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PARTICLE-LADEN FLOW IN A SQUARE DUCT WITH VARIABLE ROUGHNESS

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By

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ABSTRACT

Misty weather is one of the problems in urban areas, especially the areas where there are industries. These industries release Particulate Matter (PM) into the atmosphere that is very dangerous for people's health because these Particulate Matters are too small and can easily penetrate the lungs into the bloodstream. To overcome this hazardous effect at indoor places and because of environmental constraints, research is being carried on particle Particle-Laden flow through duct. The particle-laden flow was observed in a square duct with different structure parameters of roughness. The fluid flow in the duct contains various types of particles. The Reynolds Stress Model (RSM) and Discrete particle Model (DPM) was used to numerically simulate the flow. The characteristics of particulate flow, including velocity profile of the fluid and deposition of the particles on the surface of the duct was studied at different values of roughness. The effect of relative roughness height (r/D) and relative spacing (s/r) on the fluid flow was investigated and found that the roughness height has a greater effect as compared to the spacing. The values of relative roughness were taken between 0.024 and 0.1, while the values of spacing between elements ranged from 9.8 to 39.23.The deposition of the particles and the velocity profile of the fluid increases with enhancement of roughness height on the surface of the duct. In case of increasing the space between elements this effect is reversed.

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LIST OF ACRONYMS AND SYMBOLS

Nomenclature

C_C	Cunningham slips correction factor
C_D	Coefficient of drag
D	diameter of the duct
D_h	Hydraulic diameter of the duct
d_p	Particles diameter
L	length of the duct
N_{dep}	Number of deposited particles
N_t	Total number of particles
R_e	Reynolds number
R_d	Deposition ratio
r	roughness height
s	roughness spacing
S	particle-air density ratio
U_0	the average velocity of air
u_p	velocity of particles
u^*	frictional velocity
V_d	deposition velocity
V_d^+	non-dimensional velocity
$\boldsymbol{\varepsilon}$	turbulence dissipation rate
μ	dynamic viscosity of air
ρ	density of air
ν	kinematic viscosity
τ_w	wall shear
τ_p^+	non-dimensional relaxation time

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CHAPTER 1

INTRODUTION

1. Introduction

1.1 Issues regarding airborne particles

The particulate matter in the atmosphere has become the main cause of pollution in urban areas due to the rapid increase in industrial firms, a large number of vehicles and more energy consumption. Humans exposed to suspended small particles may contribute severe respiratory damage, cardiovascular disease, and mortality. Most of the citizen spends almost 20 hours of a day at houses. To improve indoor air quality, there needs to be a highly efficient particulate removal device [1].

Particulate Matter in the air with a diameter of less than 10 μm (PM_{10}) is a criteria pollutant regulated by agency in America. The Air Quality standard for PM_{10} is 150μg/m^3 averaged over a 24-hour period and 50μg/m^3 in a one-year period. A new standard for particles of aerodynamic size less than 2.5μm has been promulgated. It would limit $PM_{2.5}$ concentrations to 65μg/m^3 and 15μg/m^3 over a yearly average. Whether there is any perfectly safe level for human exposure to particulate Matter is unknown [2].

There is also strong epidemiological evidence indicating that ambient PM2.5 contributes to adverse human health effects. Both acute and chronic health effects have been observed to occur at particle concentrations common in US cities and at levels below the NAAQS (National Ambient Air Quality Standards). Subpopulations most likely to be at greatest risk from PM10 exposure include the elderly, young children, asthmatics and those with preexisting impairment of respiratory and pulmonary systems. it was widely acknowledged that air pollution was linked to poor human health. Public attention was more keenly focused on the health impacts of air pollution after episodes of very high Particulate Matter levels in Meuse Valley, Belgium, Donora, Pennsylvania and London, England were observed to be associated with increases in human illness and death. Epidemiological studies have demonstrated positive correlations between ambient PM10 concentrations and human morbidity and mortality [3]. While opinions are not unanimous, most epidemiologists and reviewers believe that the body of evidence strongly suggests that exposure to particulate air pollution, and especially PM2.5, is important for the assessment of risk factors for mortality, respiratory symptoms and diseases, and exacerbation of existing pulmonary and cardiovascular diseases. The link between ambient particulate concentrations and the concentration to which individuals are exposed has not been fully explained. According to behavioral studies document that most people usually spent their time in homes. Particle concentrations and sources indoors are not the same as outdoors. Most of the air breathed by individuals is indoor air, which raises some questions about the epidemiological link between ambient PM10 concentrations and human health problems [4].

Personal exposure concentrations have often been observed to be greater than indoor or outdoor concentrations, possibly due to a 'personal cloud' effect. Personal PM_{10} exposure concentrations do not correlate well with ambient PM_{10} levels in cross-sectional studies, but the two measures show a better correlation in longitudinal studies that account for personal variability. This Particulate Matter or airborne particles not only can affect human health but also affects the instruments, whether they are mechanical or electrical. If these particles are not filtered they are going to stick on the surfaces of instruments like heat exchangers, fans, condensers, and turbochargers. The particles were deposited on the surfaces of components [5, 6].

Particle deposition can also cause material wear on the turbine blade, affecting its aerodynamic performance. Pack of air-conditioning in the ECS consists of two parts that are air cycle machine and heat exchanger. Heat exchangers are also used in aircraft due to high heat-transfer efficiency can be affected. We studied from experimental data that there is a pressure drop in a compact heat exchanger due to the particle deposition on its surface [7, 8].

1.1.1 HVAC systems and indoor air quality

To understand the contribution of ambient Particulate Matter to human exposure, it is compulsory to know how the spreading of particle size is modified as outdoor air travels into a building. Particle deposition in supply air ducts reduces the indoor concentration of particles of outdoor origin. Heating Ventilating and Air Conditioning (HVAC) systems also continuously modify indoor particle concentrations as air is recalculated. Air travels from outdoors into a building via three main routes: mechanical ventilation through a ducted HVAC system, natural ventilation through open doors and windows, and infiltration through gaps and cracks in the building envelope. Most intermediate and large commercial buildings are mechanically ventilated and, for these buildings, mechanical ventilation is usually the dominant entry path of outdoor air to the indoor environment. Consequently, particle deposition in HVAC systems effects particle concentrations within buildings. This system plays a key role in maintaining the quality of air in large houses. Many researchers have observed that the dust present in the air causes the number of health issues. These can be ventilated mechanically from the houses by applying different methods [9, 10].

A National Institute for Occupational Safety and Health (NIOSH) survey found that HVAC deficiencies accounted for more than half of the indoor air quality problems in firms. For a range of primary air pollutants including Particulate Matter and microorganisms like pollens and for secondary pollutants like volatile organic compounds, ventilation can act as two things source and sink. Sufficient water in the HVAC can initiate the growth of bacteria and fungi. The water can be present in vapors form as moist air or water itself is physically there due to rain or some other factors [11].

This type of growth produces microbial volatile organic compounds (MVOCs) and can increase the number of bio-aerosols in the air stream. Secondary pollutants can cause a chemical reaction with the surface of the HVAC system and can change the nature of the surface of the duct; ultimately the particle deposition will change with it. For example, particles of biological origin often contain unsaturated fatty acids. If these deposits in ducts, they will be exposed to ozone, which can oxidize the unsaturated acids, producing aldehydes that can be released into the air stream. Particulate Matter can also become a rich nutrient or can act as a catalyst to boost the growth of microorganisms that will, in turn, be releasing MVOCs. Not only these kinds of pollutants pollute the ventilation air directly but the ventilation duct material for example sealants, fibrous insulation, and residual manufacturing oil can also pollute the air stream. In summary, particulate in HVAC systems can expose occupants of building to particles of outdoor origin and is linked to the indoor quality of the host [12, 13].

1.1.2 Secondary pollutants (Chemical and biological agents)

The airborne release of aerosolized chemical or biological agents form factories, burning waste and usage of lead-based petrol within or near a building may lead to exposure of the building occupants to these harmful substances. Agents released outdoors may be drawn into a building by the HVAC system; those released within a building may be spread to other parts of the building by the HVAC system. In either case, deposition in the supply and return duct work may significantly influence exposures. An understanding of particle deposition in HVAC ducts can also help in planning responses in terms of HVAC system operation in the event of a detected release. The deposition may also be important for post-release remediation since the HVAC system may require decontamination to minimize exposure owing to the re-suspension of contaminants [14].

1.2 Types of HVAC Systems

All equipment that helps to provide and condition indoor air constitutes HVAC systems. This includes louvers, fans, air cleaners, heating and cooling equipment, ducts, humidifiers and dehumidifiers, terminal devices and control equipment. Such systems are widely variable in terms of complexity, quality, operation, and maintenance. These systems serve the multiple purposes of providing fresh air to the indoor space, controlling internal temperature and controlling indoor pollutants by ventilation. Standards for acceptable building ventilation and thermal conditions have been established and are maintained by the American Society.

Unitary systems handle a small flow of air (0.2-2 m_3/s), serve small floor areas (~150 m_2) and have a relatively low initial cost. Multiple unitary systems, each with an independent fan, thermal control, and ductwork, may be used to ventilate larger spaces. On average, unitary systems have shorter duct runs than central units because of their decentralized locations. Ducts associated with these systems usually have a hydraulic diameter of less than 70 cm and tend to be constructed of galvanized steel, duct board, and flexible duct [15-17].

One may broadly divide HVAC systems into small unitary systems and large central units. Unitary systems provide air to a single building zone, while central units are capable of delivering air to multiple zones with different heating and cooling requirements. Interior portions of large buildings filled with people, lighting, and equipment often require cooling even during the coldest months of the year. Perimeter portions of buildings that share walls with the outdoors typically require more flexible temperature control because they are more directly influenced by outdoor temperature, wind, and direct sunlight. Central HVAC units serve large building areas (greater than 1000m2) and handle large airflow rates (5-50m3/s). Central systems are designed to operate as either constant air volume (CAV) or variable air volume (VAV) systems. Constant air volume systems provide a time-invariant flow rate of air to each space, and room temperature is controlled by means of heating or cooling the supplied air. Variable air volume systems achieve temperature control by regulating the amount of cooled air provided to each space [18, 19].

Most central systems feature continuous operation and have galvanized steel ducts of the rectangular cross-section to distribute the air. Fiberglass insulation is commonly used on the interior surface of large ducts near fans to absorb acoustic vibrations and to provide thermal insulation. The plenums and largest ducts in these systems may have a hydraulic diameter of several meters and the smallest ducts, those leading to the room supply registers; have a typical hydraulic diameter of 0.15-0.3m. Duct airspeeds range from a maximum of 10-15m/s near the fans to a minimum of 1-2m/s at supply registers. Central systems are sometimes turned off overnight when a building is unoccupied and then operated at higher than normal flow rates in the morning to flush accumulated pollutants from the building before it is reoccupied. Central systems are common in midsized to large office buildings and retail centers, as well as university buildings, theaters, and multiple-use buildings. Often, several large central systems are required to ventilate very large buildings [20, 21].

1.3 HVAC System Components and Particle Deposition

Particle deposition in HVAC systems reduces airborne concentrations within buildings but may lead to other indoor air quality concerns. Factors like particle size turbulence in the air and roughness of the surface and direction orientation of particles deposition on the surface can be affected by the deposition rate from turbulent flows. Because of the complexity of flows and variety of surfaces in even the simplest ventilation system, particle deposition rates can vary widely along the length of single duct run [22, 23].

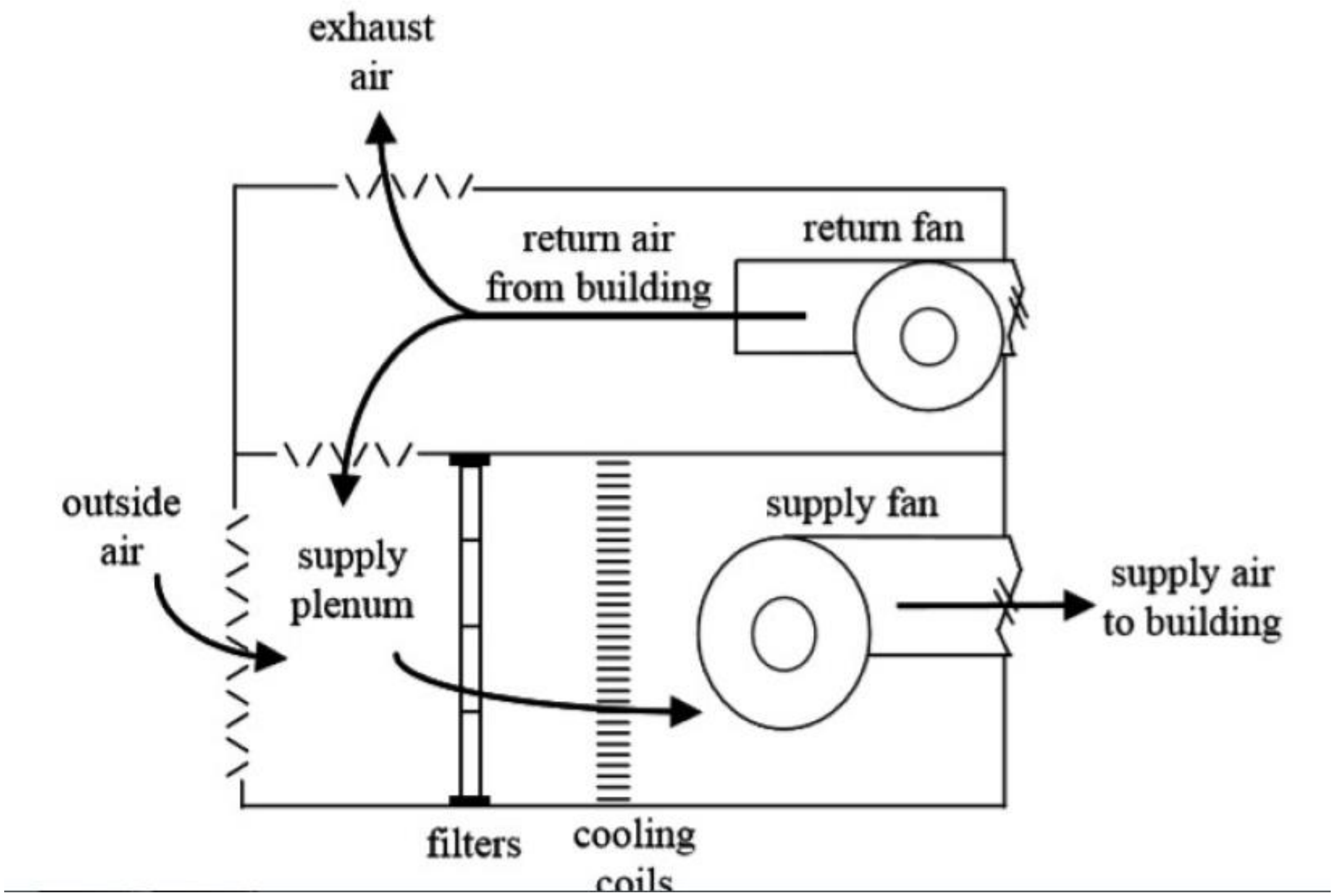

Figure 1 schematic diagram of air flow in HVAC

This air mixture is filtered, thermally conditioned, and then drawn into a supply fan that distributes the air through a branched duct system to various parts of the building. Return air intakes are located throughout the building. These intakes direct air through return ducts or plenum spaces back to the HVAC mechanical room where a fraction is re-circulated and the rest is exhausted outside the building [24, 25].

1.3.1 External air louvers, filters, cooling and heating

The fraction of exterior air in the supply air is managed by louvers at the air intake and is commonly varied by means of a control system that depends on the outdoor air temperature. Supply air may consist of only external air if it is at or near the desired temperature. By reducing the need to heat or cool ventilation air, energy savings (like electric power and cost of filter paper) increases this process is termed as 'economizer mode'. When the outside air temperature deviates from the desired supply temperature, outside air louvers partially close and a larger fraction of return air is directed to the supply.

Ventilation standards require that a minimum amount of outside air be brought into any occupied building. Because indoor and outdoor air usually carries different types and concentrations of Particulate Matter, air louvers influence particle deposition in the rest of the HVAC system by altering the type and amounts of air contaminants introduced into the system [26, 27].

Filtration in HVAC systems has traditionally been designed to protect mechanical equipment and not human health. Many HVAC filters are inefficient for particle sizes that less is than 10 micrometers and hence particle deposition method can be used saving the filter cost. The air around filters has been carefully observed and quantified. It has been estimated that 15% of the provided air does not pass through filters in a typical building. Such filter bypass flow, which could transmit particles of all sizes, is expected to increase as the pressure drop across the filter increases from usage. Return air ducts usually carry unfiltered indoor air. Thus, a broad distribution of particle sizes is expected to be present in both supply and return ducts. Heating or cooling of supply air is usually accomplished by passing air through a fin-and tube type heat exchanger. Such heat exchangers are potentially important sites for particle deposition. They are designed to promote efficient heat exchange, and mass transfer tends to be high in systems with high heat transfer. Fouling induced by particle deposition on heat exchanger surfaces can decrease the effectiveness of heat transfer, degrading temperature control and increasing operating costs through the need for a lower temperature coolant (or warmer heating fluid)[28-30].

In addition, when the supply air is cooled, water condenses from the air stream. Condensed water can reduce the size of airflow channels in the heat exchanger and alter particle deposition. If not properly drained, condensed water and the wetted surfaces in the HVAC system can become sites for microbial growth. Subsequent release of bio aerosols, such as mold spores, can constitute another source of particles in the ducts [31-33].

1.3.2 Supply fan and ventilation ducts

After being heated or cooled, air is distributed through the supply ducts by the supply fan. Particles can deposit on the fan housing and fan blades and, in the case of severe fouling, impede its performance. As particles deposit on filters, heat exchangers and ducts, the resistance to airflow through these systems may increase. For a constant air supply rate, increasing the airflow resistance increases the pressure drop along the duct, causing the fan to consume more energy; the magnitude of this increased energy consumption depends on the specific performance conditions of the fan. Ventilation duct systems consist of a very long duct after the supply fan. Duct branches bend and reducing sections are required to achieve proper air distribution and maintain air velocities. Most ducts are fabricated from sheet metal, but the smallest ducts that lead to supply registers are often made of flexible aluminum or Mylar to allow for easier installation [34].

A length of duct is made up of several short sections connected in series by various fittings. These fittings can serve as sites for local particle deposition. Air may leak through the joints between duct sections and through seams resulting from duct fabrication. Studies of duct leakage in California buildings have found average leakage rates in supply ducts as a percentage of the system flow rate at the inlet to be 25% in light commercial buildings and 10-20% in large commercial buildings. Particles will exit ducts with leakage air is positively pressured (supply) ducts and enter ducts through leaks in negatively pressured (return) ducts [35, 36].

Ideally, duct surfaces should be kept clean and dry; however, even new ducts may be soiled from storage prior to installation and debris from the building’s construction phase. In addition, new steel ducts have been identified as sources of VOCs in indoor air from residual oils left from the original machining and fabrication. Air flowing through the ventilation duct is turbulent in nature and due to that nature; the interaction between the duct surfaces and the air will be more causing the deposition of the particles on its surface. Other factors will also affect the particle deposition like settling of particles by gravity and other mechanisms and with the passage of time, the duct will accumulate particulate deposit on their surfaces [37, 38].

It was observed that such deposits could reduce the fluid flowing in ducts, having minor diameter, reduces the efficiency of the air removing system. General consistency among studies is observed for the mean and range of both the deposit density and accumulation rates, despite variability in the methods used and in the building location and age. The distribution of specks of dust that has been deposited also measured; as the total mass of the particulate in all published studies not only consist of large particles but also the small ones and large particles, debris and fibers. Measurement of deposit density has been shown to vary depending on the method used for quantification [39, 40].

Duct cleaning is an increasingly common practice in both residential and commercial buildings. It can help maintain proper duct flow rates and provide a potential preventive and corrective benefit for indoor air quality. Duct cleaning is not a major issue as in America the duct cleaning businesses are certified by the National Air Duct Cleaners Association (NADCA). National Air Duct Cleaners Association has developed standards and methods for duct cleaning and cleanliness measurement. The maximum deposit density for a duct to be considered clean is 0.1 g/m^2 based on a vacuum and filter cassette method [41, 42].

1.3.3 Duct components and terminal devices

Ventilation systems include duct components that locally modify airflow and offer surface area for particle deposition. Fin-and-tube heating and cooling coils are often installed at the end of the ducted distribution system to enable local thermostatic control of air temperature. Turning vanes, dampers, variable air volume boxes, and registers help direct the air stream, control flow rates and distribute air properly. The presence of such components and devices can alter the fate of particles that enter HVAC systems [43, 44].

1.4 Overview of the Research

The main objectives of this research were to determine particle deposition rates in air ducts and to find out the best methods for the prediction these rates. When designing the duct one should also know the particle deposition rates in air ducts to completely understand the fate of the particulate. In this research, we are using the Roughness Based Method to remove the airborne particles and to provide clean air. In Roughness Based Method we don’t use any filter paper as all separation of airborne particles is done by the mean of using rough surface or by introducing roughness elements. This method also doesn’t consume any kind of energy as there is no instrument like cyclone separator that will be used. As a result, it’s a very good method in terms of power and cost consumption and can be used easily for small areas. Smooth surface model and rough surface model both were simulated in a three-dimensional channel for the characteristics of particle deposition. The roughness was changed by using different materials and by introducing roughness elements of different shapes and designs [45, 46].

CHAPTER 2

LITERATURE REVIEW

2. Literature study

In the previous studies, the two-dimensional duct for the smooth and ribs wall duct was used. The airflow duct was designed by applying different parameters for the purpose of particle deposition. The flow condition and duct sizes are appropriate with literature. For particle deposition into the ribbed wall, there were three different types of ribbed shaped surfaces were introduced. The ribs cross-section has three types, spherical, square and triangular. While the ribbed and smooth duct have same sizes in order to do a comparison. In order to check while the flow is the fully developed condition or not, one half of the duct is considered as smooth, while the ten struts were arranged in another half with the same spacing in the stream wise direction. To check the increase in heat transfer in ribs surfaces, the lowest pressure increase with maximum heat transfer was occurred [47, 48].

The investigations are directly concerned with particle deposition in air ducts but are of questionable value owing to the poor quality of the experimental methods and the unclear data reporting. It was measured that particle penetration through a horizontal square duct of 30cm width by monitoring upstream and downstream locations with infrared particle monitors. In addition to studying a straight duct, particle penetration through a flow reducer, a single 90° bend, a double 90° bend and a flow damper positioned at four different angles were measured. A poly-disperse test aerosol was used and most data were presented as least-squares fits of the percentage of particles penetrating the duct versus the flow rate. The data for the straight duct section is presented in the traditional method of $\tau+$ versus V_{d+}. A particle diameter of 1.5μm was used to calculate representative values of $\tau+$ for the 0.5- 2.0μm poly-disperse aerosol. A comparison showed that data are clearly inconsistent with other data for deposition to nominally smooth surfaces [49, 50].

Cheong used experimental techniques and data reporting similar to Adam. When investigating the effect of the aspect ratio in rectangular ducts on the deposition of a poly disperse aerosol of unreported size distribution. These data also seem inconsistent with previously observed trends and the inconsistencies are likely to be a consequence of the unreliable methods used[51].

2.1 Deposition enhancement

In this section, we have investigated the ways to increase the particle deposition. The approach used for the increase of particle deposition is the interception by the rib surface. The number of particles that are attached to the ribs is proportional to rib height. Another approach that can enhance particle deposition is the arrangement of ribs. These measurements are favorable for an increase in particle deposition. The total deposition for smooth ducts is 0.6m. For the duct which using the ribbed surfaces, the two-dimensional area enhancement is 0.082m, 0.054m and 0.087 m for triangular, spherical and square ribs, respectively. The deposition area was enhanced by 15%, 20%. It specifies that the circular ribs have very related deposition area with that of the square. While the increase of deposition is very much low in the triangular rib than the above two[48] .

The wake region is formed by the installation of surface ribs. Huge number of particles will be apprehended by entrained to the walls and ribs and the turbulent eddies. It can be seen that the turbulent models for smooth duct are completely different from those for the ribbed duct. In the previous case, the flow is completely alongside the stream wise direction and the near-wall turbulent kinetic energy value is very small. These are not suitable conditions for enhancing deposition of particles.

The large turbulent kinetic energy and strong momentum exchange values near the wall for deposition of the particle are beneficial, as many particles would be apprehended by the turbulent vortices and entrained to the wall for deposition. It was observed that the turbulent eddies and turbulent kinetic energy values vary with different types of ribs. This conclusion is proved with collected works result for the improvement of the transfer of heat by different rib surfaces and shapes. Thus the maximum particle deposition improvement is gained by the square ribs for insignificant or small particles ($\tau<1$). However, the seizure and entrainment are affected by turbulent eddies are very weak for outsized particles ($\tau>1$) because of their greater inertias. The increase of the system for the main deposition is the trap of rib surfaces[40].

2.2 Straight tubes and ducts

Many experimental investigations have been conducted that pertain to particle deposition from turbulent airflow through ducts. Major factors that have been observed experimentally to effect depositions rates include particle size, amount of air turbulence, surface positioning with respect to gravity and roughness of the deposition surface. The best experimental investigations are those that employ a mono-disperse aerosol, have a well-characterized airflow and deposition surface, and directly measure deposited particles at surfaces. These conditions are satisfied by only a small fraction of the studies. It is further limited to investigations in which sufficient information was reported so that deposition rates could be associated with specific particle sizes for a given deposition surface [18].

Experimentally measured particle deposition velocities from turbulent flows have historically been presented as plots of V_d+ versus τ+. Figure 1 is such a plot showing most of the published data for particles depositing from flow through vertically oriented tubes of small diameter. This figure illustrates the importance of particle size, as measured by τ+, in determining particle deposition. The data for deposition from a horizontal tube is included so as to extend the lower range of τ+ and to illustrate the trends in deposition as τ+ becomes very small. The effect of gravity on deposition from this horizontal flow is expected to be negligible owing to the very small particle sizes, d_p = 0.01-0.04 µm, used in these experiments [50].

The data is divided into the following regimes: the dispersion region and the inertia curbed system. Although the data is broadly scattered in this plot, trends are still clearly visible. The diffusion area have lesser inertia due to minimum size of the particles and follow the low pressure region. Their passage to surfaces depends upon the turbulent diffusion. In a typical duct flow, turbulent diffusion is much stronger than Brownian diffusion, except extremely close to the duct wall where turbulent fluctuations decay to zero. Dimensionless deposition velocity decreases due to τ+ increases in the diffusion regime as there is a decrease in Brownian diffusivity (due to particle size increases). In the diffusion impaction regime, a particle trails turbulent air instabilities less devotedly and may fire ahead of or lag behind eddies near the wall. Hence, through this interaction between particle inertia and wake region, particles may deposit on the surface without relying on diffusion process, and V_{d+} increases substantially, even for relatively small increases in τ+. For the largest particles, those in the inertia-moderated regime, the dimensionless deposition velocity is observed to level off and become nearly independent of τ+. In this case, particles are large in size to respond near-wall eddies due to the rapid fluctuations and transport to the wall. In the center of the turbulent flow, these particles reach the wall through momentum transferred by large eddies [29].

2.3 Details about straight tubes and ducts

Particles and methods used in most of the published experimental studies on aerosol deposition from turbulent duct flows. Experiments respectively summarize experiments conducted in horizontal and vertical tubes with hydraulic diameters less than 2.7cm. Summarize studies in horizontal and vertical tubes with hydraulic diameters greater than 2.7cm. Methods for experimentally determining particle deposition velocities vary widely, but two broad schemes are available. The first method involves direct measurement of the airborne concentration and the particle flux to the surface followed by calculation of the deposition velocity. The principal alternative method is to measure airborne particle concentrations in the duct at upstream and downstream locations and infer the deposition velocity [29].

Microscopic counting of filter samples may yield high-quality results as well, but is likely to be more susceptible to errors by the investigator. Where fluorometric, radioactive or microscopic techniques were used for surface flux determination, the same technique was used for filter sample analysis. Concentrations measured by particle counters generally have a larger uncertainty than filter samples owing to variations in device performance, the increased potential for transport line losses and the difficulty of achieving is kinetic sampling with a constant flow pump. The deposition of liquid droplets in annular flow has been frequently considered experimentally. The annular flow consists of a thin liquid layer on the walls of a conduit flowing concurrently with the air stream. Disturbances at the liquid-air interface cause poly disperse droplets to be released into the air and it is the deposition of these droplets back into the liquid layer that is studied. A review of experiments of droplet deposition from the annular flow is available. Investigations of this type were not included in this review because of the poly disperse aerosols and the poorly characterized wave-like surface condition at the liquid-air interface [30].

2.4 Particle Size and air Velocity

The seminal experimental investigation into understanding particle deposition from turbulent flows was conducted. Their data showed increased particle deposition with increases in air velocity and particle diameter for particles in the diffusion-impaction regime. Subsequent measurements of deposition from small diameter tubes have confirmed these findings [32].

The experiments were conducted by using glass tubes and their findings considered as a scale for particle deposition because of the high quality of models and the recovery of data. The data demonstrate that the increase in deposition velocity in relation to the particle size and a decrease in deposition velocity as particle size increases in the diffusion impaction regime. This leveling of dimensionless deposition velocities for large values of $\tau+$ has been corroborated experimentally [12].

The Lagrangian method was used for calculating the numerical data. The test was performing at various diameters. Reynolds-averaged Navier-Stokes structures used to calculate the different parameters of particles. It was concluded that the RNG k-e model with near-wall correction gives the most accurate particle deposition. The amount of deposit airborne particle and their location mainly depended on the particle size and air velocity. They used a k-e model for simulation. The drawback of this model was that it introduces a irrelative properties at operating conditions. They also measured experimentally the deposition ratio was 11% for 1micro-m particles. When the inlet velocity was 15m/s and turbocharger was running at the high speed. The particle deposition is enhanced by roughness of ducts and by placing the roughness elements of different sizing, different placing, and different combination. Also, there are energy losses due to roughness element and wall roughness. In order to clean the air, it is important to have advance awareness and complete information of the data and parameters about the complex processes of particulate flows and particle deposition on rough surfaces [16].

2.5 Description of turbulent flow over surfaces of rigid and flexible roughness

Turbulent flow and roughness deformation for both cases the mean velocity profiles are almost the same, on the other hand, there is a substantial reduction of Reynolds stress in the flow over flexible roughness because it represent the reduction of consistency in the roughness flow pattern. In flexible the stream wise roughness buckle displays a higher energy stages at lower frequencies while the span-wise bend shows a more noticeable peak at the natural frequency of the ribbed surface. By merging the measurements of roughness kinematics and turbulent flow, the result showed a close bout of the strain energy of the flexible roughness with the failure of turbulent kinetic energy due to roughness compliance [44].

2.6 Relevance of current Data

Most of the experimental work conducted to date is not directly applicable to the case of particle deposition from flow through HVAC ducts. Several studies have focused on particle losses in aerosol sampling lines and have been performed in small diameter tubes with airspeeds and friction velocities much higher than those found in ventilation ducts. Experiments in ducts with diameters of 15cm or larger, similar to those in air duct systems, have often focused on very large roughness elements not commonly found in ventilation ducts. Few investigations have considered differences in a deposition to the distinct surfaces in horizontal rectangular ducts and no consideration has been given to complex developing turbulent flows. Experiments using real air duct materials for the deposition surface are rare. However, the experimental information does provide a mostly consistent picture that can lead to informed expectations of particle behavior in HVAC systems. The overall data set places bounds on the expected deposition behavior of particles in ventilation ducts and provides a foundation for understanding upon which more detailed questions about particle behavior in turbulent flows may be investigated [44].

The gathered data in vertical tubes have proved to be valuable as it can be used to evaluate the competences of models and the data provide assessments for expected particle deposition rates to vertical surfaces in ducts. The work in the literature to investigate deposition in a horizontal duct to a surface other than the floor is also measured like deposition rates to duct floors and ceilings. Notably, deposition rates measured were about an order of magnitude higher than the data. The data for deposition to the floor and ceiling of a 61 cm square duct as measured. The measured deposition velocities to the ceiling were one to two orders of magnitude lower than those to the floors [28].

The overall data set in the literature for particle deposition from turbulent flow has addressed a broad range of experimental conditions. While results are often not directly comparable, and measured particle deposition rates, even within individual data sets, are frequently widely scattered, clear trends and broad consistency in the data can be observed. The direct relevance of the data set to ventilation ducts is limited. It has reported differences in particle deposition to the distinct surfaces in horizontal ducts.

Air traveling through the duct system typically traverses several bends and branches that alter flow conditions from the fully developed state. No investigations have been reported regarding deposition at these sites from ducts with sizes relevant to building ventilation systems. Complexities of airflow through ducts and the surface character of insulated or used and soiled ducts are two primary factors that set the real situation of deposition of the particle in air ducts apart from all previous experimental investigations.

CHAPTER 3

OPTIMIZED DESIGN

3. Optimized Design

3.1 Methodology and Material

3.1.1 Material selection

In this study, a square aluminum duct is taken for the analysis in which the mixture of air and particles flowing, exhaust ductwork near discharge outlet and ductwork exposed to weather elements. Aluminum is relatively lenient, heavy-duty, lightweight and ductile metal with presence ranging from silvery to dull gray depending on the surface roughness. According to ASHRAE Standards, the sample duct size having the length 800mm and height of 40mm .

3.1.2 Designing of Ventilation Duct

Duct System is classified as high pressure or high-velocity ductwork and low pressure or low-velocity ductwork. The term high pressure or high-velocity ductwork includes the ductwork system. The duct has many shapes, to form a rectangular duct, the flat duct board is measured accurately and grooves are cut at the proper locations. The board is then folded into a rectangular shape. When the board is cut, an overlapping tab is left and this is then pulled tight and stapled. Tape is applied and the joint is heat-sealed. Joints between sections are made by pulling the shiplap end sections together. The joint is then completed by stapling, taping, and heat sealing the junction.

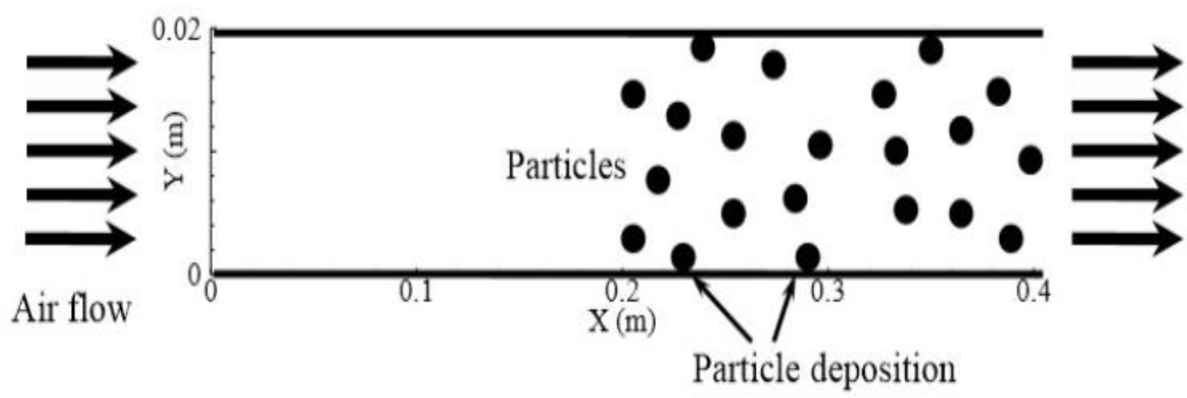

Fig. 2 Smooth Duct

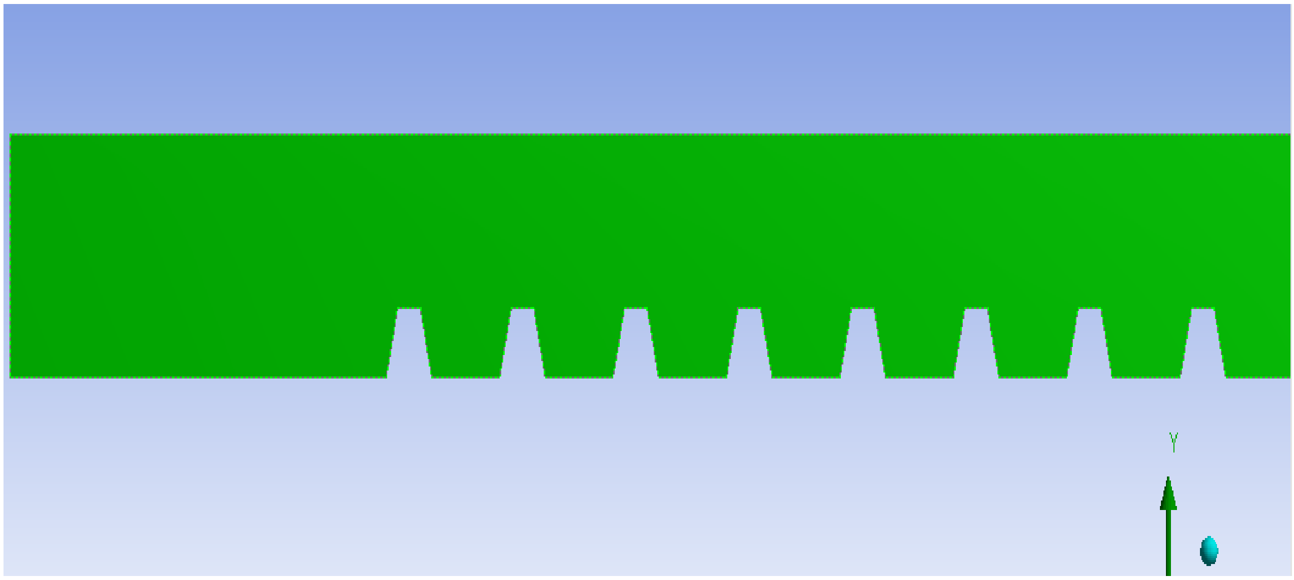

Figure 3 Rough duct

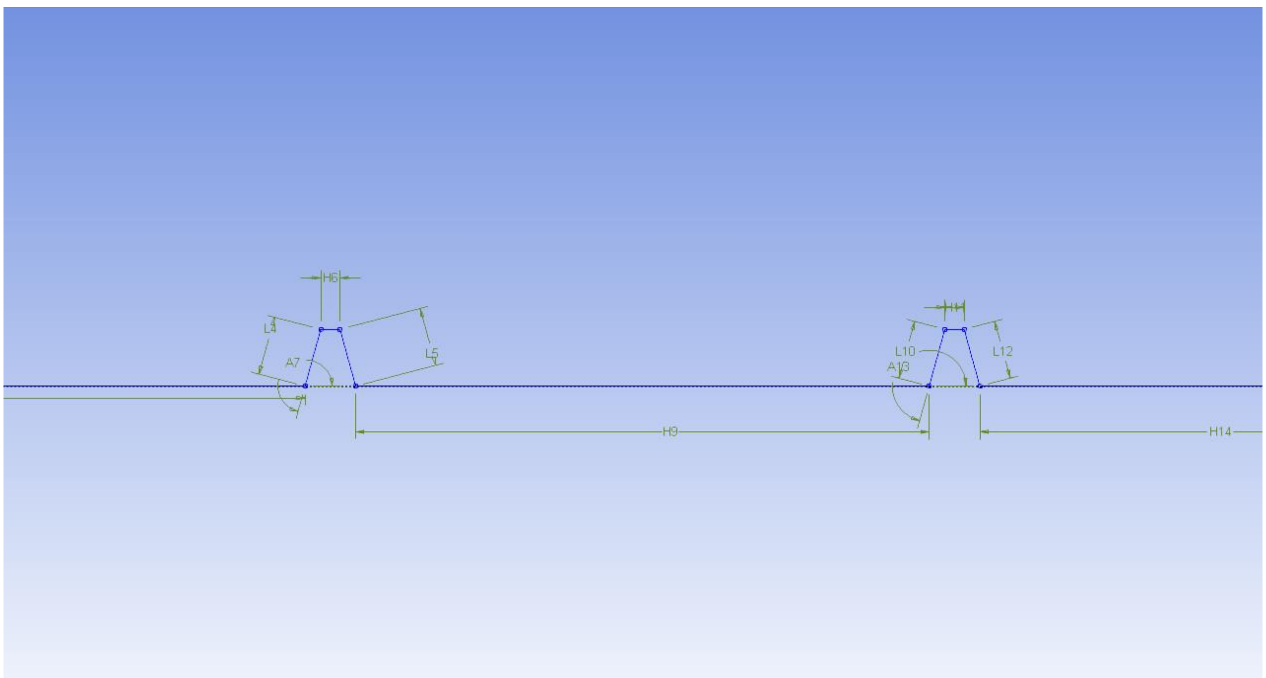

Fig.4 rough elements that are used in the duct

The flow condition and duct sizes are appropriate with literature. For particle deposition into the ribbed wall, different types of ribbed shaped surfaces were introduced. While the ribbed and smooth duct have same sizes in order to do a comparison. In order to check while the flow is the fully developed condition or not, one half of the duct is designed to smooth, while the ten ribs were arranged in another half with the same spacing in the stream wise direction. To check the increase in velocity due to ribs surfaces, the lowest pressure increase with maximum velocity was occurred.

3.1.3 Meshing

The meshing of the physical model is done by changing the size of elements and the number of divisions of elements and the whole structure is meshed with grid resolution. In the fully turbulent flow, the mesh refinement technique is used near the 2D roughness elements and the boundary layer obtained in the turbulent flow is very consistent. The numerical results for the turbulent flows tend to be more susceptible to mesh dependency than those for laminar flows. The mesh number is $6.1{\times}10^4$ at which the velocity of the fluid becomes constant; therefore it is a suitable mesh as shown in Fig.4.For the validation of mesh the suitable mesh numbers for all the cases under investigation are illustrated in Table. 1 and Fig. 5

Table 1 The suitable mesh numbers for different cases

Case numbers	Present study	Hong [1]
1	$1.6{\times}10^5$	$3.9{\times}10^4$
2	$1{\times}10^5$	$3.6{\times}10^5$
3	$8{\times}10^4$	$2.5{\times}10^5$
4	$7{\times}10^4$	$1.9{\times}10^5$
5	$6.1{\times}10^4$	$1.3{\times}10^5$
6	$1.0{\times}10^5$	$3.9{\times}10^5$
7	$9.3{\times}10^5$	$2.9{\times}10^5$
8	$5.6{\times}10^4$	$2.7{\times}10^5$
9	$5.0{\times}10^4$	$2.5{\times}10^5$

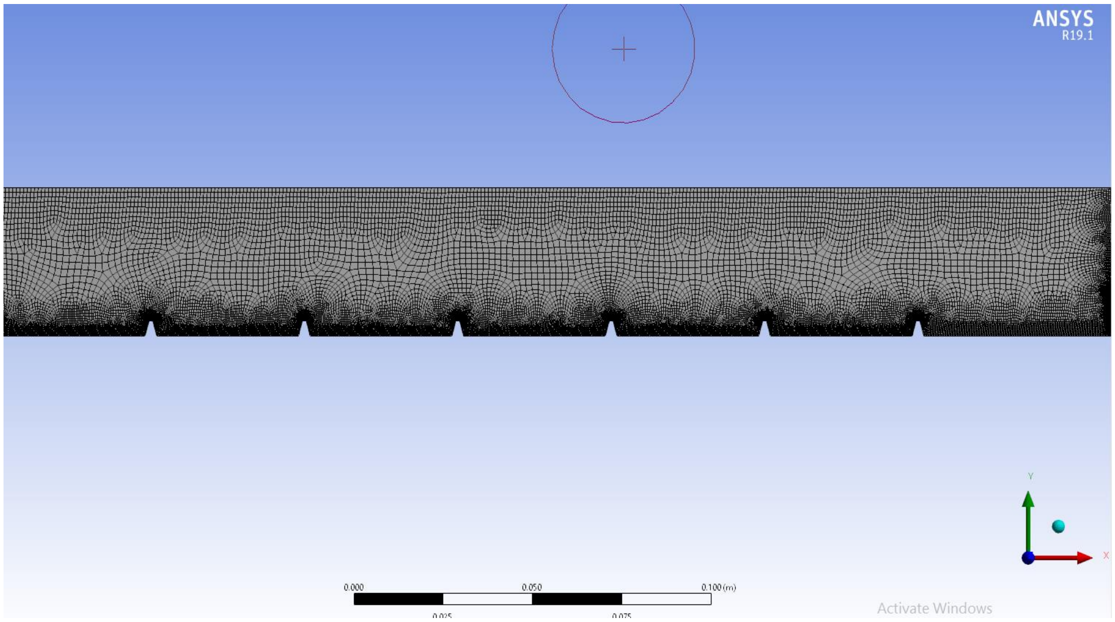

Fig. 5 Meshing

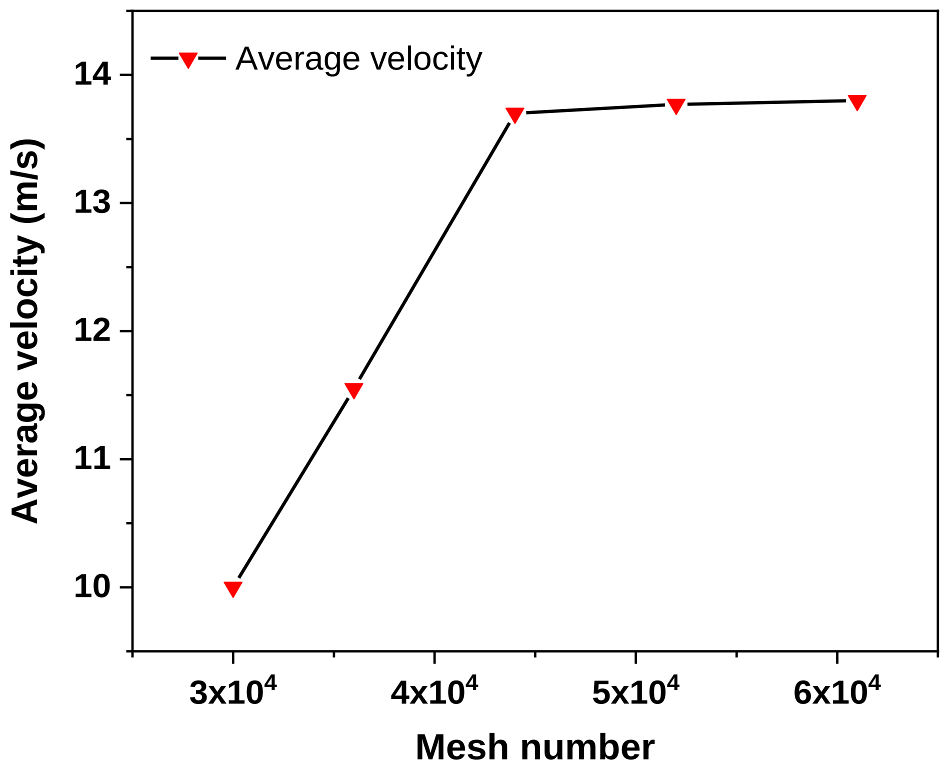

Fig. 6 Mesh validations

3.1.4 Reynolds Stress Model

The Reynolds stresses are solved to calculate turbulence of the flow at very high where the other models cannot measured. Quadratic pressure-strain option improves performance for many basic shear flows. It can be applied in simulation software to perform the analysis. It is harder to converge due to close coupling of equations but suitable for complex 3D flows with strong streamline curvature, strong swirl/rotation (e.g. curved duct, rotating flow passages, swirl combustors with very large inlet swirl, cyclones).

3.1.5 Discrete Particle Model

The discrete particle model was used to calculate the deposition of particles on the surface of the duct due to the presence of roughness elements. The rough elements were introduced in the duct to increase the velocity of the fluid mixture and due to that the turbulence effect is enhanced. The particles present in the mixture were deposited on the surface of the elements. This model is used to simulate the deposition process of the model. The validation of physical model illustrated in Table 2 and Fig.6.

Table 2 Model validation

Comparison	L_1/D	L_2/D
Present research	4.4	1.1
LES [21]	4.12	1.06
Hong [1]	4.1	1

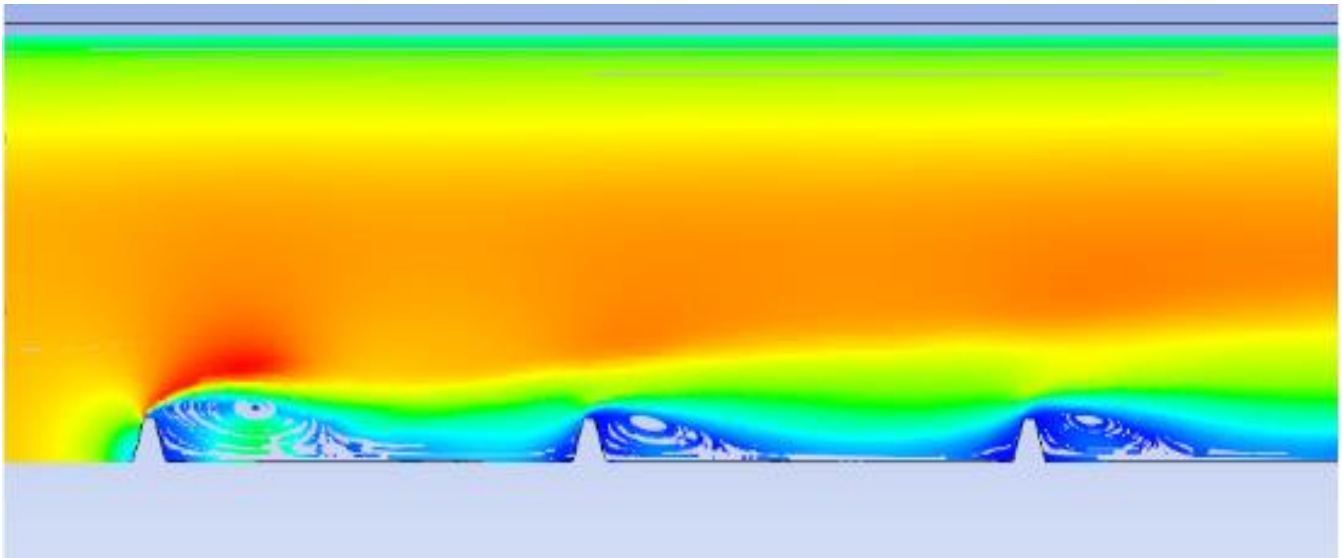

Figure 7 Eddies produced in the duct around the rough elements

3.1.6 Boundary Condition

The values of velocity and pressure at the inlet and outlet were chosen to set the boundary conditions for the analysis .Ten number of cases was analyzed in this research. The air dynamic viscosity was 1.9 × 105 kg s/m and the air density is 1.225 kg/m3 at T = 288 K. The air velocity is 10 m/s. The Reynolds number based on the mean flow velocity and duct length was very high. Meshing was performed to discrete the calculated domain by the software Ansys ICEM 19.1 for both smooth and rough duct cases. The ratio of particle density and fluid density was represented by S. It was shown how the particle deposition simulation result is affected by different particle numbers. There are 40,000 spherical and square particles were thrown into the flow fields and the air duct flow had been calculated from the convergence of the solution. Due to the fully developed airflow, these particles were released in the direction of length. The air means velocity and initial flow velocity are equal. Both the inlet boundary conditions and outlet boundary conditions for the particles are "Escape", while the boundary conditions choose for the wall and ribs are "trap". The study shows that we ignored the effect of re-suspension and rebound. An assumption had been considered that once the particles impact on the wall they will attach to it and never will be re-suspended.

3.2 Numerical Calculations

3.2.1 Particle motion model

In this study, we have used a Discrete Particle Model to simulate particle motion. Navier-Stokes Equation for x-momentum governing the present turbulent airflow is given ,

$$\frac{\partial \bar{u}_i}{\partial x} = 0 \quad (1)$$

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{1}{\rho}\frac{\partial}{\partial x_j}\left(\mu \frac{\partial u_i}{\partial x_j} - \rho \bar{u'_i u'_j}\right) \quad (2)$$

To impose a fully developed velocity and T.K.E. profile, user-defined boundary condition was used in duct inlet.

In this research, the turbulence effect can be calculated by using a Reynolds stress turbulence model which is used for modeling of highly turbulent flow. The RSM equation can be expressed as,

$$\frac{\partial}{\partial t}\left(\bar{u}'_i \bar{u}'_j\right) + \bar{u}_k \frac{\partial}{\partial x_k}\left(\bar{u}'_i \bar{u}'_j\right) = \frac{\partial}{\partial x_k}\left(\frac{v_t}{\sigma_k}\frac{\partial \bar{u}'_i \bar{u}'_j}{\partial x_k}\right) - \left(\bar{u}'_i \bar{u}'_k \frac{\partial \bar{u}_j}{\partial x_k} + \bar{u}'_k \bar{u}'_j \frac{\partial \bar{u}_i}{\partial x_k}\right) + p'\left(\frac{\partial \bar{u}'_i}{\partial x_j} + \frac{\partial \bar{u}'_j}{\partial x_i}\right) - 2\mu\left(\frac{\partial \bar{u}'_i}{\partial x_k}\frac{\partial \bar{u}'_j}{\partial x_k}\right) \quad (3)$$

*w*here, $\bar{u}_i$, represent the time-averaged velocity, x is the space position and $\boldsymbol{\sigma}$=1.0 is empirical constant.

The phase of the particles considered as a discrete phase and the model used for the discrete particle simulation is a discrete particle model. The phase equation of the particles is

$$m_p \frac{\partial u_p}{\partial t} = \frac{\pi d_p^2}{8} C_D \rho \left|u_i - u_p\right| \left(u_i - u_p\right) + m_p \frac{g_i}{\rho_p}\left(\rho_p - \rho\right) + 1.61(\mu\rho)^{\frac{1}{2}} d_p^2 \left(u_i - u_p\right) \left|\frac{\partial u_i}{\partial x_i}\right|^{\frac{1}{2}} \quad (4)$$

3.2.2 Particle Deposition and Deposition Efficiency of the Particles

For the computation of deposition velocity mostly non-dimensional velocity is considered for the calculation. In this study, the deposition velocity is defined as,

$$V_d = -\frac{DUln(1-N_{dep}/Nt)}{L} \quad (5)$$

Where the Nt is the number of total particles that are entering in the fluid and N_{dep} is the number of deposited particles on the roughened wall[22].The non-dimensional velocity can be given as,

$$V_d^+ = \frac{V_d}{u^*} \quad (6)$$

Here u^* represent the frictional velocity and it can be calculated as,

$$u^* = \sqrt{\frac{\tau_w}{\rho}} \quad (7)$$

Where, τ_w is representing the wall shear stress.

The non-dimensional particles relaxation time is given as

$$\tau_p^+ = \frac{Sd_p^2\, u^{*2}}{18\nu^2} C_c \quad (8)$$

Where S is the particle to fluid density ratio[24].

The deposition ratio of the particles can be calculated by the formula given as,

$$R_d = \frac{N_{dep}}{N_t}\, x100\% \quad (9)$$

Where, N_{dep} is the number of deposited particles and N_t is the total number of particles in the fluid

Chapter 4
Results and conclusions

4. Results and Discussions

4.1 Results analysis

A fully turbulent flow was analyzed in a square duct .The duct was divided into two sections, the first one is smooth and the other has roughness. The rough section has elements of different shapes to make changes in the fluid flow at different conditions. The velocity profile of the flow in a smooth duct is shown in fig 5. where the magnitude of the velocity is not increased significantly. However in fig.6 it can be observed that the value of velocity is improved up to 15 m/s that represent the effect of roughness on the flow. The comparison of both conditions signifies the cause of roughness on the developing boundary layer as the thickness of boundary layer increases with the enhancement of elements height.

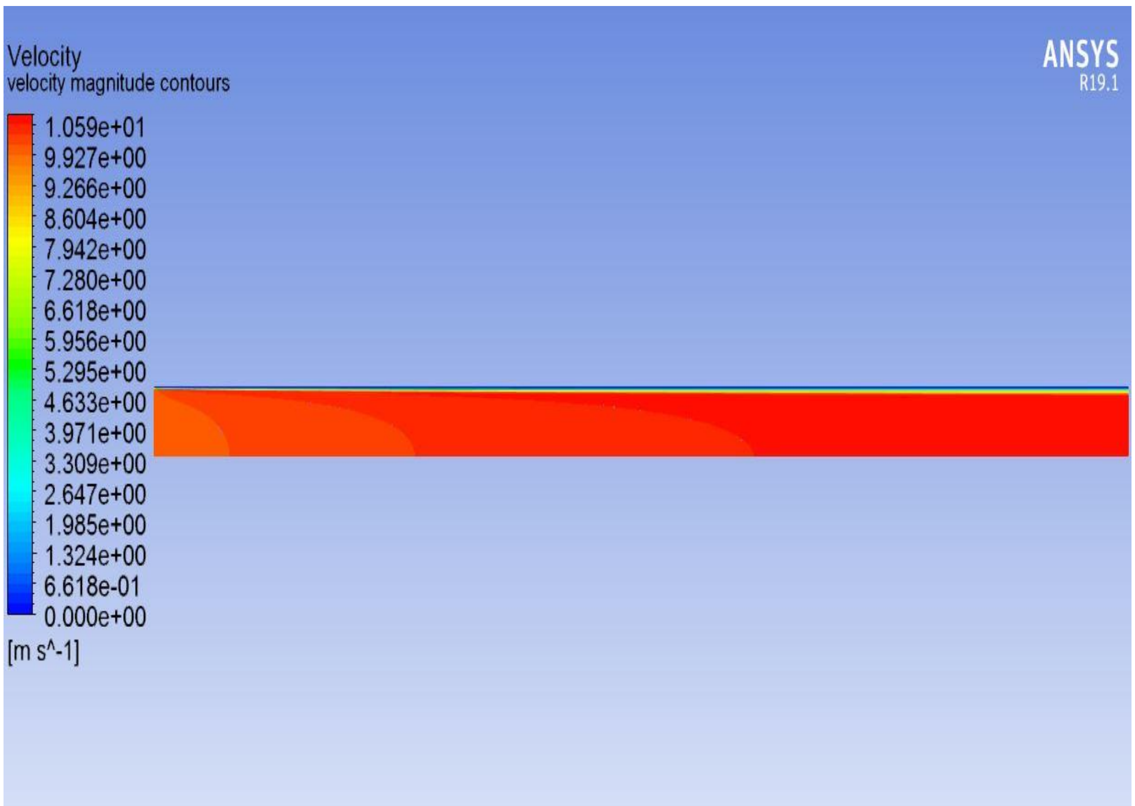

Fig. 8 the Square without rough elements

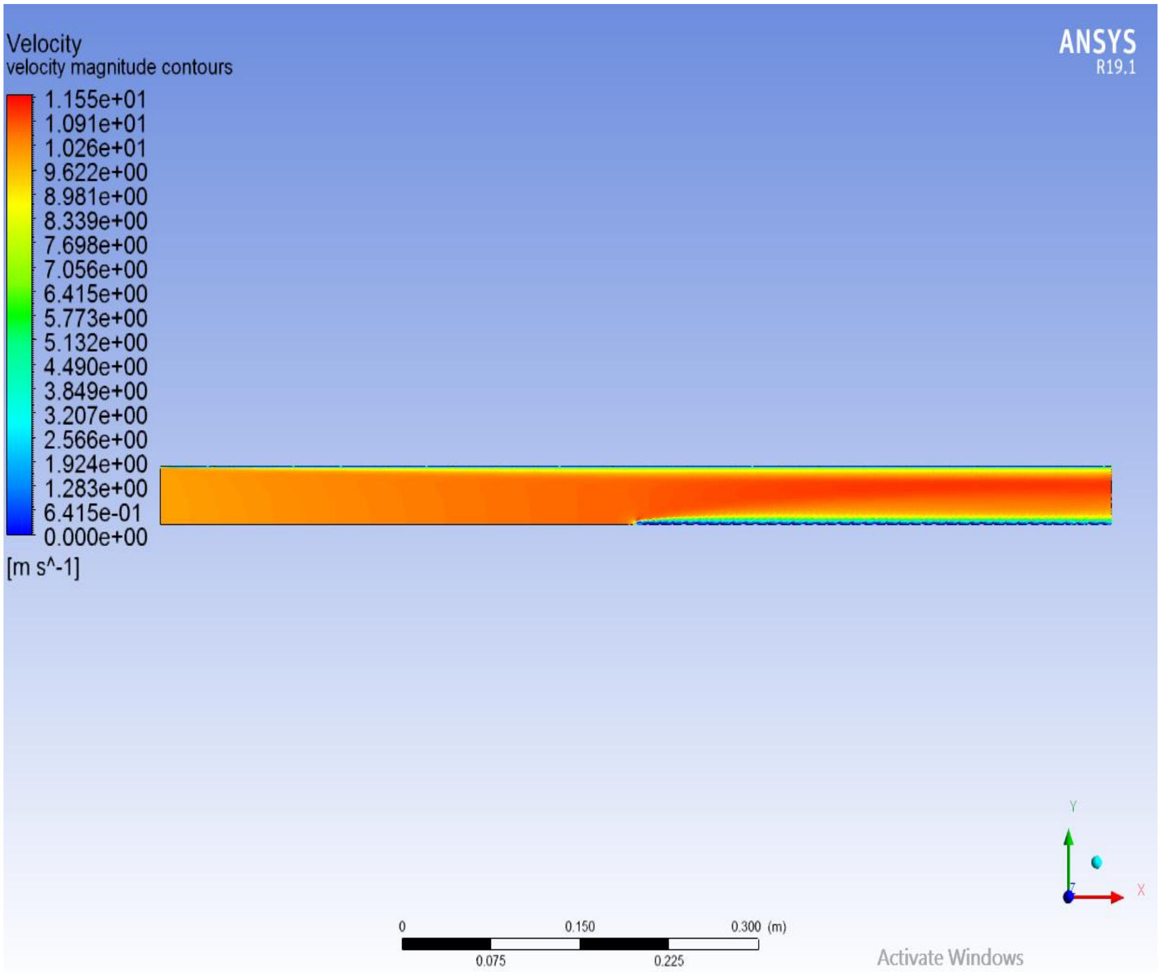

Fig. 9 The duct with and without rough rough elements

It can be seen that at the length X= 400mm the boundary layer is suddenly changed and its thickness is enhanced. Therefore, the rough surface has greater effect on the fluid flowing in the duct.

4.2 The effect of roughness and spacing on the flow velocity

The velocity of the fluid flowing in the duct was increased due to a region produced between the elements which is also called eddy region. The eddy region made the boundary layer very thick because of low pressure and the turbulence effect becomes greater as compared to the flow in a duct without roughness. The flow fields of different cases are in Fig.7 to Fig 14.

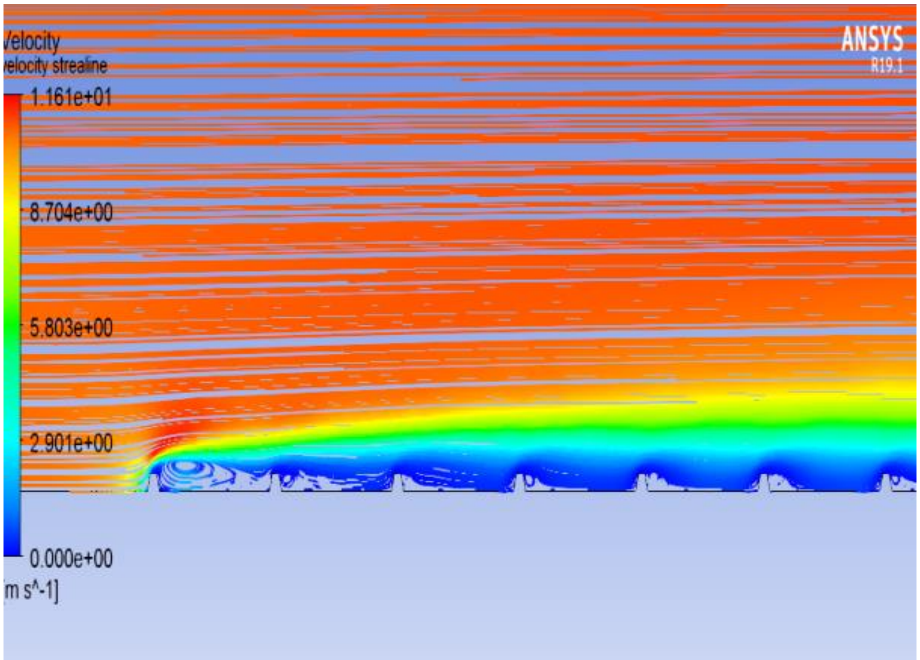

Fig. 10 r/D=0.024 s/r=9.8

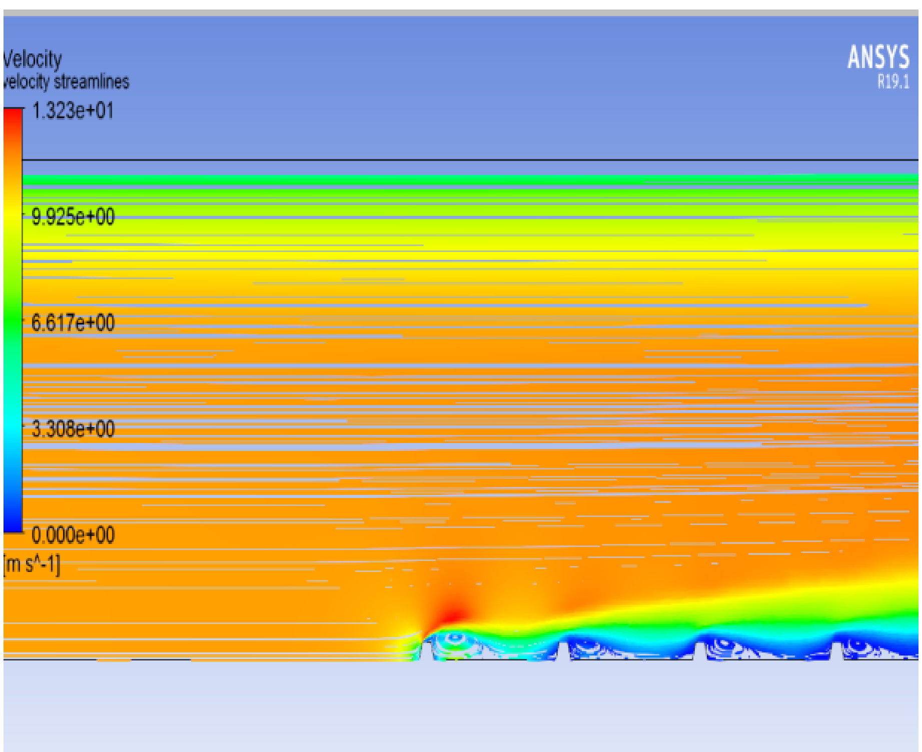

Fig. 11 r/D=0.036 s/r=9.8

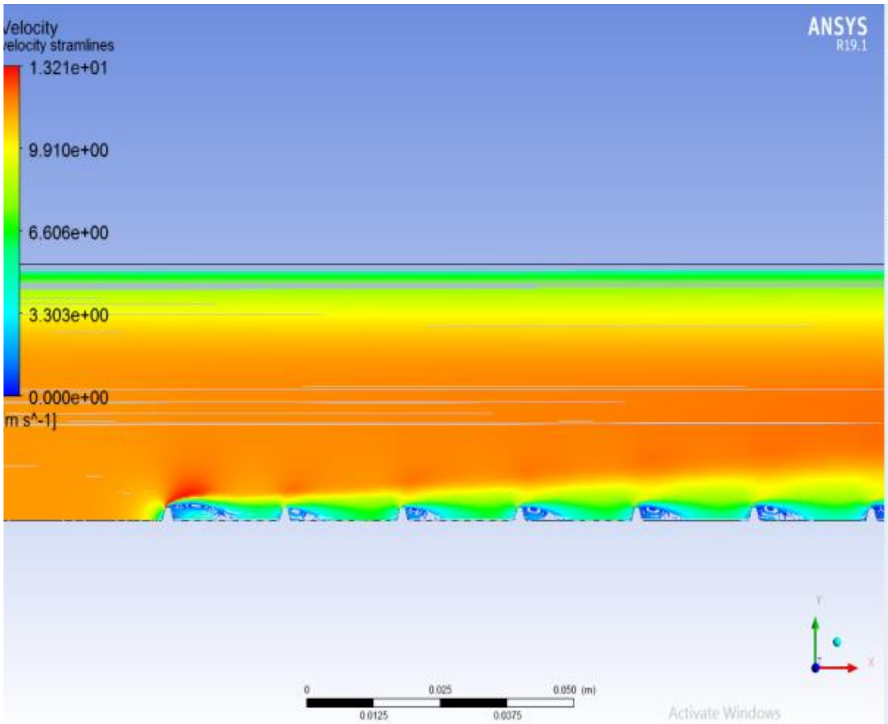

Fig. 12 r/D=0.051   s/r=9.8

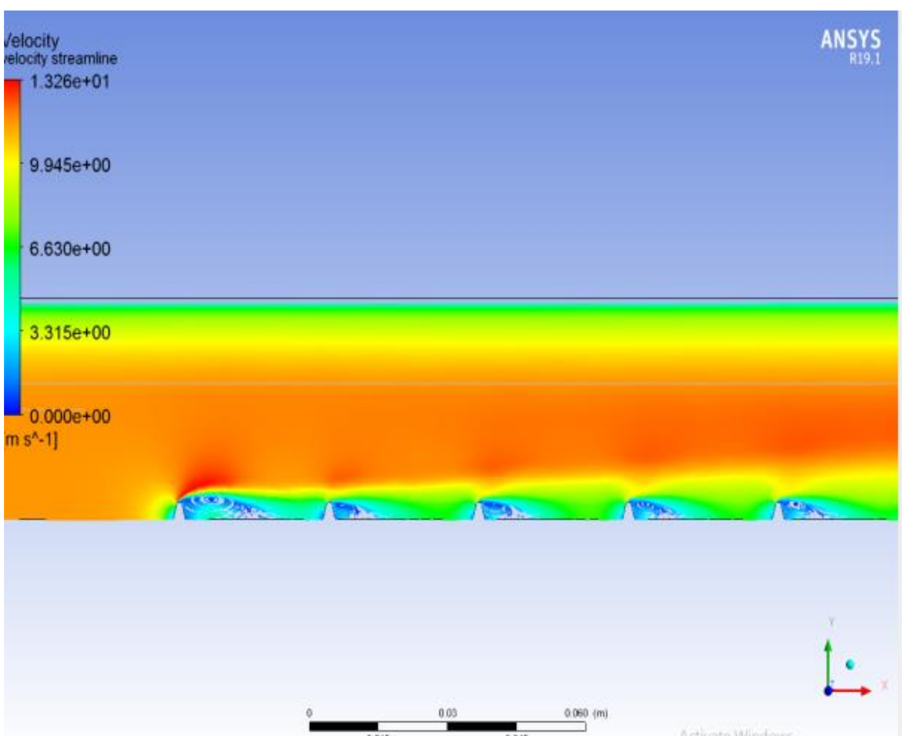

Fig. 13 r/D=0.076   s/r=9.8

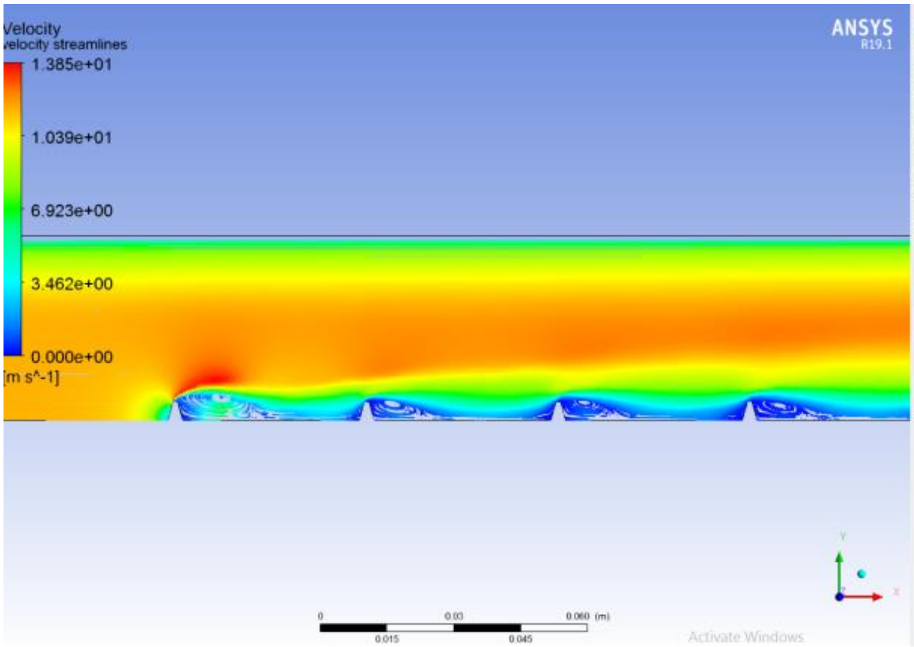

Fig. 14 r/D=0.101   s/r=9.8

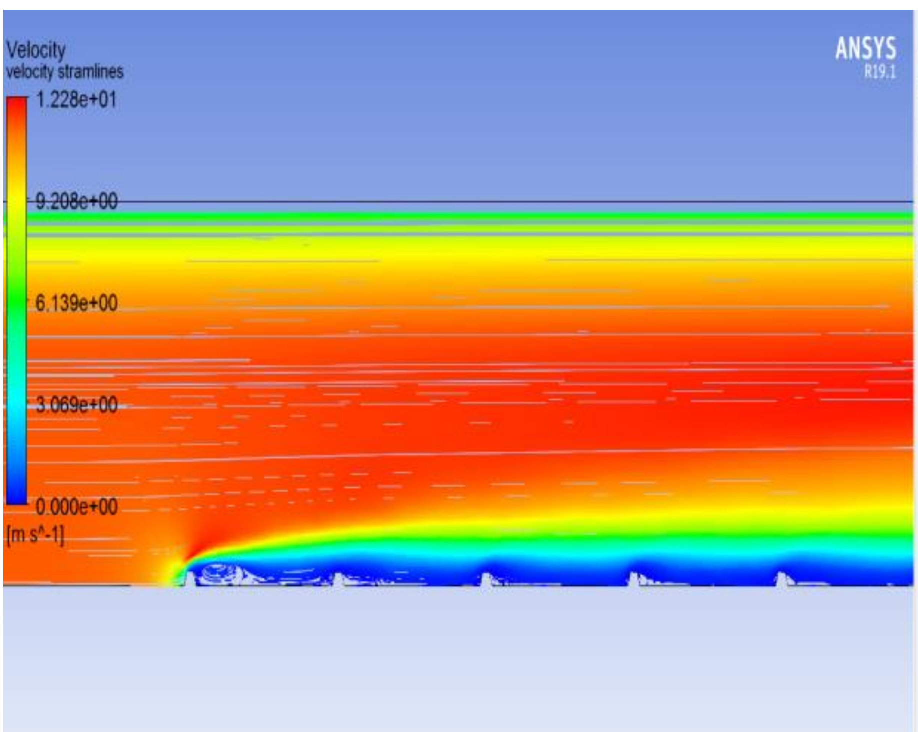

Fig. 15 r/D=0.036   s/r=7.93

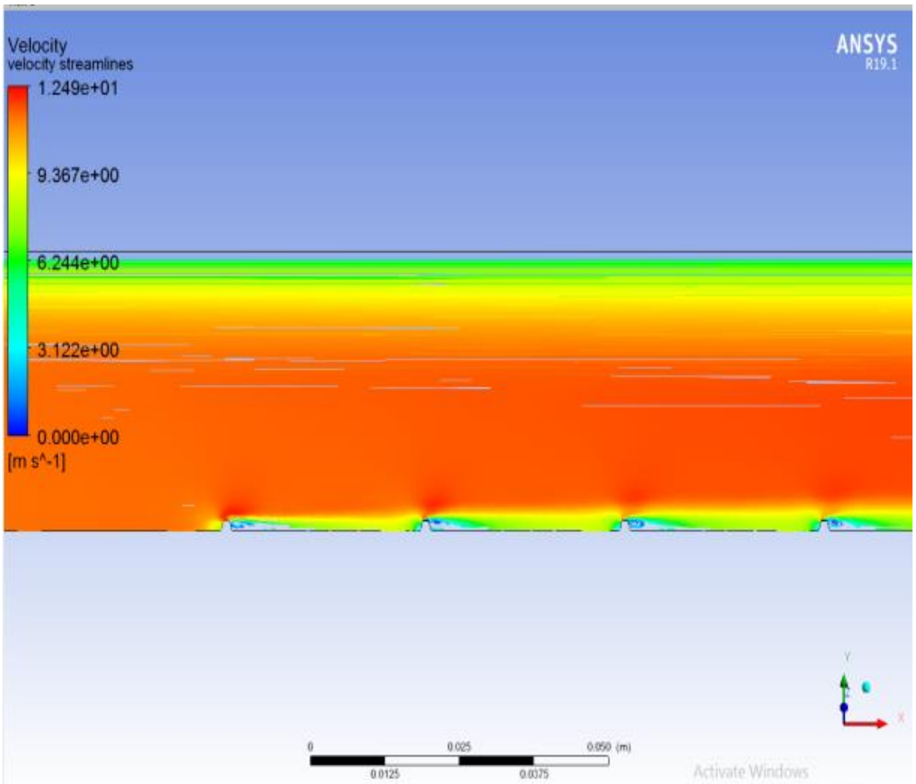

Fig. 16 r/D=0.036 s/r=14.06

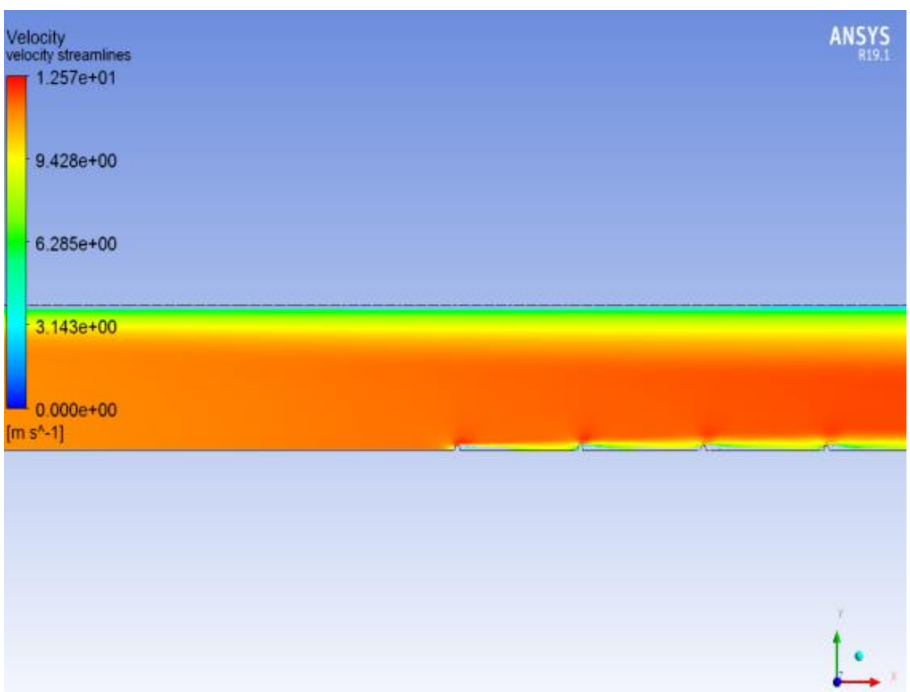

Fig. 17 r/D=0.036 s/r=27.05

The rough section in the duct is considered for the investigation instead of smooth section. All the cases from Fig 7 to Fig 14 express the velocity profile at different values of roughness height and relative spacing. It was found that a wake region is formed between the elements which contains two eddies. One is just after the element and other is before the elements. The size of low-pressure area is different at both positions as the section over the crude elements is larger than the other one. It can be seen in the Table.1 all the computational cases have different parameters especially explain the number of elements used in the duct. The ribbed surface has greater impact on the fluid in the duct as compared to the relative spacing. The contours of velocity magnitude become more visible when the height of elements was increased and the distance between elements remains same.

Table 3 Computational cases

No.	D(mm)	d_p(μm)	r (mm)	s (mm)	r/D	s/r	Element numbers
1	40	5	0.965	9.5	0.024	9.8	40
2	40	5	1.45	14.3	0.036	9.8	25
3	40	5	2.02	19.8	0.051	9.8	18
4	40	5	3.04	29.8	0.076	9.8	12
5	40	5,10,15,20,30	4.05	39.8	0.101	9.8	9
6	40	5	1.45	11.5	0.036	7.93	30
7	40	5	1.45	20.5	0.036	14.06	18
8	40	5	1.45	39.3	0.036	27.05	12
9	40	5	1.45	55.5	0.036	38.23	10

4.3 The effect of roughness on the particle deposition velocity

The non-dimensional deposition velocity was considered for the analysis to observe the deposition process. It is used because to find the more satisfactory results of particle velocity and relaxation time. For the validation of results according to the previous research the graph of non-dimensional velocity was plotted against the relaxation as time shown in Fig.15.The ribbed surface enhanced the value of velocity. This velocity is represented by V_d^+ and the ribbed surface specified by r/D. The Fig.16 shows that at constant valve of spacing the non-dimensional deposition velocity reaches the maximum value due to increase in height of roughness. In fig.17

it can be seen that when the value of roughness spacing increases the value of non-dimensional velocity decreases gradually and then become constant where the value of roughness is fixed.

If the results of fig.16 and fig.17 are compared then it can be seen that the roughness height has a greater effect as compared to the roughness spacing.

4.4 The influence of roughness on the efficiency of deposition

The result of different parameters like height and spacing of optimized design were analyzed to explain the deposition process of particles. The multiphase flow was considered for the investigation. The fluid flow in the duct is the fully turbulent at the roughest section as described in case 5 as shown in table 1.The different number of elements were used for the observation and in that case 9 elements were installed. It was found from the analysis that when the flow reached to the half of the duct the particles are started to deposit on the elements of roughness. It can be seen in all cases most of the particles are deposited on the first element as compared to others. The particles are also trapped between elements due to the formation of eddy region. It was also observed that this process also occurs on the others elements and becomes constant after some extent.

The ratio of particles deposition process is improved with the enhancement of relative roughness as described in Fig. 18.The particles find more space to deposit because of large roughened area. The Fig. 19 shows that when the spacing between the elements becomes large the deposition of particles on the rough surface is minimized. It is due to that when the spacing between elements enhanced the strength of the deposited particles becomes weaker and therefore the particles escape from the outlet of the duct. When spacing is larger the particles are also deposited on other surfaces and escape through the outflow of the duct, but as compared to the rough surface the deposition of particles is almost five times less. The deposition ratio becomes a maximum of almost 14% when the value of roughness r/D is 0.101 and the value of s/r is fixed therefore it is the validation of the results.

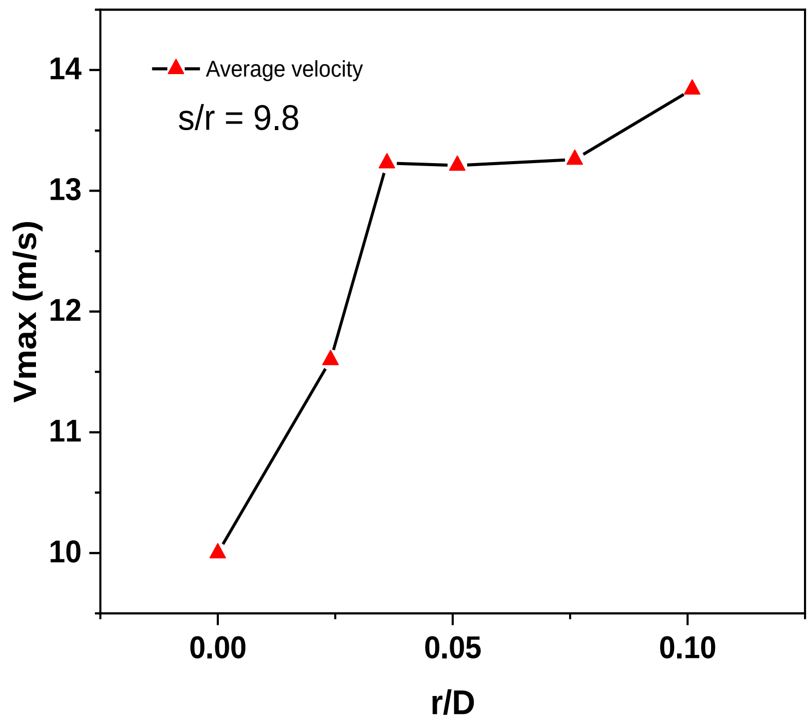

Fig.18 Maximum flow velocities with different value of r/D

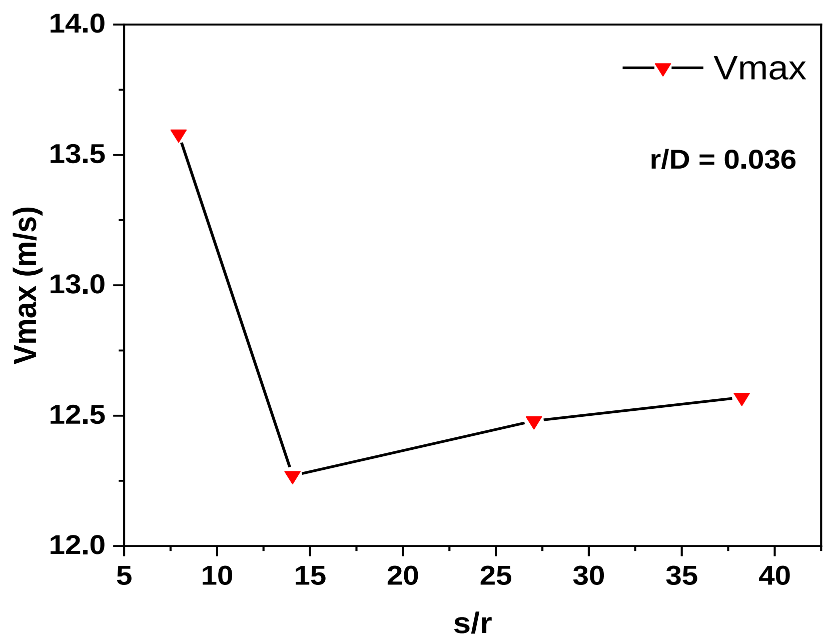

Fig. 19 Maximum flow velocities with different value of s/r

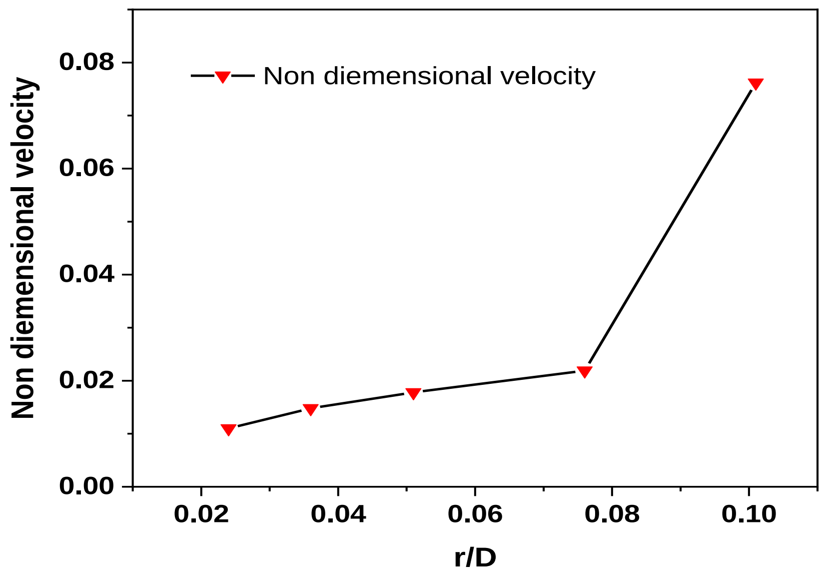

Fig.20 The non-dimensional deposition velocities with different values of r/D

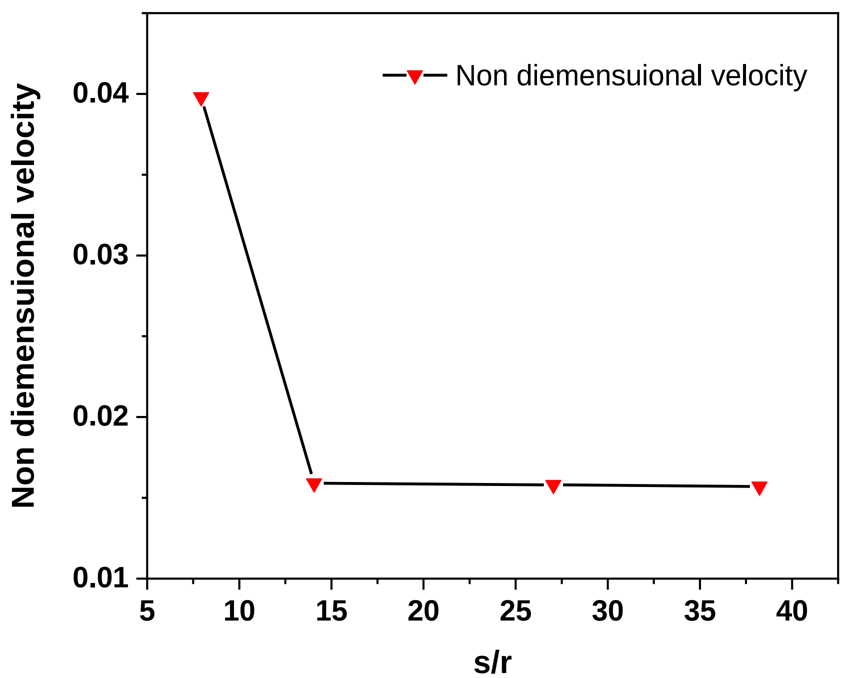

Fig.21 The non-dimensional deposition velocities with different values of s/r

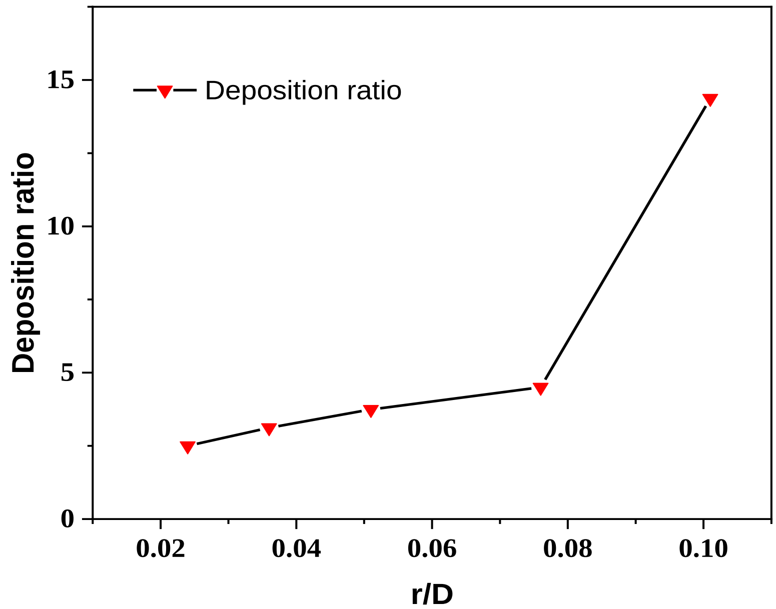

Fig. 22 Deposition ratio of the particles with different values of r/D

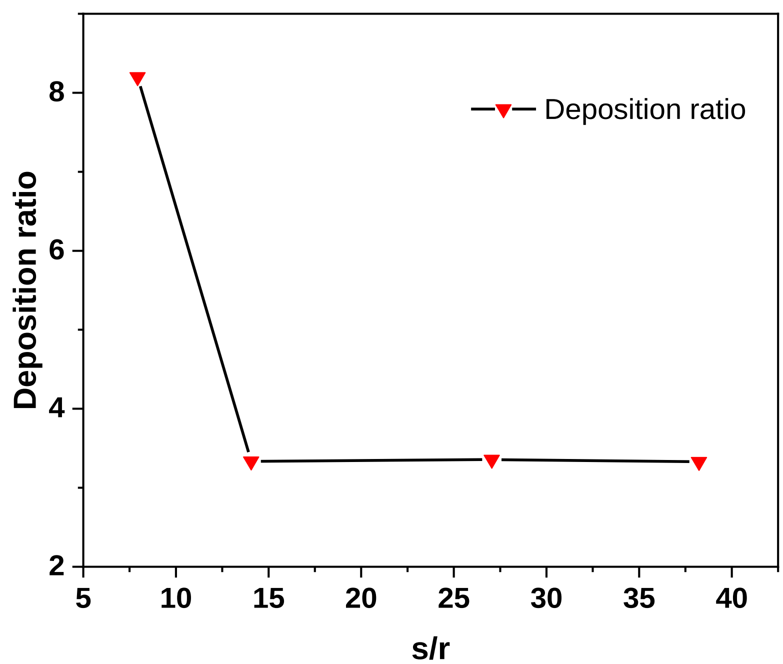

Fig. 23 deposition ratio of the particles with different values of s/r

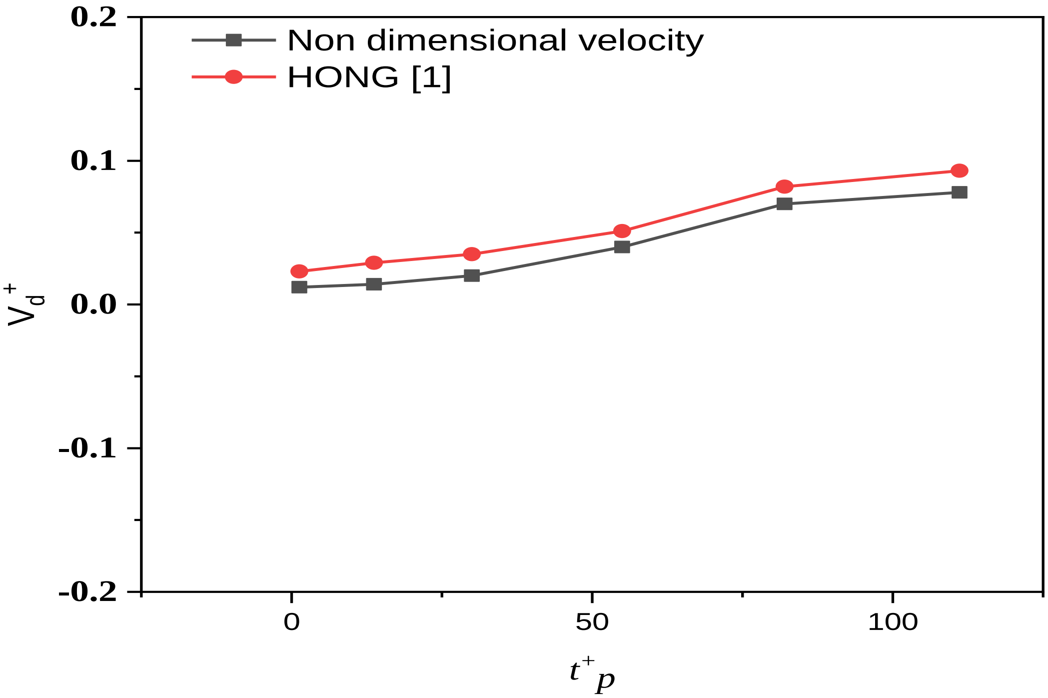

Fig. 24 Validation of non-dimensional deposition velocity

Chapter 5

Conclusion

5. Conclusion

In this research, the particle-laden flow was analyzed and the deposition of particles in a square duct with different values of roughness height and spacing was investigated. The numerical models used for this study are the Reynolds stress model and the discrete phase particle model. The Reynolds stresses model is used for the simulation of highly turbulent flow and the discrete phase particle model is used for studying the deposition characteristics of the particulate flow. From this research following conclusions are obtained,

1. The velocity of the fluid flow increases in the presence of 2D roughness elements and the boundary layer thickness also increases. When the height of the roughness increases the low-pressure region is produced between the elements called as eddy region. Due to that phenomenon the turbulent effect of the fluid increases as well as the velocity of the fluid.
2. The particles deposition ratio increases with the increase of roughness height. When the height of rough elements increases the turbulence effect is increased due to eddies produced between the elements and the particles are deposited on the rough surface. On the other hand, when the spacing between elements increases the deposition ratio has decreased because the eddy region becomes weakened due to the large space between the elements. Therefore, most of the particles are escaped from the outflow.
3. The particle deposition velocity increases with the increase of relative roughness height as compared to the relative value of space between elements. Therefore the relative roughness has a greater effect on the particle deposition velocity because when its value reaches maximum the deposition velocity becomes almost constant.

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