NUMERICAL AND EXPERIMENTAL ANALYSIS OF THE POWDER FLOW STREAMS IN THE LASER AIDED MATERIAL DEPOSITION PROCESS

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Abstract

Axial powder stream concentration between the nozzle end and the deposition point is an important process parameter in the laser aided material deposition process. The powder concentration is greatly influenced by the nozzle geometry in use. This paper describes the numerical and experimental analysis of this important parameter in relation to the coaxial nozzle. The experiments are performed with the different nozzle geometries to generate various flow patterns of the gravity fed powder in a cold stream. The results of the experimental analysis are compared with the numerical simulation and found justified. These results are used in concluding the significance of important nozzle parameters for various powder concentration modes.

Introduction

Laser deposition process consists of feeding the metal powder into a hot spot called as melt pool to form a melted zone which solidifies into a bead. The coaxial nozzle is widely used for this metal deposition process [3, 9]. The metal powder is fed through the nozzle in the melt pool in a coaxial system instead of the external tubes as in the side nozzle. Laser aided deposition quality largely depends on the powder stream structure below the nozzle [7]. The variation of the powder stream concentration in axial direction affects the material delivery rate at the deposition point and the interaction of the laser beam radiation with the powder stream [4]. High efficiency of the powder deposition in a coaxial system is an important subject for the study. The focusability of the stream structure is a key factor of the energy utilization and catchment efficiency of the coaxial nozzle [5]. It is found that most of the laser power reaches the substrate with some energy loss in the particles in laser deposition process [9]. This is sometimes caused by the shadow effect of one particle over another due to the absorption of the beam energy by the powder stream. The stream structure is mainly influenced by the powder flow settings and nozzle arrangements [5]. It is also found that the powder catchment increases with increase in the powder flow velocity [9]. The process of deposition involves control of various parameters like powder type, powder flow velocity and gas velocities. Though these are actual process parameters, the initial powder flow is defined by the nozzle geometry in use. Thus, optimizing the deposition nozzle for such process is not an easy task and hence requires a lot of experimentation and numerical simulation.

It is difficult to find the literature explaining about the effect of nozzle geometry at the powder outlet area of the coaxial nozzle on the powder concentration mode. Though the above mentioned studies have been carried out, the detailed study needed to be done entailing the effect of the nozzle geometry at the powder passage on the flow mode. The initial consideration should be given in generating various types of powder streams by using different nozzle geometries at the powder outlet area. It is necessary to understand the proper powder flow behavior to determine the displacement of the powder between the nozzle and deposition point. This will help in getting the value for the distance of maximum concentration point of the merging streams of the powder from the nozzle end. This will further assist in studying the relationship between the melt pool and the powder stream. The effects of different nozzle geometry parameters on the powder stream mode are examined here. This paper describes a particular system by the experiments, numerical simulation and the image analysis method.

Experimental arrangement

The experimental arrangement used to characterize the powder stream by artificial vision is explained here. The figure 1 shows the schematics of the same. This experimental visualization of the powder from the coaxial nozzle in turn helps in characterizing the nozzle performance. As shown in the figure, a laser light source was used in the experiments to catch the cold flow near the end of the nozzle. The powder material used was H-13 tool steel of mean diameter of 90µm. The mass flow rate of 5g/min for the powder was used for the experiments. A screw feeder was used to supply the powder to the coaxial nozzle. The inner and outer shielding gas velocities were strictly controlled at 2m/s and 5 m/s respectively. Nitrogen was used for both type of shielding gases. These are the normal settings for this particular system. Various nozzle geometries were considered for the different experiments. These geometries are explained in the next part. A series of visualization experiments were photographed by the digital camera.

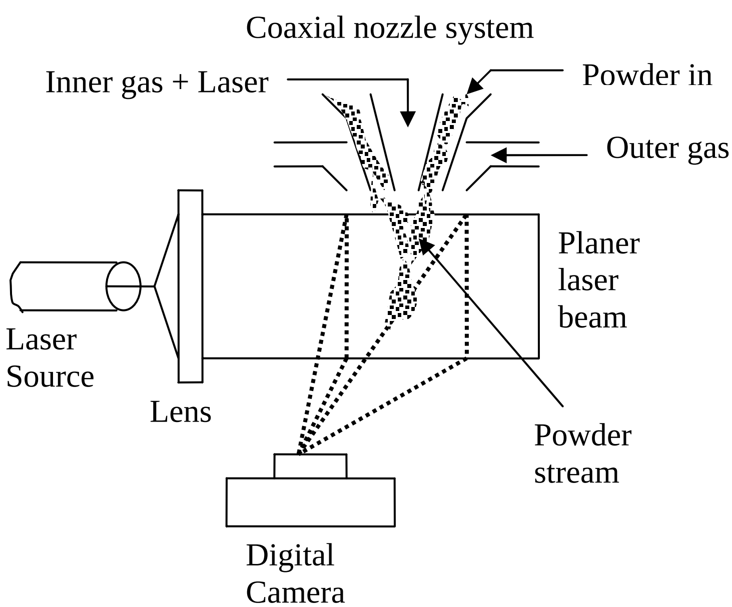


Figure 1: Experimental arrangement

Nozzles for testing

The diameters of the powder streams are assumed as the linear functions of the spraying angle and the opening diameter of the nozzle. A proper arrangement of the nozzle exit is essential for controlling the powder impingement on the substrate under laser radiation [5]. Therefore different geometry profiles were considered for this study. The reason for different settings was to generate different flow structures to control the powder spraying and change the powder concentration. Thus, the focused and non focused streams were both generated by using the coaxial nozzle. Though the actual nozzle would be of copper for its excellent reflectivity and thermal conductivity properties, the test nozzles were made from the FDM rapid prototyping machine for saving the time and cost. It was ensured that the surface properties of the test nozzles match with the actual metal nozzle. The typical coaxial nozzle assembly is shown in figure 2.

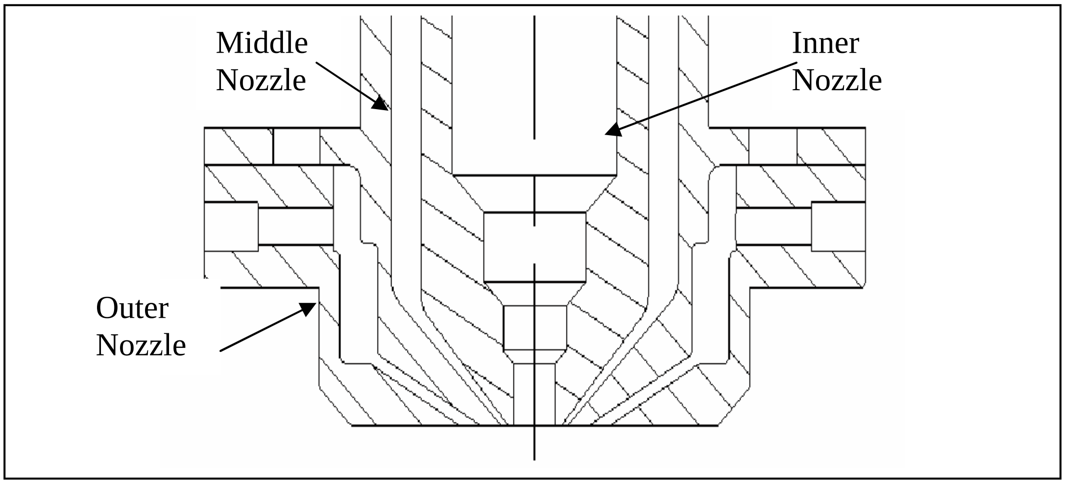


Figure 2: Sectional view of the coaxial nozzle assembly

Inner nozzle

The outer inclination angle settings for the inner nozzle are same as that of the inner inclination angle settings for the middle nozzle. This helped in getting the even gap between the two nozzles through which the gravity fed powder flows down towards the melt pool. The laser beam and inner shielding gas enter through the inner nozzle into the deposition area.

Middle nozzle

The inner inclination angle of the middle nozzle is measured from the horizontal axis. The two level full factorial designed experiments were conducted for the two factors of the middle nozzle geometry. The two factors are middle nozzle inner inclination angle and the opening diameter of the middle nozzle. The angle levels are low (45º) and high (60º) while the opening diameter levels of the middle nozzle are 6.35 mm and 7.11 mm. These settings form gaps of different shapes between the inner nozzle and the middle nozzle and in turn tend to have the influence on the powder flow from the nozzle. Initially, the middle nozzle with 30º setting was also tried but not found good in terms of free powder flow without accumulation and therefore not considered further for the analysis purpose. Also, larger nozzle diameters tend to form more spraying of the powder after leaving the nozzle and not taken into consideration. These, four dimensions were used for forming four different settings for the experimental study.

Outer nozzle

The outer shielding gas is supplied through the outer nozzle. The inner inclination angle of the outer nozzle with the horizontal axis was 30º. The setting of the outer nozzle was same for every experiment. Also, the same outer shielding gas velocity was used for each nozzle setting. This was required so that the focus on finding out the effect of the middle nozzle geometry settings on the powder flow was satisfied.

Tools for analysis

The analysis of the experiments done was performed by image processing technique. The results of the image processing method were compared with the numerical simulation results. These two methods are explained below in detail.

Image processing

The images from the scattered light from the powder stream taken by the digital camera reveal the cold powder stream structure. These series of images taken at high speed were used as an input to the special image processing software. The method of image analysis used is founded on the theory of scattering of light by small particles [4]. The 30mw laser source was used in generating the planer beam of approximately 2mm thick for illuminating the stream structure. The typical high speed image taken by the camera is shown in figure 3. The series of images were taken for randomly selected settings so that data would be statistically valid. The images taken for each setting were converted to the gray level and averaged out to give the resultant image for the further analysis of powder concentration. It is known that luminance intensity would be the linear function of the powder concentration [4]. The Microsoft excel software tool was used for processing the data obtained from the image processing software.

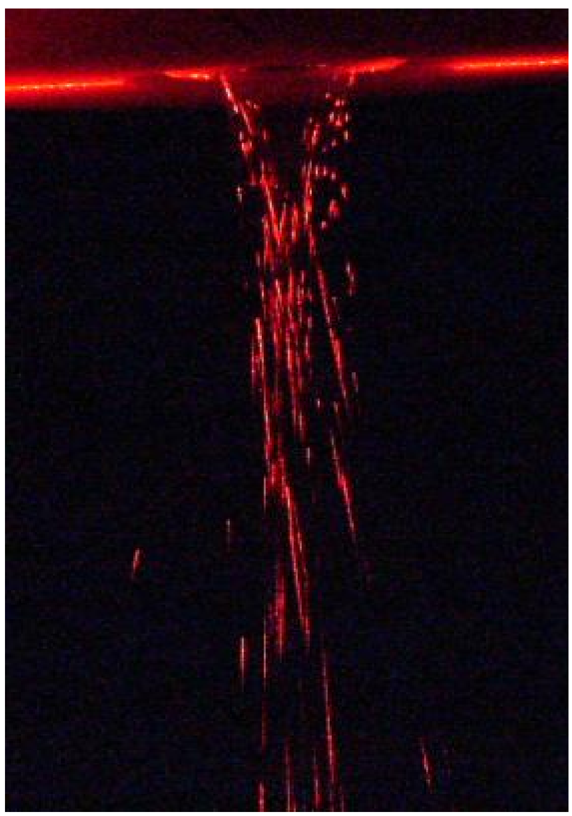


Figure 3: Typical image of the powder stream taken by digital camera

Simulation method

The discrete particle method was used to validate the results obtained with image processing technique. The powder stream structure was obtained numerically by considering the particle-wall interactions. Portion of the collisions were considered as non-spherical collision so as to simulate actual particle dispersion in nozzle. The governing equations can be referred to [7]. The different nozzle settings were evaluated numerically. The important parameters under consideration were nozzle geometry such as inclination angle, opening diameter, nozzle surface roughness properties and powder particle characteristics. The Navier-stokes equations were applied in getting the flow field for outer/inner gas. The visualization results from the simulation method were analyzed in the same manner as for the image processing results so that both can be compared. The results are mentioned in the later part of the paper.

Results of image processing analysis

The influence of nozzle geometry parameters is assessed by the stream structure of the powder flow in a coaxial system in this paper. The non-intrusive measurement approach of image processing can estimate the powder concentration along the axial and radial direction based on recorded luminance intensity from image data. The experimental analysis based on image processing technique to answer the questions is explained here. It was found out earlier that catchment efficiency can be increased if the powder stream can be made to have a smaller diameter at the impact point based on stream geometry [9]. The powder distribution within the laser beam was found to be typically of Gaussian mode [2]. The luminance intensity analysis was used here to compare the concentration profiles from the different image data in this work. The results of the particle concentration mode variation for different nozzle geometries are explained here. The typical averaged out image with the use of the software is shown in figure 4.

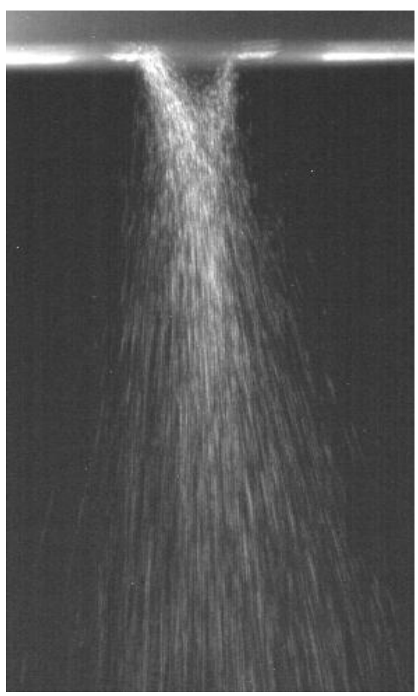


Figure 4: Typical visualization result (Average image).

More than 50% of the laser energy could be lost sometimes in the powder stream [5]. Thus merging pattern of the powder is very important in coaxial laser deposition for better laser energy utilization also. The profiles of the normalized powder concentration which is proportional to the luminance intensity were plotted using Microsoft excel tool from the data obtained with image processing. These plots are shown in figure 5 [a - b] where axial distribution for the various nozzle settings can be observed. The plots show the luminance values at various distances from the nozzle end along the central axis of the nozzle. The distribution is obtained by the illumination of the planer stream of the powder with the low power laser beam. It can be seen that the powder concentration varies along the beam axis. The focal positions where the maximum value of the concentration is observed vary with the nozzle geometry in use. The distance of this maximum concentration point is found to be around 6 - 8 mm. The powder concentration is reduced by 25 -30 % as observed by changes in peak luminance value with increase in the nozzle opening diameter which in turn increases the stream width. The plots show that the 45º setting has approximately 15 % higher concentration values than for 60º nozzle setting at maximum observed luminance intensity level. These concentration values for 45º nozzle are higher than that of the 60º nozzle setting for both the middle nozzle opening diameter settings. This could be the result of more merging of the powder particles at a point in axial direction when 45º angle was used. It was observed from the images that after merging at a point the stream diverges more for 45º setting than for 60º setting.

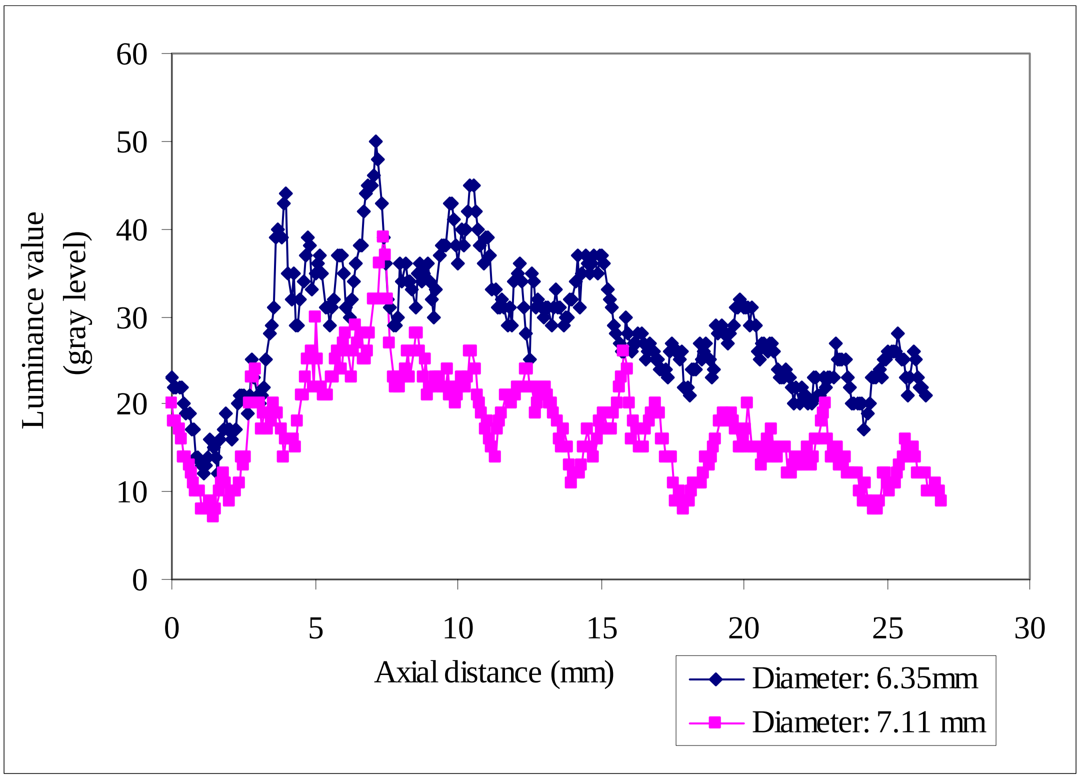


Figure 5 (a): Axial distribution profile for 45º setting (Powder flow rate: 5 g/min)

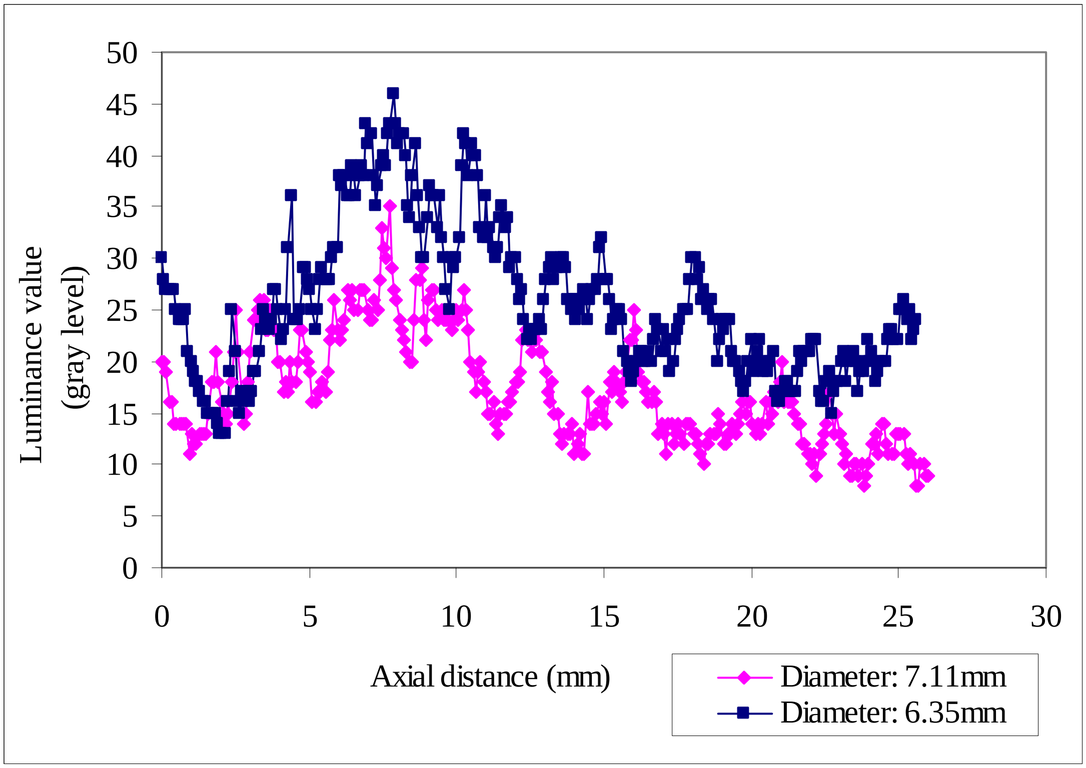


Figure 5 (b): Axial distribution profile for 60º setting (Powder flow rate: 5 g/min)

The focused streams can give peak catchment efficiency at their focal points [5]. Therefore, radial concentration profiles were plotted at a point of maximum luminance value for each setting. These plots are shown in figure 6 [a - b]. The amount of spread in these graphs over the radial distances can be used to explain about the merging pattern for each setting. The nozzle with 45º middle nozzle inclination angle gives the higher concentration values and radial concentration plots show that the streams are more concentrated for 45º setting than for 60º setting. Though it seems to be important property of concentrating the powder at a point along the axis, there is some literature saying that focused powder streams can’t improve catchment efficiency too much due to its high consumption of the laser energy in the powder cloud at the stream focus [5]. Dense powder concentration is not recommended in coaxial laser cladding at low power [5]. The figure 6 (b) shows that the spread of the powder is more for 60º than for the 45º setting in the radial direction. This is due to less focused stream structure formed by the 60º nozzle. It was found that columnar streams are better for the low power laser applications [5]. Thus, the nozzle with 60º setting could be very useful in the direct laser deposition process mentioned over here.

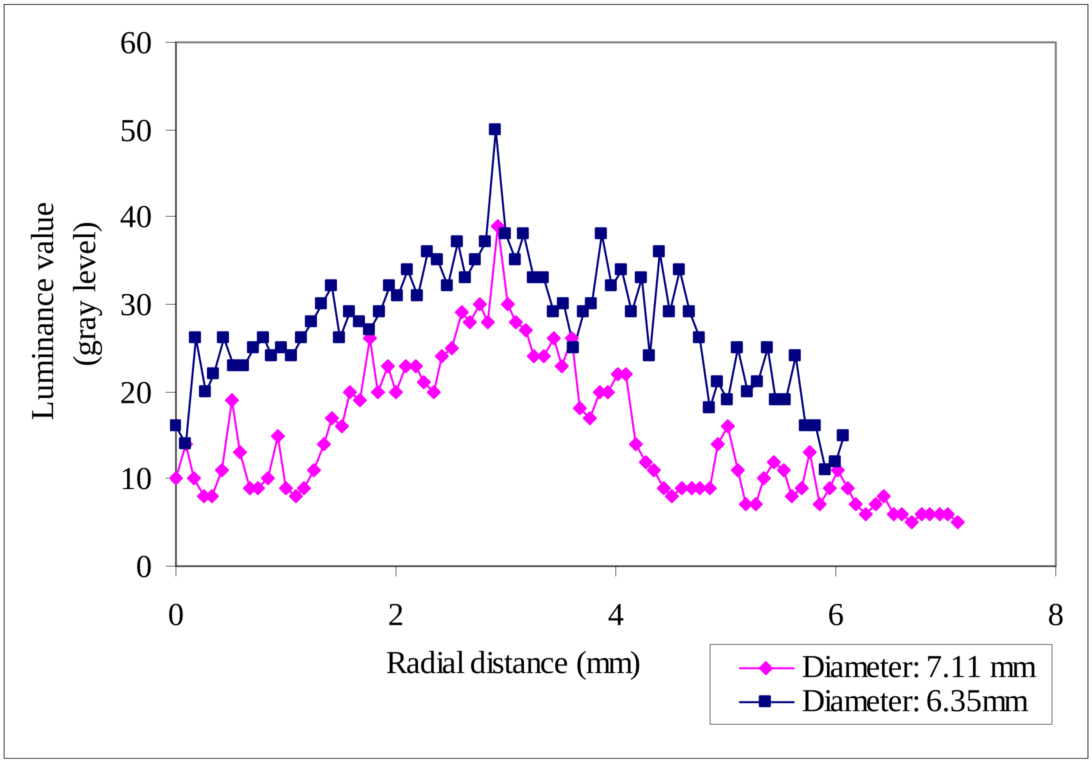


Figure 6 (a): Radial profile for 45º setting (Powder flow rate: 5 g/min)

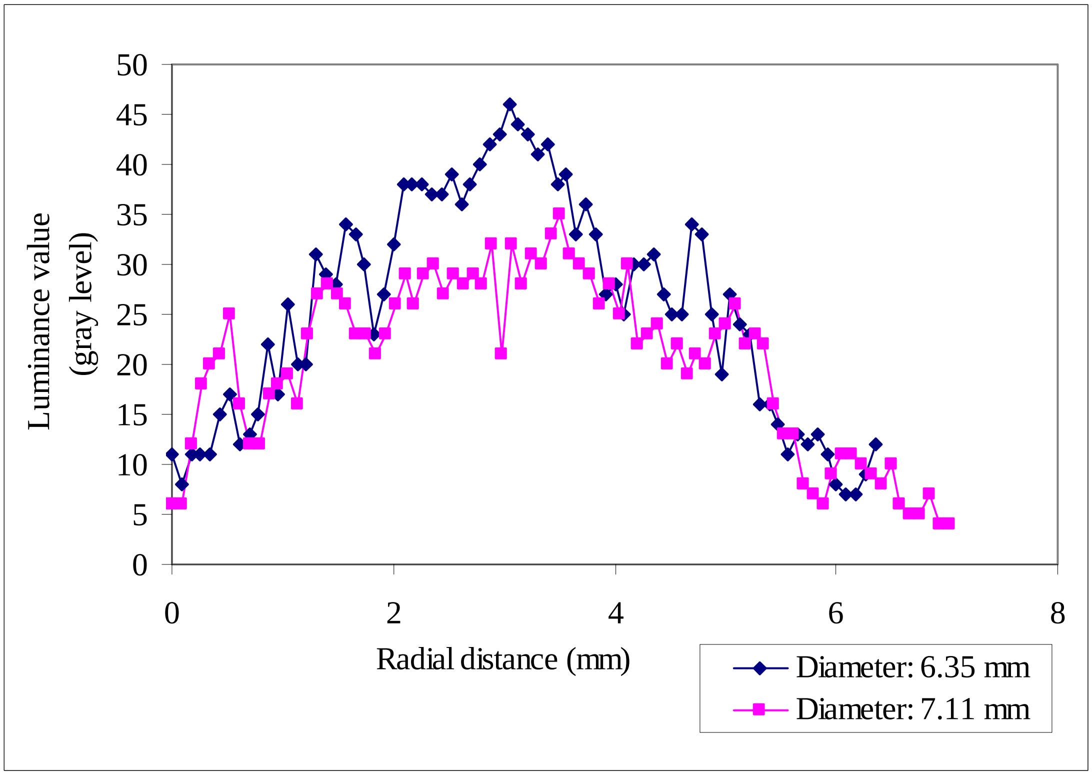
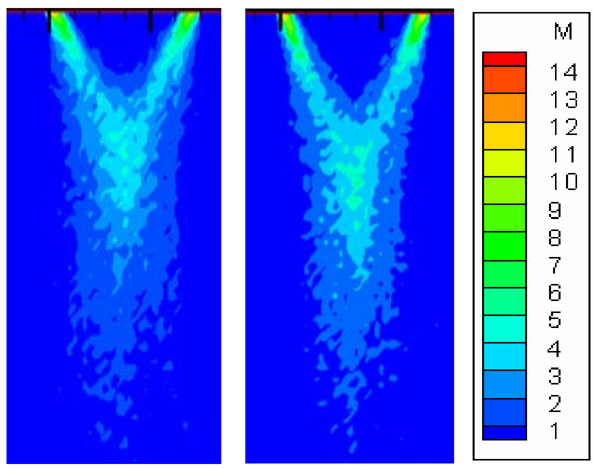


Figure 6 (b): Radial profile for the 60º setting (Powder flow rate: 5 g/min)

Discussion of simulation results

The visualization results of the numerical simulation are shown in figure 7 [a - b]. The figure 7 (a) shows the distribution of the powder particles with 45º. It can be seen that the powder tends to focus more at a point with this setting. The powder stream shows the columnar distribution with 60º setting. The plot in figure 8 shows the axial distribution of the powder particles for both angle settings. These plots also indicate that the peak values are higher for the 45º nozzle settings than for the 60º setting. The distances of peak points from the nozzle end are approximately same to those observed by the experimental analysis which is around 6 – 8 millimeters. The radial distribution profile shown in figure 9 indicates more focusing of the powder particles with higher concentration values over a small region for 45º setting than 60º setting. Thus, simulation results justify the experimental results closely.



(a) (b)

Figure 7: Simulation results: (a) 45º setting, (b) 60º setting

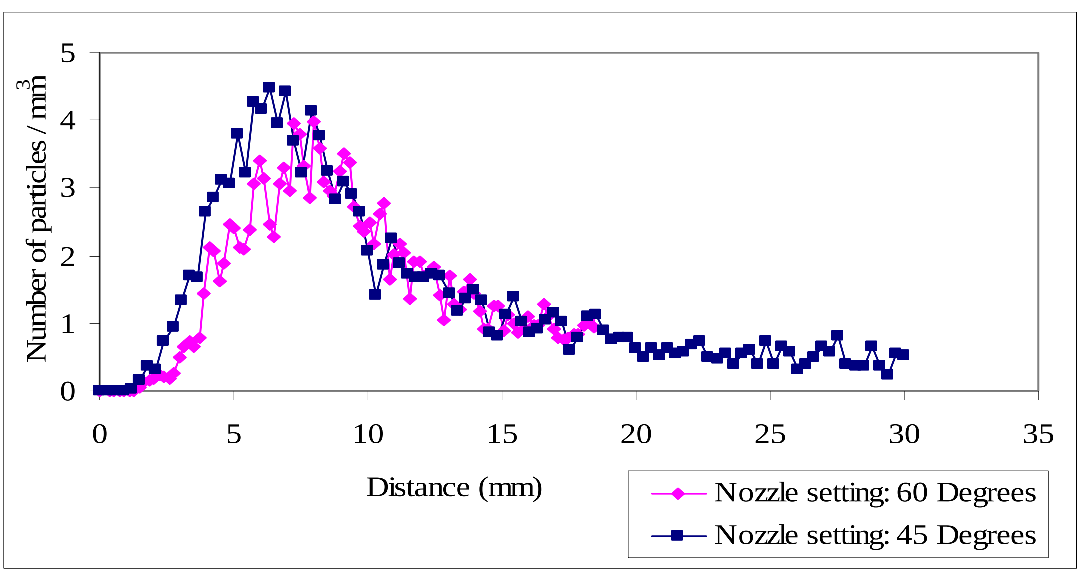


Figure 8: Axial distribution obtained with simulation method

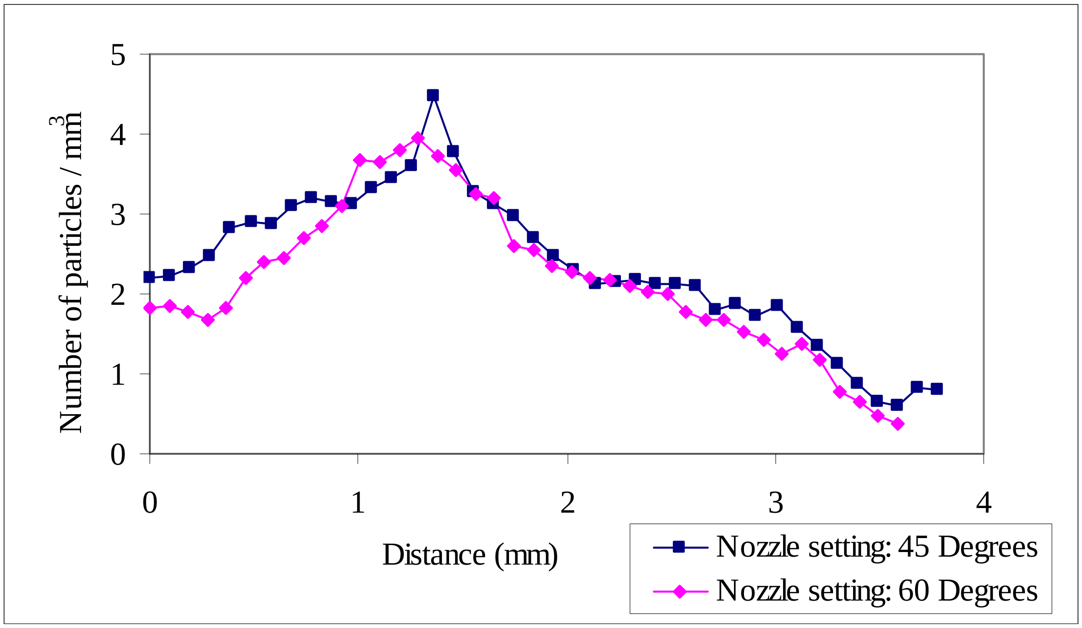


Figure 9: Radial distribution obtained with simulation method

Conclusion

The control of the nozzle geometry parameters help to generate the desired stream structure of the powder. The experimental results are compared with the simulation results. It was found earlier that the efficient way of laser energy transmission is through columnar stream due to less absorption of laser energy in the stream structure [5]. Thus columnar streams can be generated with higher inclination angle (60º). The reduction in the nozzle angle tends to focus the powder at a point near the axis. The opening diameters also contribute towards the distribution of the powder in the stream. The smaller opening diameter of the nozzle gives smaller stream diameter at the peak value. This would be helpful in increasing the catchment efficiency [2]. It was observed that the powder flow is smooth with less collision of the particles for the higher angle settings. The concentration distribution along the beam center could be obtained uniformly for better laser energy utilization by increasing the middle nozzle inclination angle to a certain level and reducing the opening diameter of the middle nozzle depending upon the system in use.

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Author autobiography

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