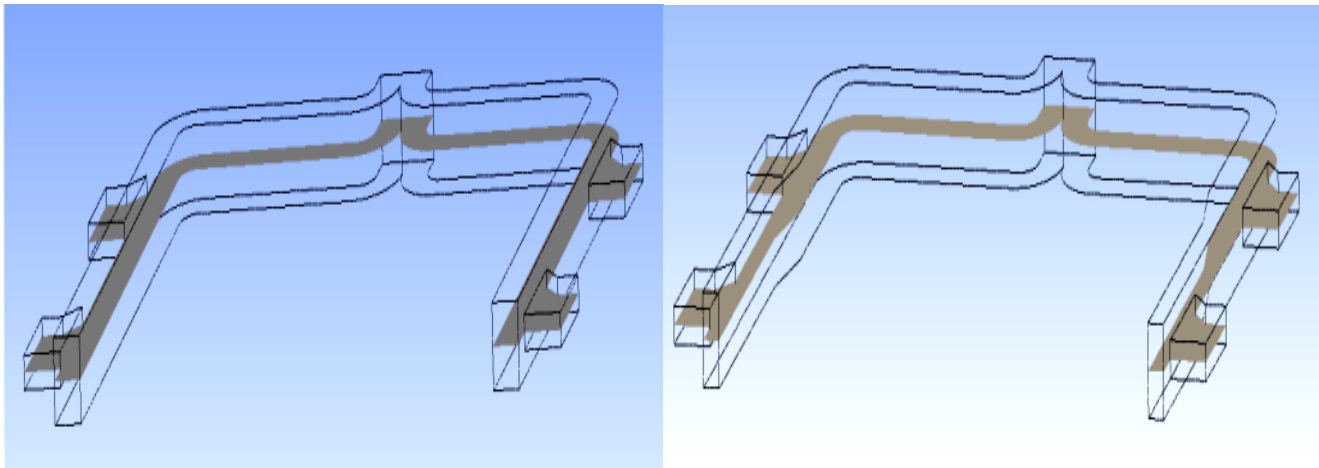


Fig- 6: Residual Curve for both Duct Systems

5. Results and Discussion

To obtain the variations in pressure and velocity contours results, a centre plane was taken at the mid height of both duct systems on the **XY plane**, as shown in figures.

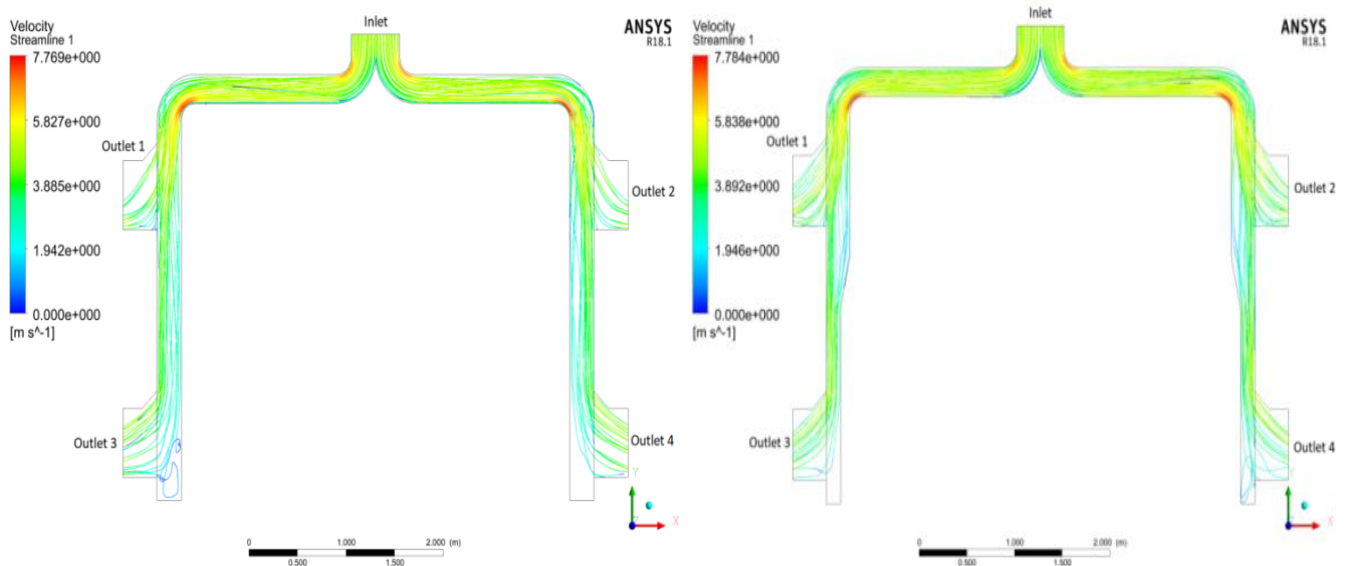


(a) Extended Plenum Duct System

(b) Reducing Trunk Duct System

Fig- 7: Centre Plane for both Duct Systems

5.1 Velocity Streamlines contour



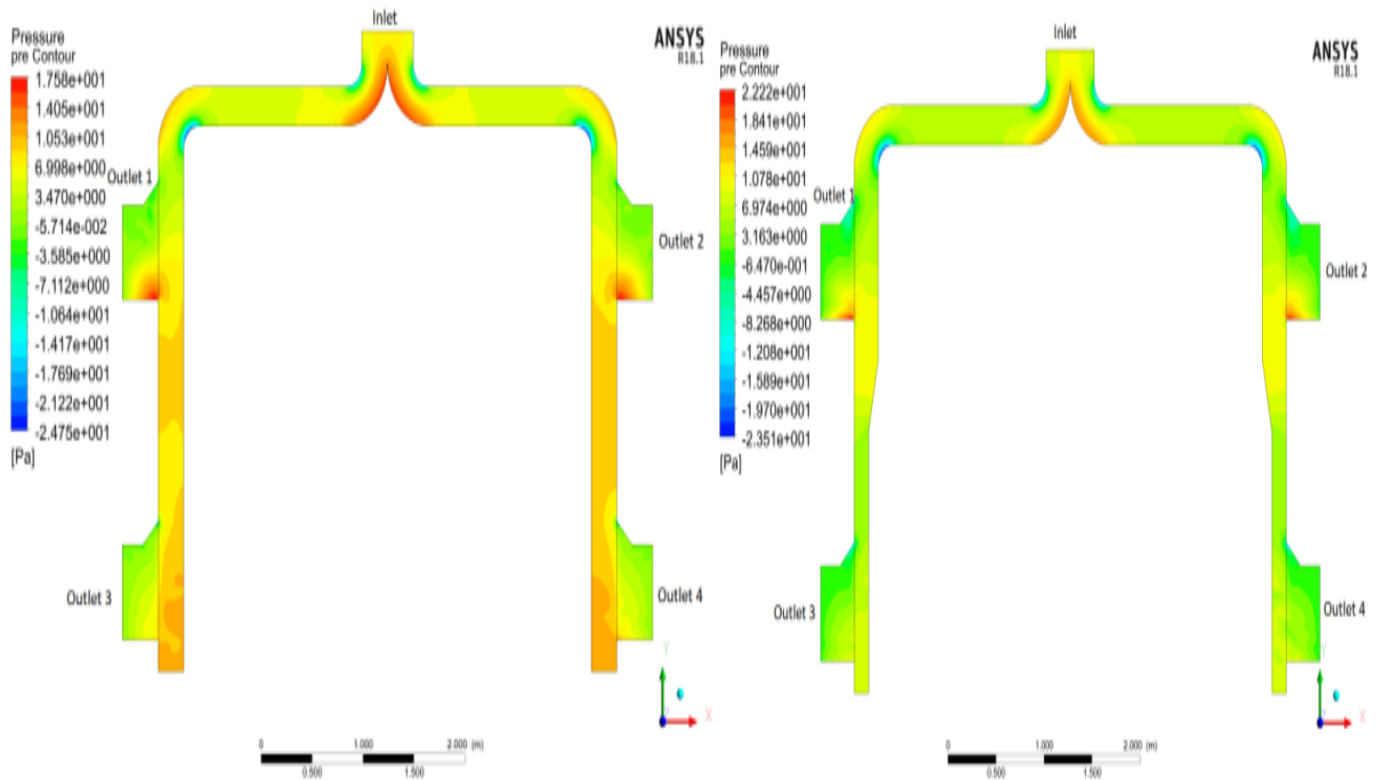
(a) Extended Plenum Duct System

(b) Reducing Trunk Duct System

Fig- 8: Velocity Streamlines Contour for both Duct Systems

Figure 8 shows that outlets 3 and 4 are almost fully filled with air in both duct systems, whereas outlets 1 and 2 in the extended plenum duct system are not as well filled, indicating uneven distribution and non-uniform airflow.

5.2 Pressure contours



(a) Extended Plenum Duct System

(B) Reducing Trunk Duct System

Fig- 9: Pressure Contours for both Duct Systems

Figure 9 shows that the reducing trunk duct system exhibits a more uniform pressure distribution compared to the extended plenum duct system.

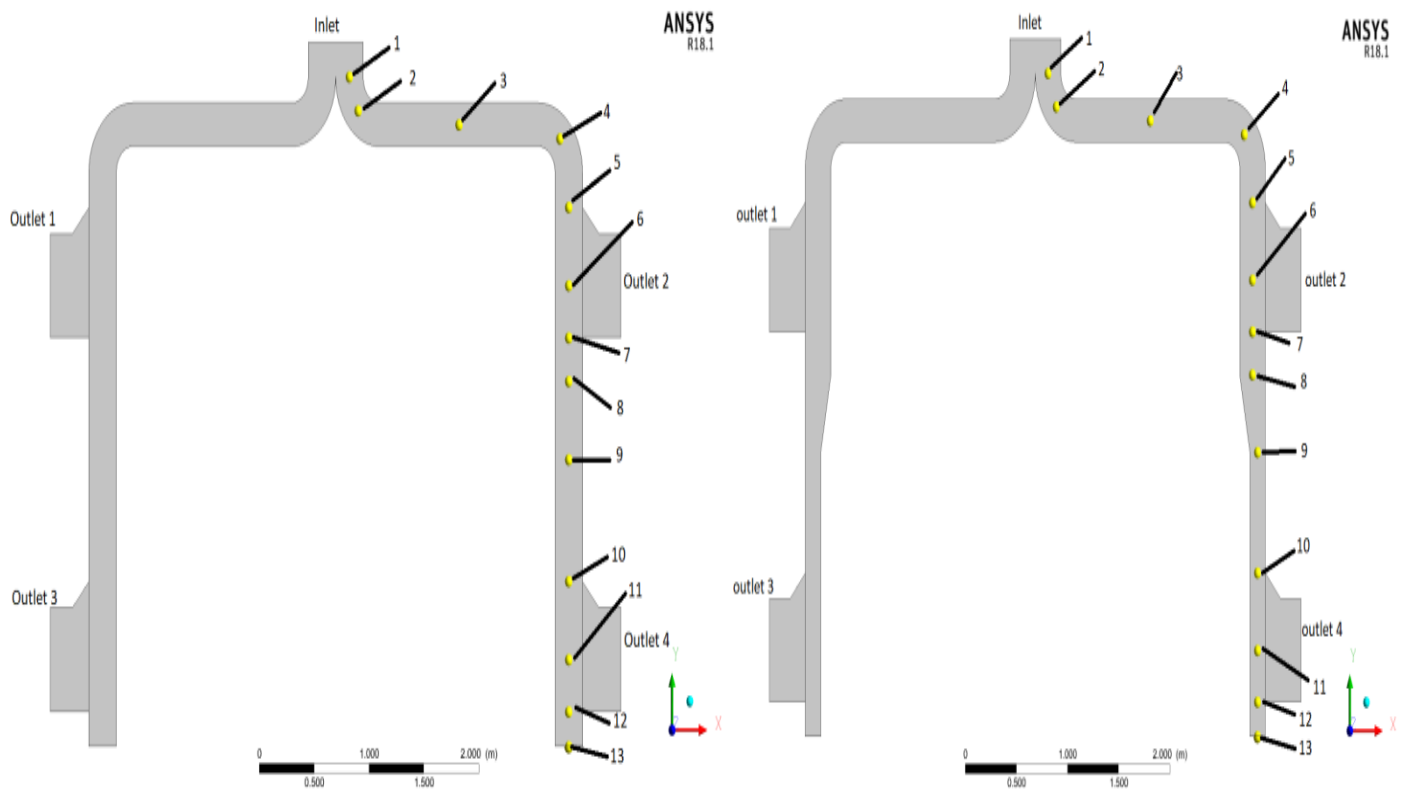
5.3 Pressure variation along the streamline flow on the centre plane for both duct systems

The following coordinate system was applied, with $X = 0$, $Y = 0$, and $Z = 125$ mm located at the centre of the inlet for both duct systems. We selected different points on only one side of the centre plane, from the inlet to the outlets, for both duct systems, because they are symmetrical about the XY and YZ planes; therefore, results from one half apply equally to the other half.

Table 1: Coordinates of Points 1 to 13 along the Streamlines on the Center Plane, from the Inlet to Duct End Cap.

Points	Extended plenum		Reducing trunk	
	X (mm)	Y (mm)	X (mm)	Y (mm)
1	125	-200	125	-200
2	205.55	-394.45	205.55	-394.45
3	1125	-475	1125	-475
4	2044.45	-555.55	2044.45	-555.55
5	2125	-950	2125	-950

6	2125	-1400	2125	-1400
7	2125	-1700	2125	-1700
8	2125	-1950	2125	-1950
9	2125	-2400	2175	-2400
10	2125	-3100	2175	-3100
11	2125	-3550	2175	-3550
12	2125	-3850	2175	-3850
13	2125	-4050	2175	-4050



(a) Extended Plenum Duct System

(B) Reducing Trunk Duct System

Fig- 10: Mark the Points on the Centre Plane from the Inlet to Duct End Cap for both Duct Systems

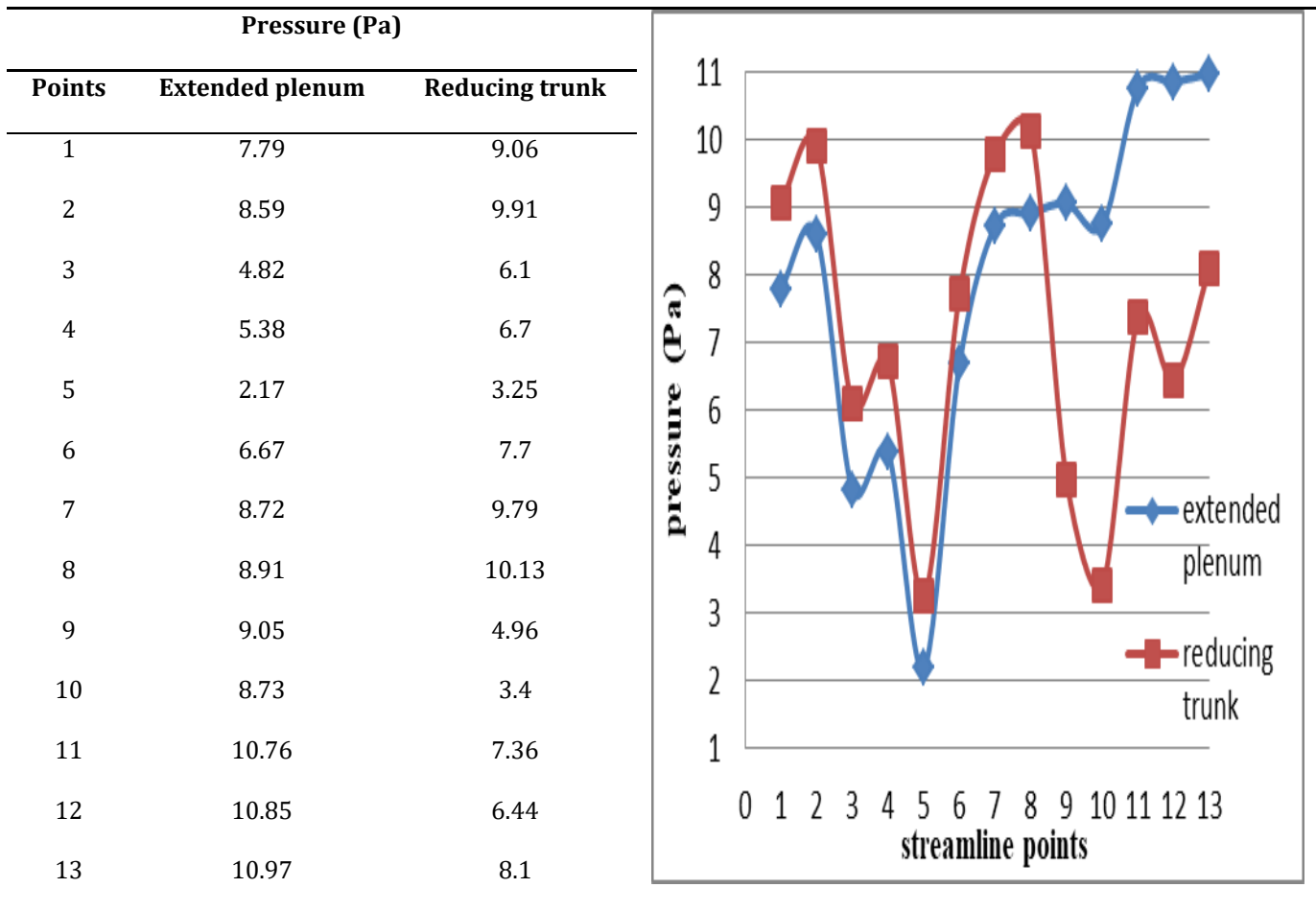


Fig- 11: Pressure Variations at Points 1 to 13 along the Streamline Flow on the Centre Plane for both Duct Systems

Figure 11 shows that in the extended plenum duct system, a comparatively greater pressure rise occurs after the first branch, creating an adverse pressure gradient. This effect can cause increased air recirculation and flow separation, leading to higher fan power requirements and energy losses.

5.4 Pressure at the Stagnation Point (End Cap)

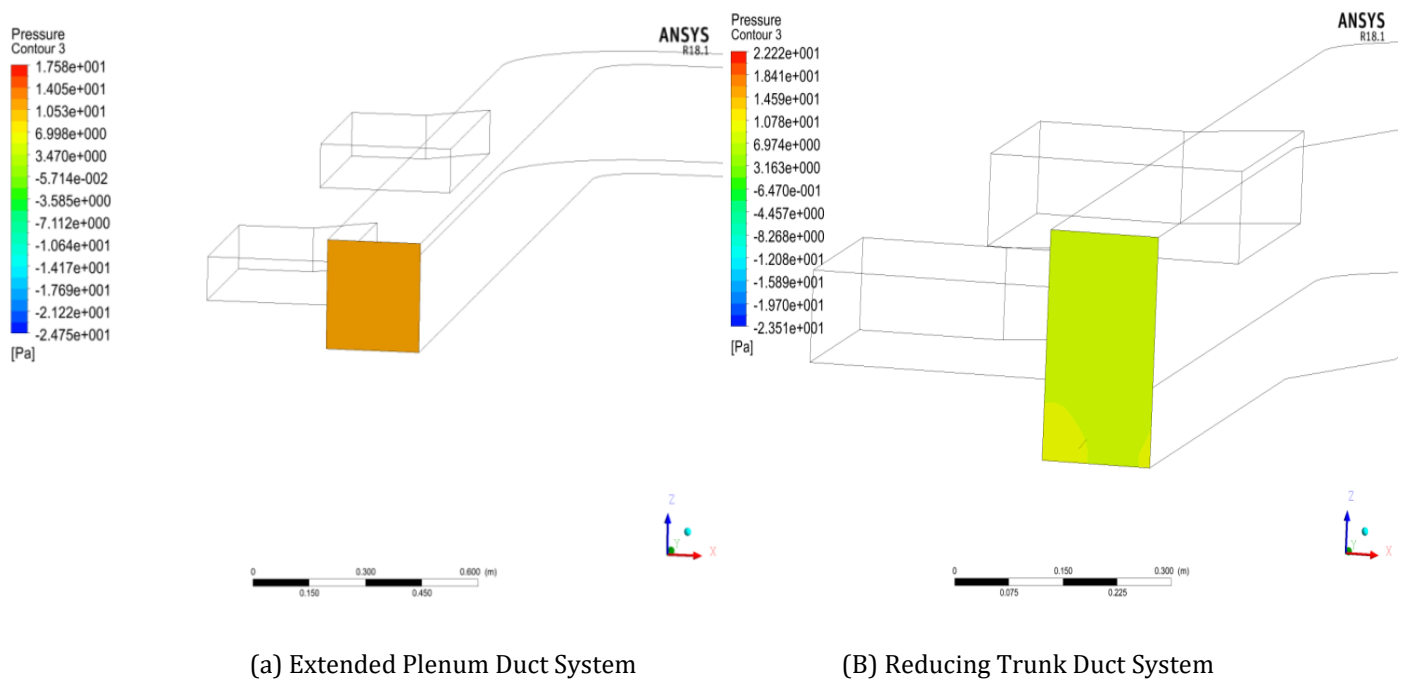


Fig- 12: Pressure Contour at Stagnation for both Duct Systems

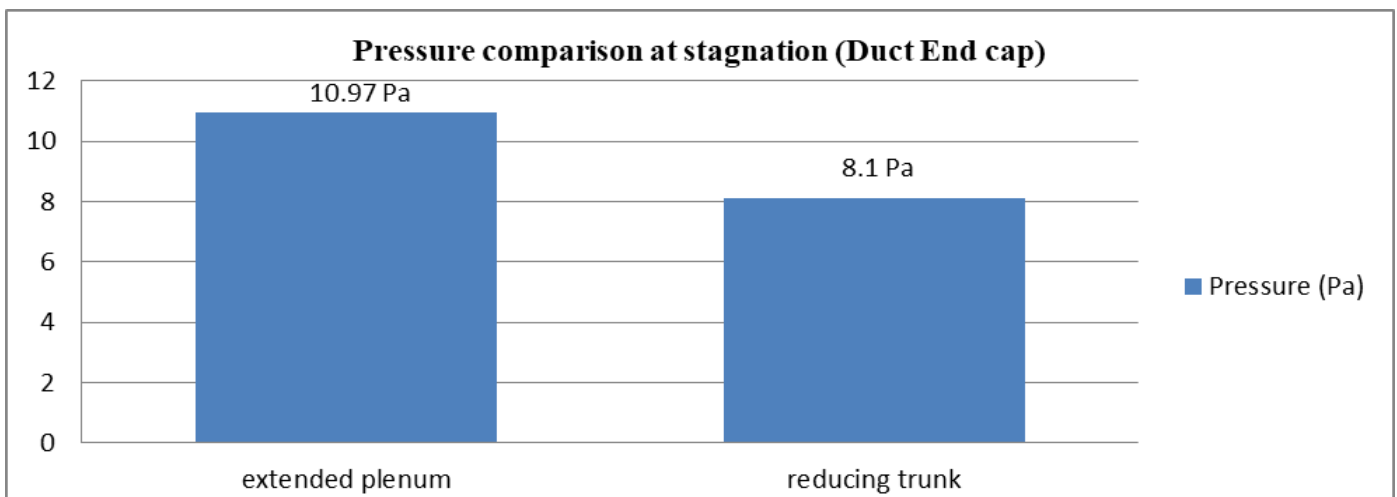
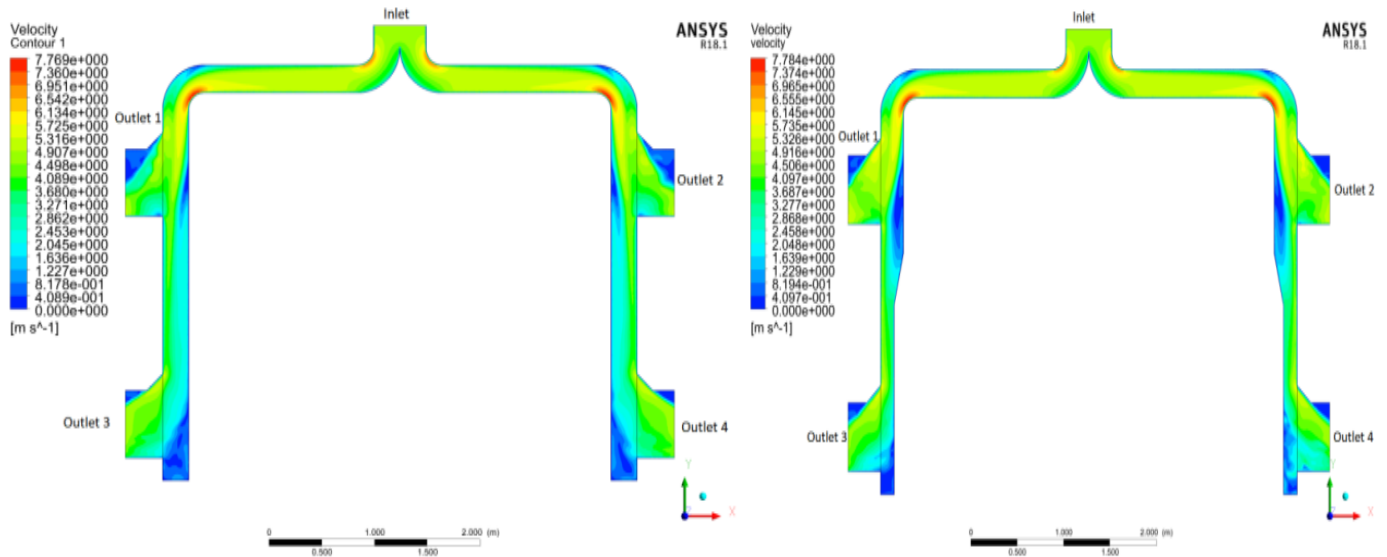


Fig- 13: The Values of the Pressure Accumulation for both Duct Systems

Figures 12 and 13 show the Pressure accumulation is present in both duct systems, with values of **10.97 Pa** for the extended plenum and **8.10 Pa** for the reducing trunk system.

The extended plenum exhibits approximately **35 %** higher accumulation pressure than the reducing trunk system. Due to the comparatively higher stagnation pressure in the extended plenum, back pressure can form and propagate upstream, generating turbulent eddies, reducing the airflow rate through the system, and causing uneven air distribution across diffusers or grilles.

5.5 Velocity contours

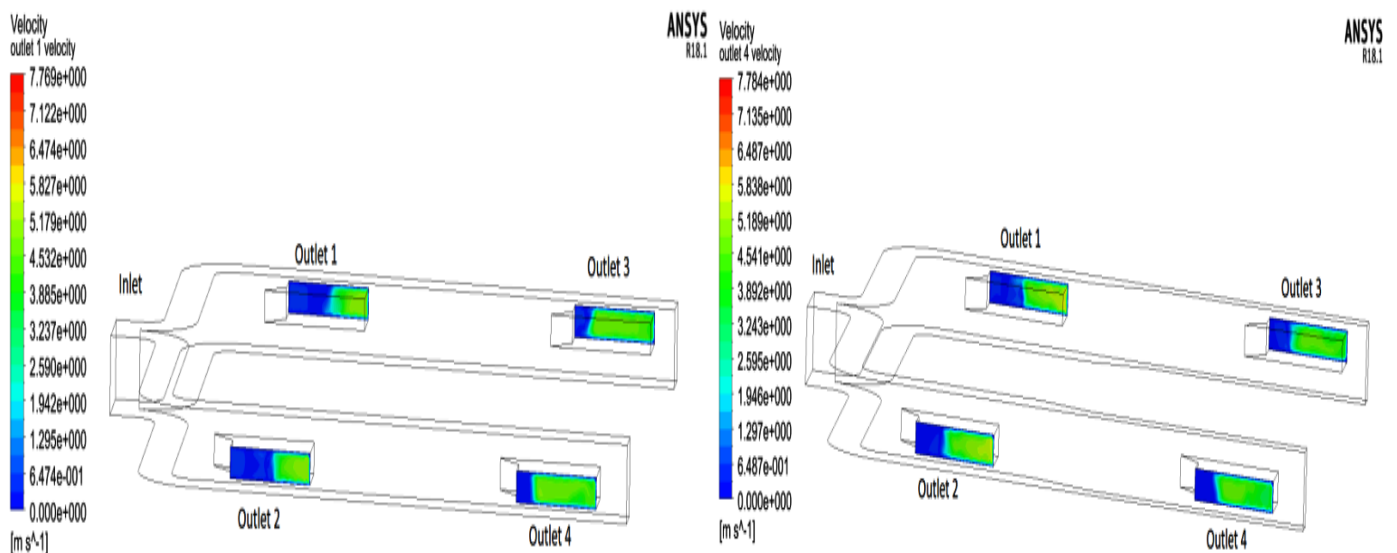


(a) Extended Plenum Duct System

(B) Reducing Trunk Duct System

Fig- 14: Velocity Contours on Centre Plane for both Duct Systems

5.6 Velocity contours at all outlets



(a) Extended Plenum Duct System

(B) Reducing Trunk System

Fig- 15: Velocity Contours at all Outlets for both Duct Systems

Figures 14 and 15 show the variations of air velocity at all outlets in the extended plenum duct system, whereas in the reducing trunk duct system, the velocity remains nearly constant.

5.7 Mass flow rate comparison at all outlets

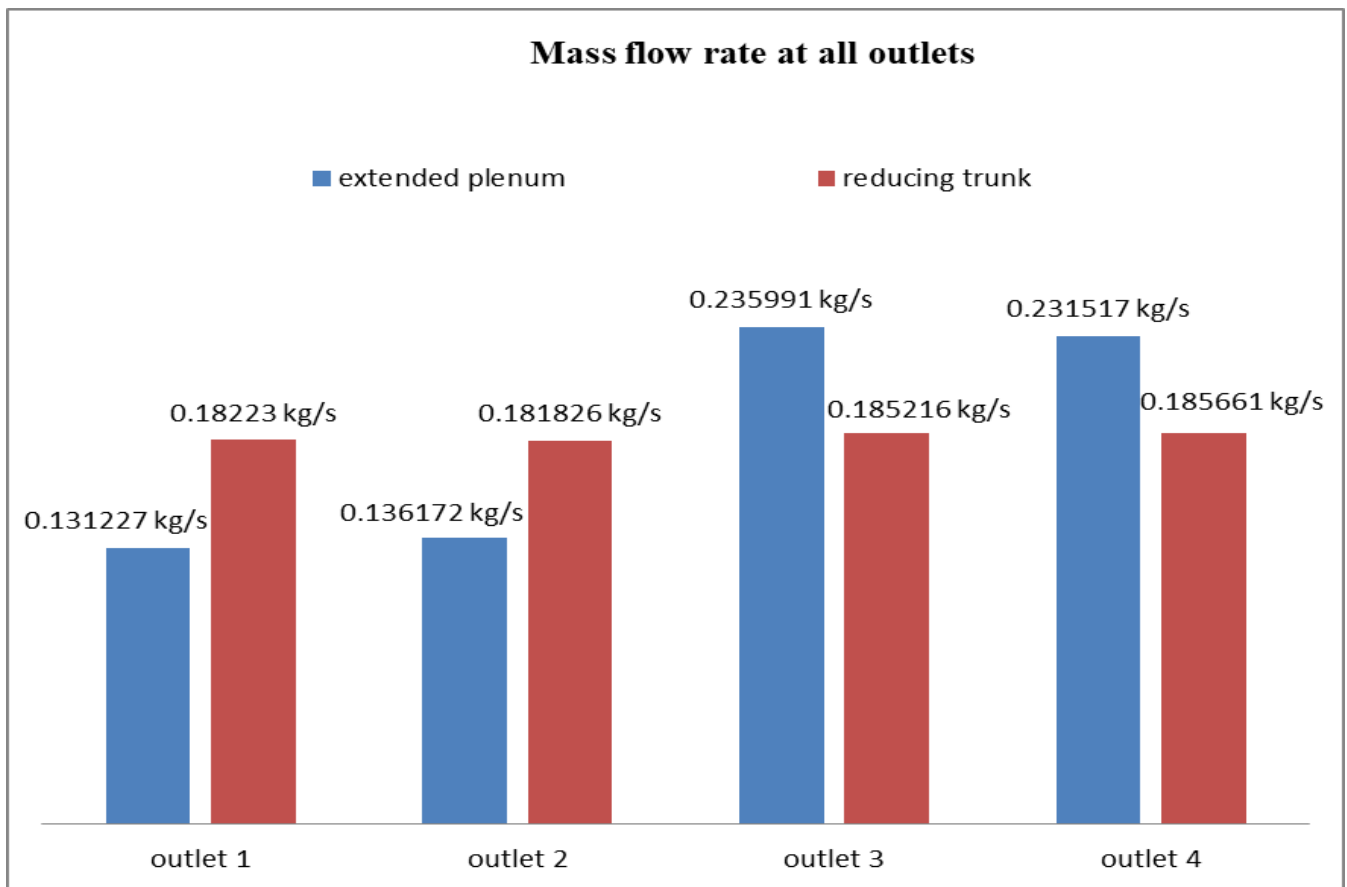


Fig- 16: Mass Flow Rate at all Outlets for both Duct Systems

Figure 16 shows that in the reducing trunk duct system, the mass flow rate of air at all outlets is nearly constant and meets the supply requirements, whereas in the extended plenum duct system, the values vary by about **0.1 kg/s** from the starting outlets to the last outlets.

6. CONCLUSIONS

This comparative CFD analysis has shown clear performance differences between extended plenum and reducing trunk ductwork systems under the same identical operating conditions. According to this analysis, the reducing trunk ductwork system gives better uniform air flow throughout the duct length, and air is evenly distributed at all outlets compared to the extended plenum system. Reducing trunk duct system balances velocity and pressure in the whole duct system, so properly balanced air flow supply will reduce noise and damper requirements. An Extended plenum duct system accumulates pressure at the last length (End Cap) of the duct, so unnecessary extra pressure and more fan power will be consumed. Although at the time of duct design, calculations of external static pressure and fan motor power were higher in the reducing trunk duct system compared to extended plenum. This small difference can be compensated for by the improved uniformity of airflow and balanced pressure and velocity distribution along the entire duct length. Additionally, the extended plenum duct system is easier to design and install for short-length ducts but requires more duct material compared to the reducing trunk duct system. The overall conclusion is that reducing trunk duct system is better in terms of pressure drop, smoother velocity profile, less recirculation and flow separation, lower turbulence, flow uniformity and better outlet performance, and these are all important in reducing energy loss and improving ductwork system stability. Some drawbacks of reducing trunk duct systems are high

cost, design complexity and more fabrication effort. The results are very useful in duct design and suggest the use of reducing trunk ductwork systems for balanced branch flows.

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