EFFECT OF PROCESS PARAMETERS ON THE SUBSTRATE SURFACE IN COLD SPRAY COATING

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SUMMARY

In this work, we used the cold spray process to coat a surface and investigated to understand the influence of various process parameters on the substrate surface temperature. The parameters we varied included the pressure, temperature, particle size, and particle speed of the titanium powder that we used in the cold spray coating process. It is a unique finding in the field of cold spray coating. For the substrate material, we chose steel and simulated the spray geometry using a two-dimensional axisymmetric model. This model employed a k-ε turbulence model with an implicit pressure-based solver of second-order precision. Our observations revealed that the surface temperature of the substrate reached its maximum value when the length of the injector was 15 mm. We also found that the most compatible length for the nozzle barrel was equal to the length of the particle injector.

KEYWORDS

Nozzle, Cold spray, CFD (Computational Fluid Dynamics) analysis, Barrel length, Particle injector length

NOMENCLATURE

R	The volume flow rate (m^3/s)
A	The flow area (m^2)
v	Fluid speed (m/s)
ρ	Fluid density (kg/m^3)
U	Velocity vector (m/s)
τ	Stress tensor (Pa or N/m^2)
g	Gravitational Acceleration (m/s^2)
ρ	Fluid density (kg m-3)
Q	Heat (Joules, J)
U	Internal energy (Joules, J)
PE	Potential energy (Joules, J)
KE	Kinetic energy (Joules, J)
P	Pressure (Pa or N/m^2)
V	Volume (m3)
W	Work (Joules, J)

1. INTRODUCTION

Cold spray coating is a process that uses particles with low temperatures and high velocities to apply a layer of material on a surface. The particles do not melt or oxidize during the process. The Russian Academy of Science created and developed the cold spray coating which is a purely new finding and technique to coat, in the 1980s, and it has been used for different materials and conditions in manufacturing and coating applications (Li et al. 2007; Lupoi et al. 2020). In contrast to the thermal spray coating technique, the cold spray coating technique's particle temperature was kept lower than the melting point of the material particles, in this way the material properties were not affected in the cold spray coating process technique (Li et al. 2012; W. Li et al. 2016). The cold spray coating technique is a modern process that applies a material layer on a surface with low-temperature and high-velocity particles. The cold spray coating process has many benefits over other spray coating practices, such as avoiding thermal degradation and oxidation of the materials. Therefore, its importance has grown significantly over the decades (Maledi et al. 2017; Srikanth et al. 2019).

Cold spray coating applies a material layer on a surface using high-speed particles that do not melt or oxidize (Li et al. 2014; W.Y. Li et al. 2016). The temperature of the substrate can affect the adhesion and properties of the cold-sprayed coatings. According to some studies, increasing the substrate temperature can improve the coatings' bond strength, electrical conductivity, and hardness and reduce the residual stress and porosity (Shayegan et al. 2014; Shah et al. 2017; Lin et al. 2019; Oviedo and Valarezo 2020). This is because higher substrate temperature can enhance the plastic deformation and bonding of the particles and

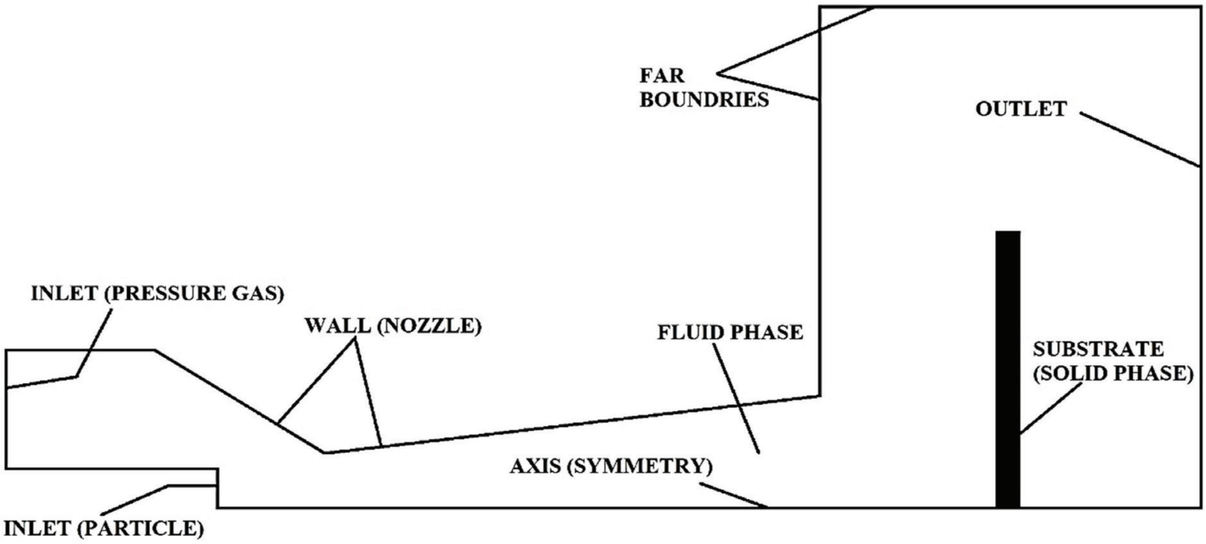


Figure 1. Boundary conditions for simulation of the axisymmetric model

remove the surface oxide layers (Maritime and 2020; Lomas et al. 2011; Willemen et al. 2020) the optimal substrate temperature may vary depending on the coating, substrate materials, spraying type, and combination (Yin et al. 2013). In this technique, the coating material is in powder form and has particle diameters as small as nanometres and as large as millimeters (Meyer et al. 2016; Xie et al. 2016).

The cold spray coating process depends on three core parameters: a. the pressure, b. the temperature mainly at the nozzle and particle inlet, and c. the stand-off distance from the substrate. The temperature can be controlled by pre-heating the substrate or by heating the air at the nozzle inlet (Khan et al. 2020; Khan et al. 2021; Khan et al. 2023a; Khan et al. 2023b). The critical velocity of the powder particle must not exceed its actual velocity. This is where pressure and temperature become crucial factors. There are also several techniques at our disposal to determine the parameters for spraying (Goyal et al. 2012; Lupoi et al. 2020). Due to high kinetic energy, plastic deformation and heat generation in the particles occur, directly affecting the microhardness and bond strength of cold spray coating. Microhardness impacts the microstructure, which results in porosity and cracks for lower microhardness. The microhardness of a layer with a high Nickel concentration is more complicated than having more alumina (Winnicki et al. 2021). The effect on pre-heat and impact velocity depends on the propelling gas type used in cold spraying, as noted in the simulation results with helium gas. The pre-heat temperature improves at a low amount of helium, and with a high amount, the impact velocity. The size of particles plays a vital role in enhancing temperature and velocity; with a large diameter of feedstock powder, the temperature and velocity are higher than smaller diameter particles (Khan et al. 2021; Khan et al. 2023b).

The cold spray coating method is a contemporary technique that minimally alters the characteristics of the material being coated. This method has recently become a significant area of research in the field of coating technology. Typically, the properties of the coating are determined through experimental analysis. However, numerical analysis is gaining popularity due to its ability to produce results closely aligned with experimental findings. This study begins the exploration of the optimal length for the particle injector to achieve the most suitable substrate temperature during the coating process. The analysis of the injector length for particle impact velocity and temperature was conducted using numerical simulation under various states for cold sprays, like pressure, temperature, particle size, and particle speed for varying injector lengths.

2. COMPUTATIONAL MODEL

2.1 GEOMETRY AND BOUNDARY CONDITION DOMAINS

The schematic plan of the cold spray computational model geometry includes a region beyond the nozzle and is named the exterior region, which is exemplified in Figure 1, which also recapitulates the applied boundary conditions in the current simulation. A 2-dimensional axisymmetrical model was used to diminish the computational cost. The cross-section area of the nozzle, including pressure inlet, particle inlet, throat, and nozzle exit, remains constant to keep an appropriate expansion ratio. A steel substrate was positioned at a 35 mm distance from the nozzle exit along the centreline. Our design incorporated a circular convergent-divergent nozzle with a barrel featuring a convergent section measuring length of 55 mm and a divergent section of 170 mm. The diameters of the nozzle throat section, propelling gas pressure inlet, and nozzle outlet were set at 3 mm, 19 mm, and 7 mm, respectively. A barrel of 15 mm in length was affixed before the convergent section. We experimented with four distinct injector lengths – 15 mm to 30 mm with a step of 5 mm each while maintaining a consistent diameter of 2.5 mm. We placed the substrate at a 35 mm stand-off distance from the outlet of the nozzle which is kept common throughout the whole analysis. The substrate had a diameter of 60 mm and a thickness of 6 mm. SolidWorks software was used to design the model to avoid any chances of error in the geometry.

ANSYS (Fluent) software was used to predict different parameters to optimize the best possible injector length. In the process of computational analysis, the domain under consideration was systematically divided into multiple quadrilateral cells to facilitate precise calculations and simulations as shown in Figure 2 (i), (ii), (iii) and (iv), grid mesh of geometry, inlet mesh grid, throat area mesh grid and nozzle outlet mesh grid respectively. To attain a grid-independent solution, it was necessary to employ a varying number of cells, ranging from 75,000 to 125,000, within the computational domain. The most likely number of cells, which embraces nodes and elements, stayed at 96210 and 94926, respectively. The pressure and temperature of propelling gases were 3 MPa and 573 K respectively at the nozzle inlet. The pressure and temperature at the outlet of the computational domain were taken just above the atmospheric pressure 1 MPa and 300 K (likely a hot day), respectively, to stop the external influence, if any. Following the standard no-slip condition, it was assumed that both the wall of the nozzle and the substrate surface would exhibit zero velocity about the fluid, implying that there would be no relative motion between them and the fluid. The boundary of the nozzle was considered ideal, i.e., no heat flow through the wall was considered.

2.2 SIMULATION PARAMETERS

In a prior research investigation, it was discovered that a specific blend of propelling gases, namely Nitrogen (N_2) and Helium (He), when combined in a ratio of 4:6 (N_2: He), resulted in the most optimal impact velocity as well as temperature for the coating powder particles (Khan et al. 2023b).

This finding underscores the importance of the precise composition of the gas mixture in achieving desired particle behavior (Khan et al. 2023a). In this study, we utilized a specific blend of nitrogen and helium gases. The proportion of these gases was carefully chosen based on previous research findings, with nitrogen and helium mixed in a ratio of 4:6. This particular combination was selected due to its proven effectiveness in achieving optimal conditions in similar experimental setups. Nitrogen and Helium mixture is used as the gaseous phase and is regulated by the ideal gas law, which accounts for the effect of compressibility. The equations that govern compressible flow can be expressed in the following tensor notation (Huang et al. 2014):

Continuity equation:

$$R = A \cdot v = \text{constant} \tag{1}$$

Momentum equation:

$$\rho \frac{D\mathbf{U}}{Dt} = \nabla \cdot \tau + \rho \mathbf{g} \tag{2}$$

Energy equation:

$$Q + (U + PE + KE + PV)_{in} = W + (U + PE + KE + PV)_{out} + (U + PE + KE + PV)_{stored} \tag{3}$$

A study state solution was obtained using an implicit pressure-based solver in ANSYS Fluent workbench with second-order precision. We used the ideal gas law to compute the gas properties and assumed a constant density. In our study, we applied the standard K–ε turbulence model, a feature of computational fluid dynamics software FLUENT, to accurately simulate the turbulent flow conditions. This model is widely recognized for its effectiveness in capturing the complex behavior of turbulent flows. Additionally, for the treatment of flow conditions near the wall, we opted for the standard wall function. This choice was made due to its proven reliability in handling near-wall flow dynamics, thereby ensuring a comprehensive and accurate representation of the flow field in our simulations. In our study, we conducted simulations on titanium particles intending to examine the impact of the applied pressure on the propelling gases through the nozzle inlet and particle inlet on both the velocity and temperature. This was done to optimize the length of the particle injector. Furthermore, we explored the impact of various factors, like temperature, particle size, and velocity of particles, on the length of the nozzle injector. This comprehensive approach allowed us the expand of understanding of the dynamics in our experimental setup. We used an axisymmetric model with varying injector lengths to analyze the cold coating technique. The orientation adopted for the substrate and the nozzle were horizontal and 35 mm apart. We sprayed spherical titanium powder particles with a size of 40 µm. In our simulations, the particles were initially set to a velocity and temperature of 40 m/s and 300 K respectively. The outcomes were assessed at a 35 mm stand-off distance from the exit of the nozzle. The model utilized fundamental equations about

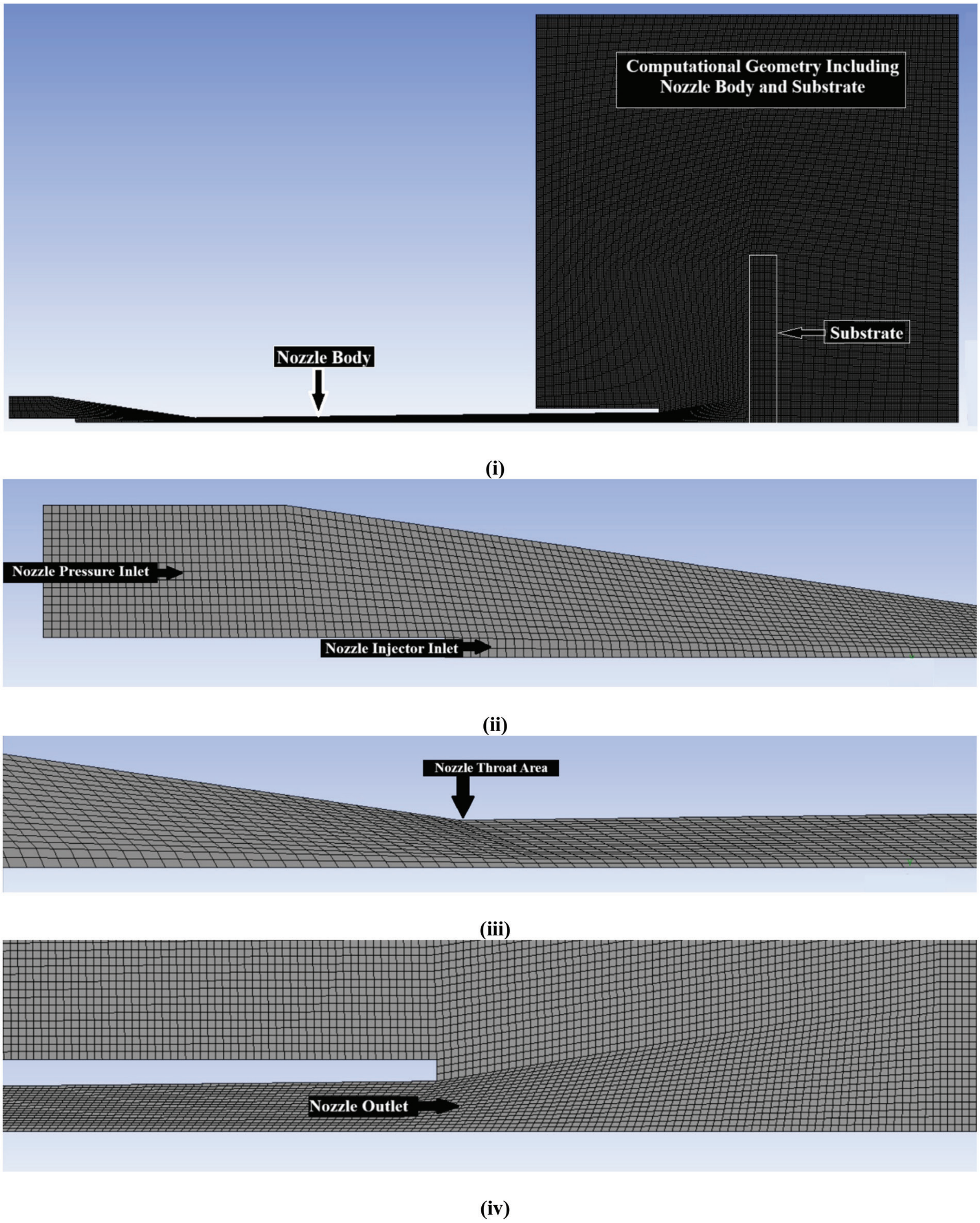


Figure 2. Quadrilateral grid for meshing, which includes (i) geometry's mesh grid, (ii) mesh grid for the inlet, (iii) mesh grid for the throat area, and (iv) mesh grid for the nozzle outlet

fluid dynamics and particle dragging, the details of which can be referred to in the cited references (Yin et al. 2012).

3. EXPERIMENTAL CALIBRATION

In our study, we undertook a calibration process for the numerical model using titanium as the material of choice. This process involved a detailed comparison of the results derived from our simulations with those obtained from actual experimental measurements. The maximum percentage error during the whole process was found to be below 5%. As depicted in Figure 3, we were able to observe the temperature of the substrate surface at various points. Upon analysis, it was found that the numerical results exhibited a

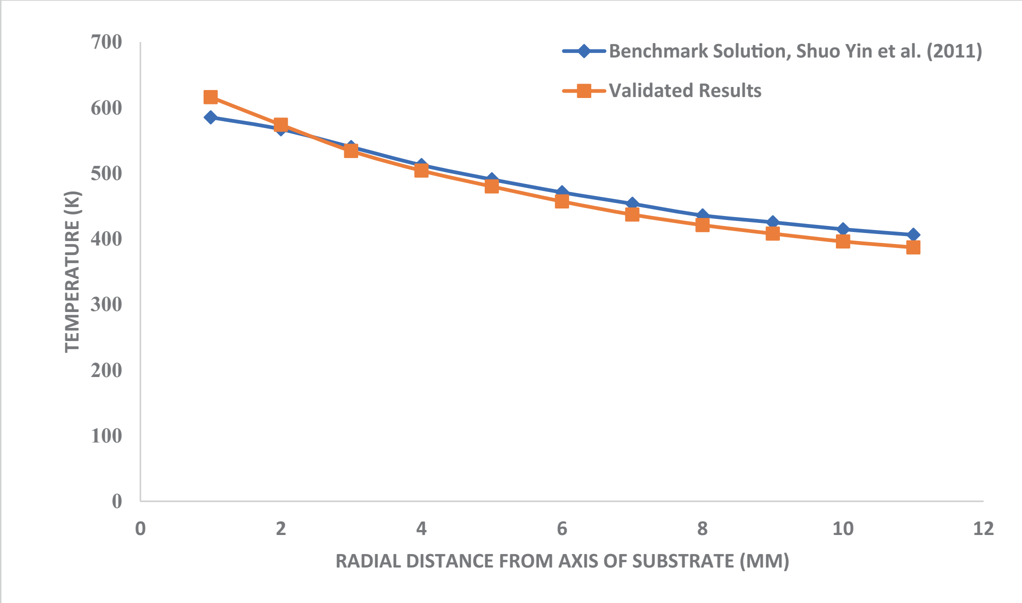


Figure 3. Experimental calibration for titanium-based substrate with validated results (Shuo Yin et al. 2011)

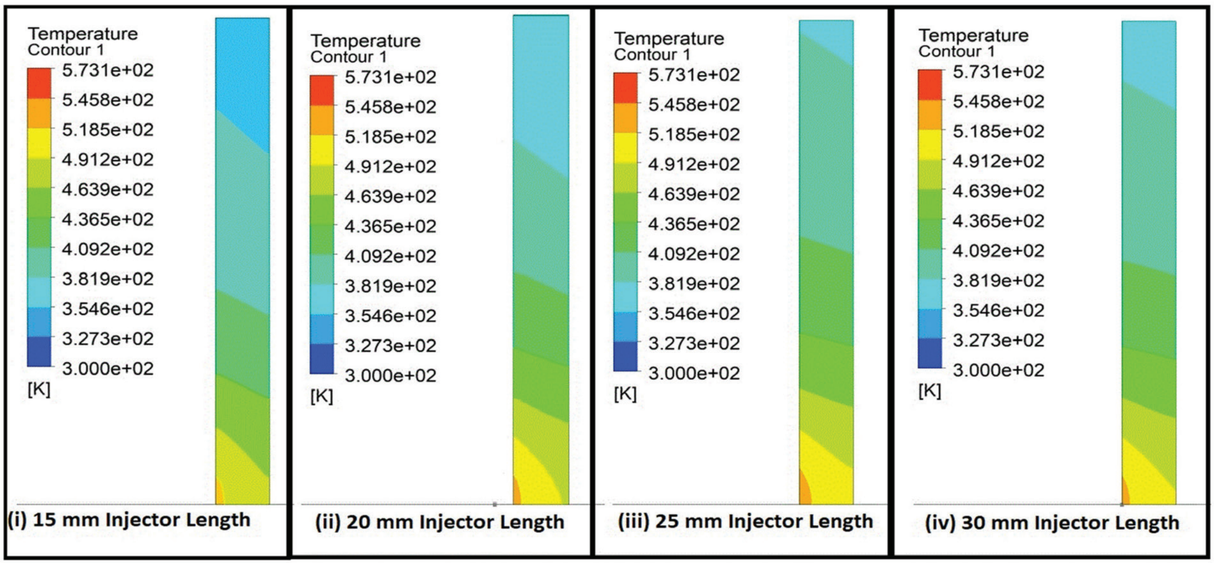
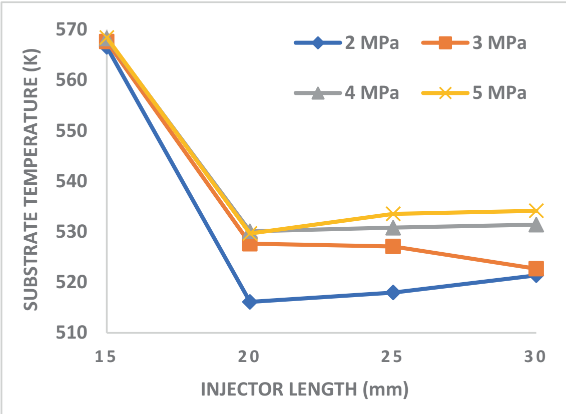


Figure 4. Temperature contours of substrate with varying injector lengths

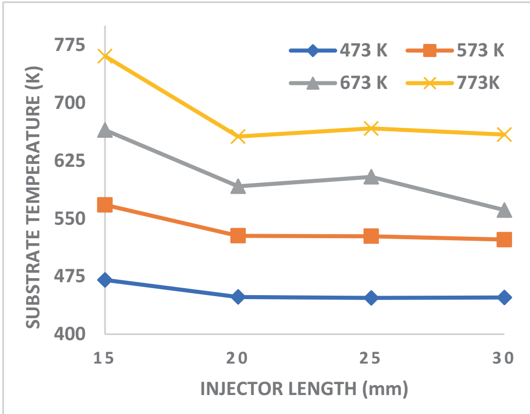
high degree of agreement with the experimental data. This concurrence serves as a validation of the precision of the numerical model employed in this simulation study, thereby reinforcing the reliability of our findings (Yin et al. 2011).

4. RESULTS AND DISCUSSION

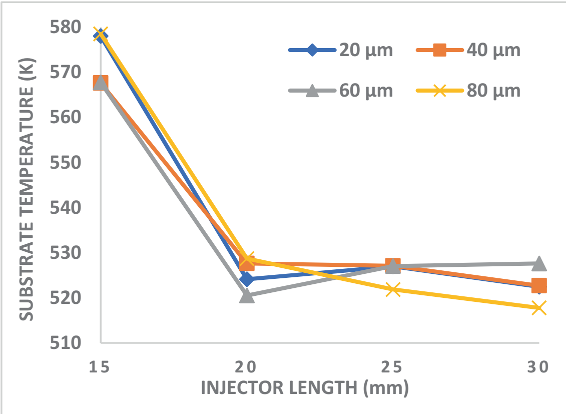
According to previous research studies (Khan et al. 2020; Khan et al. 2021), to previous research studies [16,24], it has been established that the most effective length for a nozzle injector, when not accompanied by a barrel, is 20 mm. However, in the context of this study, we have chosen to explore a range of injector lengths, varying from 15 mm to 30 mm, while maintaining the nozzle dimensions as outlined in section 2.1. The objective of this exploration is to identify the optimal length for the particle injector that would yield the highest possible particle velocity. This is a crucial aspect of our study as it directly influences the effectiveness of the process under investigation. To study the influence of various factors, we analyzed under different gas conditions, particle sizes, pressure and temperature conditions, etc. We fixed the nozzle dimensions in some simulations and varied the injector length from 15 mm to 30 mm with 5 mm increments. We also varied the



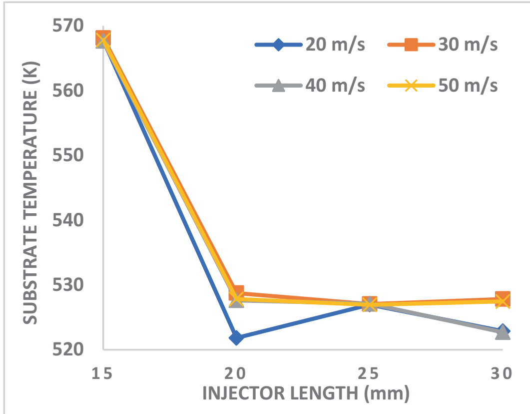
(i) Effect of Pressure on Substrate Temperature



(ii) Effect of Temperature on Substrate Temperature



(iii) Effect of Particle Size on Substrate Temperature



(iv) Effect of Powder Particle Speed on Substrate Temperature

Figure 5. Impact of different parameters on the temperature of the substrate surface concerning changes in injector length

pressure, temperature, propelling gas, particle size, and speed/velocity in each simulation. The substrate reached the maximum temperature at its center. Therefore, we took all the observations at the center. Figure 4 gives the temperature distribution of the substrate with injector lengths of 15 mm to 30 mm.

4.1 EFFECT OF PRESSURE ON SUBSTRATE SURFACE TEMPERATURE

The pressure at the pressure inlet increases from 2 MPa to 5 MPa with a 35 mm fixed stand-off distance for this particular case. The effect of substrate temperature and injector length is studied. The surface temperature distribution is shown in Figure 5 (i). The substrate temperature decreases with an increase in particle injector length. From our observations, it becomes evident that when the nozzle with the shortest particle injector length is used for the fabrication process, the resulting coating tends to be of superior quality. This is primarily because the substrate surface temperature reaches the maximum as the length of the particle injector is minimum. Therefore, a correlation between the particle injector length and the substrate surface temperature plays a crucial role in determining the cold coating quality. Figure 5 (i) illustrates the influence of the particle injector length on the substrate temperature, with the latter being considered as a function of particle velocity. This graphical representation provides a clear understanding of how these parameters interact with each other in the context of our study. The substrate temperature decreases from injector length 15 mm to 20 mm and then slightly increases at 25 mm and lastly decreases with low pressure and slightly increases at high pressure. Therefore, with no effect on the inlet pressure, the 15 mm length of the injector found the maximum temperature of the substrate surface. This means with low injector length. The powder particles and inlet air mixture were found best to keep the temperature almost constant with changes in the pressure. The turbulence present in the gas flow can indeed have an impact on the particle temperature. This outcome becomes particularly noticeable when the length of the particle injector is varied. In other words, changes in the length of the particle injector can lead to variations in the turbulence of the flow gases, which in turn can influence the particle temperature.

This interplay between the injector length, turbulence, and particle temperature is a crucial aspect to consider in our study.

4.2 EFFECT OF TEMPERATURE ON SUBSTRATE SURFACE TEMPERATURE

In the conducted simulation experiment, the gas temperature at the inlet was systematically increased from 473 K to 773 K, while keeping the stand-off distance constant at 35 mm. A comprehensive study was carried out to comprehend the impact of both the temperature of the substrate and the length of the injector. The results of this study are presented in Figure 5 (ii), which clearly illustrates the effect of an increase in the inlet gas temperature on the temperature of the substrate. As the inlet gas temperature rises, noticeable changes in the temperature of the substrate can be observed. It is very clear that the temperature of the surface of the substrate increases with a temperature increase of the inlet gas, the higher the inlet gas temperature, the higher will be the substrate surface temperature. Although injector length also affects the substrate surface temperature, with equal length of injector and barrel, the effect of temperature is maximum. As the injector length increases, the substrate surface temperature decreases comparatively. Our observations indicate that the highest substrate temperature is achieved when the injector length is at a minimum of 15 mm, and this coincides with the maximum temperature of the inlet gas. As the length of the particle injector increases, there is a corresponding decrease in temperature, reaching a minimum when the injector length is extended to 330 mm. It's worth noting that the quality of the coating fabricated using the nozzle is superior when the particle injector length is at its minimum. This is because the substrate surface temperature is at its maximum when the length of the particle injector is minimized. Therefore, the length of the particle injector plays a decisive part in determining both the temperature conditions and the quality of the coating.

4.3 EFFECT OF PARTICLE SIZE ON SUBSTRATE SURFACE TEMPERATURE

In the experiment, the particle size was systematically increased from 20 µm to 80 µm, while maintaining a 35 mm constant stand-off distance. The impact of both the particle size and the length of the particle injector on the substrate surface temperature is depicted in Figure 5 (iii). It was observed that the behavior of the particles is predominantly determined by the length of the particle injector. Specifically, with the particle injector length of 15 mm, the substrate temperature was found to be high. However, as the length of the particle injector was increased from 20 mm to 30 mm, the substrate temperature declined. This declination in temperature can be attributed to the increased turbulence of the inlet gas caused by the longer injector length.

4.4 EFFECT OF POWDER PARTICLE SPEED ON SUBSTRATE SURFACE TEMPERATURE

The powder particle speed was increased from 20 m/s to 50 m/s having a common stand-off distance of 35 mm. Figure 5 (iv) shows the effect of powder particle speed and particle injector length on substrate surface temperature. The influence of turbulence can be observed from particle injector length 20 mm to 30 mm, without impact of powder particle speed. Our findings indicate that an injector length of 15 mm results in the highest substrate surface temperature. However, as the length of the particle injector increases starting from 20 mm to 30 mm, there is a corresponding decrease in the substrate surface temperature. This trend underscores the significant role that the length of the particle injector plays in influencing the temperature conditions within the system. Therefore, the influence of turbulence of inlet gas with the same barrel and particle injector length plays an important role in maintaining the higher temperature of particles and propelling gases. Therefore, taking into account the variations in substrate surface temperature with different parameters, an injector length of 15 mm emerges as the most optimal choice. This length provides the best balance between the various factors at play, ensuring the most effective performance for the process under investigation.

5. CONCLUSIONS

The conclusions that can be drawn from the outcomes obtained in this work are as follows:

1. The surface temperature of the substrate is significantly influenced by the pressure of the gases entering the inlet. The substrate surface temperature reaches its peak when the particle injector length is at its minimum, specifically 15 mm.
2. The surface temperature of the substrate is greatly affected by the temperature of the gases entering the inlet. As the length of the particle injector decreases, the substrate surface temperature tends to rise, but only to a certain point.
3. The powder particle size and speed also influence the substrate surface temperature in the same manner as the case of the pressure of the inlet gases.

In the course of this work, a simulation analysis was conducted to determine the optimal length of the particle injector, to achieve the most favorable substrate surface temperature for the cold spray coating process. The best possible particle injector length obtained is 15 mm, as observed in the analysis, the minimum injector length taken in this analysis is equal to that of the barrel length, keeping in mind there is a need to find the relation between the barrel length and the particle injector length. Although the results confirm the best compatible nozzle barrel length equal to the particle injector length.

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