Coating Technology By Two – Phase (Cold gas – Solid particles) Flow

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Abstract :

The surface coating process which is known as a cold spray (CS) of solid particles is performed by acceleration the solid particles for a certain metal to supersonic speeds through nozzle gas flow , are subsequently deposited by impact onto surface . Also this paper presents an analytical model for (CS) process , by assuming one dimensional isentropic flow , to demonstrate the dynamics of dilute two – phase (powder particles plus carrier gas) flow . Furthermore the equations for particle model are introduced , when heat transfers between the solid particles and assumed gas.

The velocity of the solid particles must be achieved to a critical value for carrying out an optimal deposition efficiency and a high coating quality , also several parameters , including gas condition such as stagnation pressure and temperature , the density of gas , in addition the particle characteristics and nozzle geometry affect on particle velocity then on the quality of coating .

Keywords . Coating , Two-Phase , Cold Gas, Gas- Particle

1- <u>Introduction</u>

Cold Gas Dynamic Spray (CGDS) is a rapidly emerging coating technology in which particles in solid state are deposited on a substrate via high-velocity impact, at temperature lower than the melting point of powder material [1]. Further of(CGDS) there are different approaches Known by different names, such as Cold Spray (CS), Kinetic Spraying, High Velocity Particle Consolidation (HVPC), High Velocity Powder Deposition (HVPD), and Supersonic Particle/ Powder Deposition (SPD)[2].

The basic principle of the cold spray process employs supersonic nozzle by using a delavad or similar converging/ diverging nozzle into which solid particles of feedstock material are introduced and accelerated with high velocity(300 to 1200 m/s) toward a substrate, either forming thin surface coating, or being directly embedded as isolated particles in small depressions on the surface[3].

For best understanding of providing improvements in cold spray technique it is necessary to consider typical scheme of cold spray system(Fig.1)[4] .

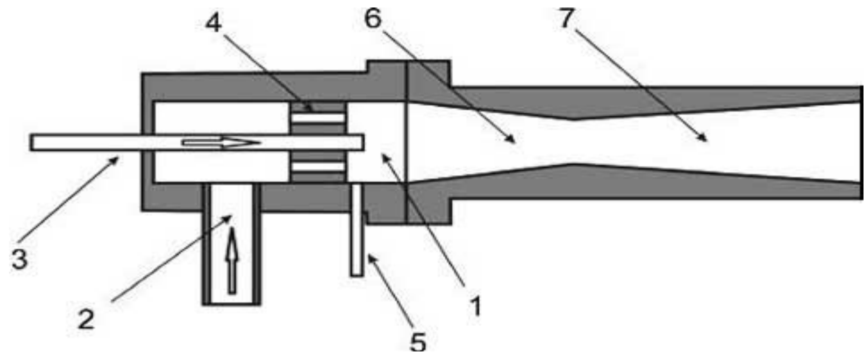

Fig.(1): Spray unit design :1- Prechamber, 2-Main gas ,3-powder mix, 4-honeycomb-type collimator , 5- control sensors , 6- converging region ,7-diverging region [4].

The cold spray was developed in the mid(1980) at the institute of Theoretical and Applied Mechanics of the Siberian Division of the Russian Academy of Science Novosibirsk [5,6] , while studying models subjected to a supersonic two-phase flow (gas + particle) and performing supersonic wind tunnel tests, scientists observed that above a critical particle velocity (which varies for different material) there was a transition from particle erosion of a target surface to rapidly increasing deposition material [5].

During the period (1990-2000) the leader of the cold spray group in Russia (Anotoli Papyrin), moved to the USA, built a system of the cold spray and carried out basic studies .

In the period (2000-2006). German Armed Forces University, did a large and exhaustive study on all aspects of the cold spray process including theory, modeling, design and development of guns and nozzles, preparation and characterization of coatings, and development of application coatings[7] .

After(2006) to the present time the cold spray method is recognized by world leading scientists and specialists. The governments of various countries have realized the importance of this technology and various projects are sanctioned to commercialize this technology .

2-Cold Spray (CS) system

The cold spray system can be designed in portable or manual and robotic or fixed system. The working gas of static pressure near(0.6-3.5MPa) is heated in gas heater up to temperature($100C^o$-$600C^o$). Powder from the powder feeder moves into the spray unit and is mixed with a working gas.

The gases are generally used to propel the powder particle are having an aerodynamic properties such as.

1- Helium , 2- Argon , 3-Nitrogen ,4-mixture of He and N_2, 5-Dry air(79%N_2-21%0_2), and the powder used is in the range (1 to 50µm) in diameter . The main components of(CS) are be shown in Fig(2) [4] .

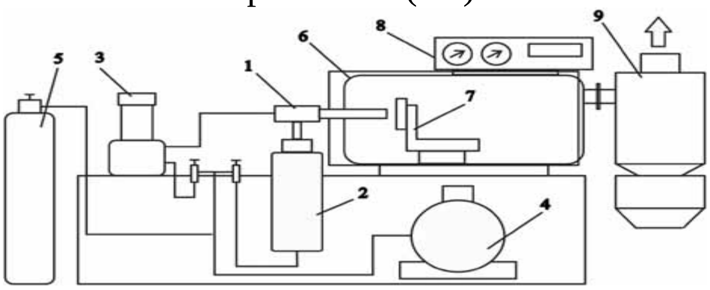

Fig.(2): Basic elements of (CS) system:1-Spray unit composed of prechamber and supersonic nozzle; 2- gas heater; 3- Powder feeder; 4- compressor; 5-gas container; 6- Spray tank; 7-substrate; 8-control panel; 9- powder separator [4] .

3- Types of(CS) System

There are two methods of injecting the spray materials into the nozzle were patented, which is known today as High Pressure Cold Spray (HPCS) and low Pressure Cold Spray (LPCS) system. The two main distinctions of these two systems are , the utilization of(5-10 bars) pressure gas in LPCS instead of(25-30 bars) in HPCS, and radial injection of powder in LPCS instead of axial injection in HPCS [8,9].

3.1-Low pressure cold spray (LPCS)

In the LPCS the accelerating gas, usually air or nitrogen, at relatively low pressure(5-10 bar) and preheated (up to550 C^o), within the gas heater to optimize its aerodynamic properties and then forced through a 'Delavad' nozzle. At the diverging side of the nozzle, the heated gas is accelerated to velocity is about in the range of about (300 to 600m/s). Solid powder particles are radically introduced downstream of the throat section of the supersonic nozzle and accelerated toward the substrate as shown in the(Fig.3) of the LPCS system [9,10].

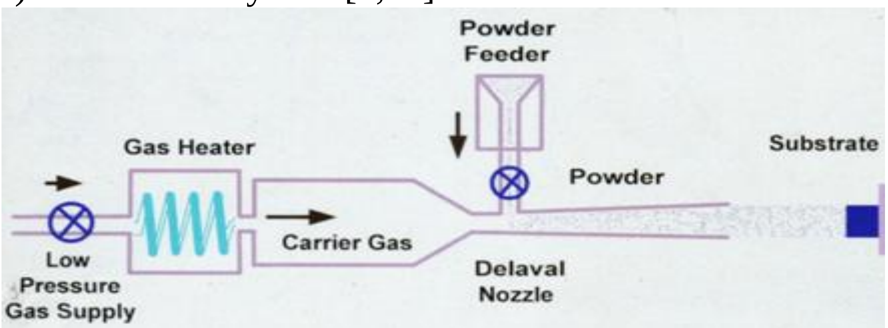

Fig.(3) : Operation principle of low-pressure cold spray[9,10].

Due to the elimination of the need of a high pressure delivery system in LPCS, there is improvement in its operational safety, the system is more portable- flexible in automation, and spraying cost also reduced significantly than a HPCS system, but the deposition efficiency in LPCS typically do not exceed 50%. Also in the system the powder particles does not pass through the throat, hence wear of the nozzle walls occurs only in the supersonic portion of the nozzle and, this ensures a longer service life of the nozzle.

3.2- High Pressure Cold Spray (HPCS)

In HPCS the accelerating gas helium or nitrogen at high pressure(25-30 bar) is preheated(up to 1000C^o) to optimize its aerodynamic properties(not to increase particle temperature) and then forced through a converging-diverging nozzle. At the nozzle, the expansion of the gas produces the conversion of enthalpy into kinetic energy , which accelerates the gas flow to supersonic regime (1200m/s) while reducing its temperature. The solid powder feedstock particles mix with propellant gas in the pre-chamber zone and are then axially fed into the gas stream, upstream of the converging section of the nozzle at a higher pressure than the accelerating gas to prevent back flow of the carrier gas to the powder feeder as shown in(fig.4).

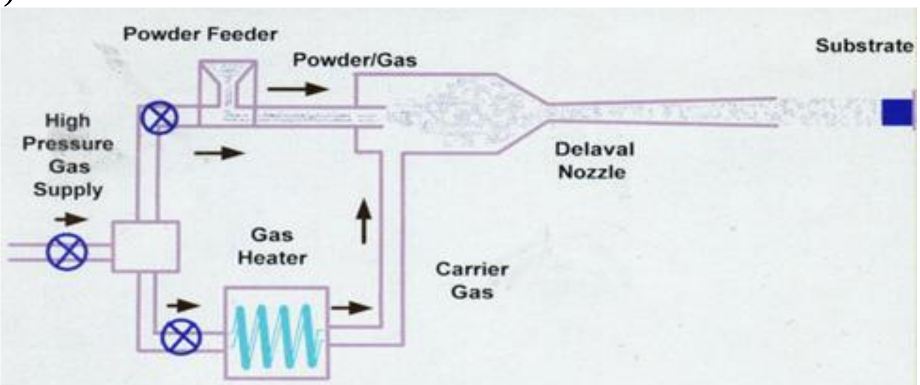

Fig.4: Operational principle of high pressure cold spray[9,10] .

The accelerated solid particles (600 to 1200 m/s) impact the substrate with enough energy to induce mechanical and /or metallurgical bonding. The spray efficiency in this HPCS system is very high , reaching up to 90% as compared to 50% in LPCS system . Moreover, temperature of particles remains substantially below the initial gas preheat temperature due to short contact time of spray particles with the hot gas called dwell time and hence the name cold spray coating [9,10].

4- Isentropic Gas Flow Model

In this section a, brief overview is given of the cold-spray gas-flow model developed by Dykhuizen and Smith[11].The model considers a typical geometry of the(CS) converging/diverging nozzle(fig.5), and involves a number of assumption and simplification such as.

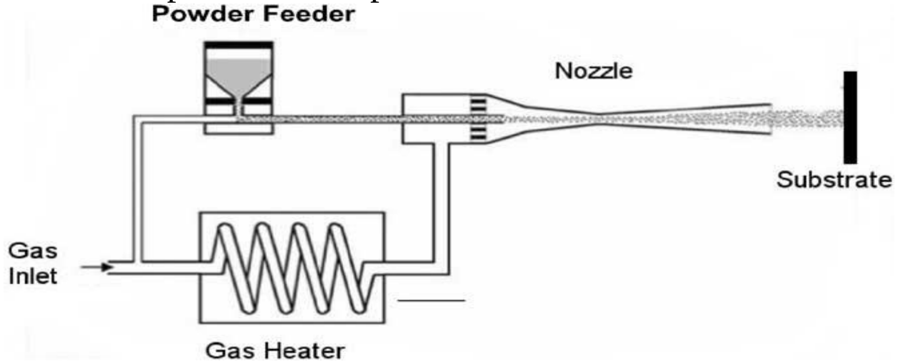

Fig.5: Schematic of a typical cold – gas dynamic – spray system[11].

1.the gas flow is assumed to be one dimensional and isentropic (adiabatic and frictionless).

2.The gas is treated as a perfect (ideal) gas.

3.the constant-pressure and the constant-volume specific heats(C_p , C_v) of the gas are assumed to be constant.

The carrier gas flow is assumed to originate from a large chamber where its velocity is zero and the pressure is " P_o" (referred to as the "stagnation" pressure) and the temperature "T_o" (as the "total" gas temperature) . The (CS) process is furthermore assumed to be controlled by the user who can set the mass flow rate "$\dot{m}$" and the total temperature "T_o". The corresponding stagnation pressure can then be calculated by using the following procedure:

At the beginning, employ the basic dynamic and thermo dynamic relations for the compressible fluid flow to find the gas temperature (T^*) at the smallest cross-sectional over area of the converging/diverging nozzle (means the nozzle throat) where the Mach number is unity, (it should be noted that the superscript (*) denotes to the quantities at the nozzle throat and the gas under the sonic conditions and (o) refers to the stagnation state "prechamber").

The equation of (T^*) can be derived by applying the energy equation to the control volume indicated for steady one- dimensional flow, between the nozzle throat nozzle (static state) and prechamber (stagnation state) which is [12].

$$h^* + \frac{V^{2*}}{2} + z^* g - q = h_o + \frac{Vo^2}{2} + z_o\ g + w_s \quad (1)$$

"g" is gravitational constant, and "h" is the enthalpy, "q" and "w_s" represents the quantities of heat and shaft work crossing the control surface per unit mass. "V" : is the velocity of gas. "z" is the high of the system in the field of gravity. Since the flow of gas is assumed isentropic i.e adiabatic without any energy exchange, then (q=w_s=o) , and frictionless i.e change in entropy is (ds=o), and by introducing the concept of stagnation state which is defined as the state where fluid exiting in it with zero velocity and potential, thus equation (1) becomes

$$h_o = h^* + \frac{V^{2*}}{2} + zg \qquad (2)$$

Where "h_o" is called the total enthalpy corresponding to the section of throat, and when dealing with gases the potential changes are usually neglected then we get.

$$h_o = h^* + \frac{V^{2*}}{2} \qquad (3)$$

And from definition of Mach number (M) and expression for sonic-velocity (a) in a perfect gas which are give by relations

$$M = \frac{V}{a} \; or \quad V^2 = M^2 a^2 \qquad (4)$$

$$a = \sqrt{\gamma R T} \qquad (5)$$

"R" is the universal gas constant divided by the gas molecular weight , "γ" is defined as $\gamma = \frac{c_p}{c_v}$ (6)

But at the throat the velocity (V^*) equals to sonic velocity(a) where(M) is unity and temperature denotes by (T^*) thus we have at throat.

$$V^* = \sqrt{\gamma R T^*} \qquad (7)$$

Hence the eq(3) becomes

$$h_o = h^* + \frac{\gamma R T^*}{2} \qquad (8)$$

Also from definition of (γ) and R=(C_p-C_v) then

$$C_p = \frac{\gamma R}{\gamma - 1} \qquad (9)$$

And the eq(8) produces

$$h_o = h^* + \frac{\gamma - 1}{2} C_P T^* \qquad (10)$$

But in general (h=$C_P T$) then (h^*=$C_p T^*$ and ho=$C_p T_o$)

Therefore we get [12]

$$h_o = h^* (1 + \frac{\gamma - 1}{2}) \qquad (11)$$

or $$T_o = T^* (1 + \frac{\gamma - 1}{2}) \qquad (12)$$

If there is no sonic condition at throat the eq (12) must be written as.

$$T_o = T^*(1+\frac{\gamma-1}{2}M^2) \qquad (13)$$

Typically the (γ) sets to (1.66) for monoatomic gases like helium and(1.4) for diatomic gases like nitrogen and oxygen, and it is clear that from equation(7) when monoatomic gases are used (low molecular weight) , hence large values of "R" , and "γ" will be occurred, and the sonic conditions at throat are preformed. Hence the helium is better selected carrier gas than high molecular weight, diatomic air since for the same total gas temperature (To). From the known mass flow rate "$\dot{m}$" (user selected), the sonic gas density can be computed as[13,14] .

$$\rho^* = \frac{m^\bullet}{V^* A^*} \qquad (14)$$

" A*" : is the cross-sectional of the nozzle throat. The gas pressure at the nozzle throat (P*) can be determined by using the ideal gas law.

$$P^* = \frac{RT^*}{\rho^*} \qquad (15)$$

Once the throat "P*" is computed, the stagnation pressure"P_o" can be calculated when using the following isentropic relation.

$$\frac{P_o}{P^*} = \left(\frac{T_o}{T^*}\right)^{\gamma/(\gamma-1)} \qquad (16)$$

Then $P_o = P^*(1+\frac{\gamma-1}{2})^{\gamma/(\gamma-1)}$ (17)

After all the gas dynamics quantities (T^*,V^* , P^* andρ*) are calculated at the nozzle throat, one can proceed to determine these quantities along the diverging section of the nozzle. Toward that end the nozzle cross-sectional area along the diverging section is varied and the relation of area at the end(A) relative to the throat area(A*)for isentropic compressible flow is given by the relation[13].

$$\frac{A}{A^*} = \left(\frac{1}{Me}\right)\left[\left(\frac{2}{\gamma+1}\right)\left(1+\frac{\gamma-1}{2}M_e^2\right)^{\gamma/(2\gamma-1)}\right] \qquad (18)$$

Where "Me": is the mach number at end diverging section thus if (A) is specified which then allows determination of the corresponding Mach number (Me), and then the remaining corresponding gas quantities (P,T, V, and ρ) at the exit of nozzle can be calculated by using the following isentropic relationships[14] , and for more detailed one can be retuned to [12] to derive these relationships which are as the following .

$$T = \frac{T_o}{\left[(1+(\frac{\gamma-1}{2})M_e^2\right]}\gamma/(\gamma-1) \qquad (19)$$

$$V = Me\sqrt{\gamma RT} \qquad (20)$$

and $$p = p^*\left(\frac{\gamma+1}{2+(\gamma-1)Me^2}\right)^{\gamma/(\gamma-1)} \qquad (21)$$

$$\rho = \frac{\rho_o}{\left[1+\frac{(\gamma-1)}{2}M_e^2\right]^{1/(\gamma-1)}} \qquad (22)$$

5-Particle dynamics model

The interactions of the carrier gas with spray particles under the approximation of a diluted two phase (gas + solid particles) were also analyzed by[11,14] and the particle velocity " V_p " can be determined by solving the following differential equation.

$$m_p\frac{dV_p}{dt} = m_pV_p\frac{dV_p}{dx} = \frac{C_DA_p\rho(V-V_p)^2}{2} \qquad (23)$$

Where " V_p" velocity of particle m_p and "A_p" are the average mass and cross sectional area of the particle respectively. "C_D" is the drag coefficient, "t" the time, "x" is the axial distance traveled by the particle (from the nozzle throat).The equation(23) can be integrated if the gas velocity and density are held constant, and the drag coefficient is assumed constant, thus equation(23) can be integrated to yield

$$.\ \log\frac{V-V_p}{V} + \frac{V}{V-V_p} - 1 = \frac{C_DA_p\rho x}{2m_p}. \qquad (24)$$

When the " V_p" is very small in comparison to gas velocity, equation (24) can be simplified as

$$Vp = V\sqrt{\frac{C_DA_P\rho\, x}{m_p}} = V\sqrt{\frac{3C_D\rho\, x}{2D_P\rho_P}} \qquad (25)$$

"D_p": is the particle diameter , "ρ_p" average density of the particles where the eq(25) is consistent with experimental observations [13,14]. A simple analysis of eq(23) shows that the ultimate " V_p" is equal to the gas velocity "V". Furthermore, examination of eqs(18) (19) (20) indicates that the "V" of gas depends on the total gas temperature and on the cross-sectional area of the nozzle at given axial distance(x). and not on the gas pressure. Whereas eqs(20) (21) (22) indicate that the initial particle acceleration $\left(\frac{dV_p}{dt}\, at\, V_p = o\right)$ is linearly dependent on the stagnation pressure, and not on the total temperature .

The " V_p" is one of the most important parameters in cold spraying. It determines whether deposition of particle or erosion of a substrate occurs on the impact of a spray particle generally. For a given material, there exists a minimum particle velocity "V_C" for transition from erosion of the substrate to deposition of the particle occurs[10] . The critical particle velocity as reported by many authors [1,2,16,17] changes with the spray material, approximately(560-580), (620-640)(620-640) (680-700) m/s for Cu, Fe, Ni and AL respectively.

The above equations of " V_p" based on assumption that the " C_D" is constant and medium is dilute (no interaction between gas and solid particles such heat exchange) whereas[15] introduced another set of differential equation of " V_p" , by introducing the function of Drag f_D(M,Re) as the following.

$$f_D(M\ ,\mathrm{Re}) = \frac{C_D \mathrm{Re}}{24} \qquad (26)$$

Where" Re" : Reynold number of gas relative to the solid particles which equals to

$$\mathrm{Re} = \frac{\rho(V - V_p)2r}{\eta} \qquad (27)$$

"η" is the viscosity of gas, "r" is radius of particle and the relative Mach number is be

$$M^{'} = \frac{(V - V_p)}{a} \qquad (28)$$

The eq(23) can be rewritten as

$$\frac{4}{3}\pi\rho_p \frac{dV_p}{dt} = C_D \pi r^2 \frac{\rho_p (V - V_p)^2}{2} \qquad (29)$$

and $$\frac{dV_p}{dt} = \frac{9}{2} f_D\left(M^{'}_e, \mathrm{Re}\right)\frac{\eta}{r^2 \rho_p}(V - V_p) \qquad (30)$$

hence $V_p \dfrac{dV_p}{dx} = \phi_1 (V - V_p)$ where $\phi_1 = \dfrac{9}{2} f_D \dfrac{\eta}{r_2 \rho_p}$ (31)

the convection of heat between particles and gas is descry
ibed by the next relation

$$\frac{4}{3}\pi r^3 \rho_p C \frac{dT_p}{dt} = -4\pi r^2 \alpha (T_p - T) \qquad (32)$$

"C" :heat capacity of material (solid particles), "T,T_p": the corresponding temperatures of gas and particles respectively, "α": is the convective heat transfer coefficient from particles to gas.

Introducing the Nusselt (Nu) and prandtl (Pr) numbers as the following .

$$Nu = \frac{2r\alpha}{\lambda_T} \quad , \quad \mathrm{Pr} = \frac{C_p \eta}{\lambda_T} \qquad (33)$$

"λ_T" Thermal conductivity coefficient of gas , then the eq (32) becomes

$$T_p \frac{dT_p}{dx} = \phi_2 (T - T_p) \qquad (34)$$

Where $\phi_2 = \frac{3}{2}\frac{Nu}{p_r}\frac{C_p \eta}{\rho_p C r^2} = \frac{Nu \phi_1 C_p}{3 \Pr f_D C} \qquad (35)$

Eq(35) gives the relation between φ_1 and φ_2 and then between (V_p and V), furthermore [15] studied the equations of conservation of energy and mass concerning with above situation and received another differential equations for finding the parameters of gas and particles such as (P, ρ, ρ_p, V_p, V and T, T_p) .

6-Applications

- Cold spray (CS) applications include both production and restoration in the field of medical , aerospace , electronics , automotive and petrochemical industries [10][18][19] . Any defect may be easily removed by this process to save production quality.
- (CS) technique is used to fabricate the AL– tube heat exchanger ,used air conditioning equipments for all types of vehicles these days.
- (CS) can also be used for the fabrication of complex conductive patterns in solar cells , to enhance surface performance in components made of advanced polymer – matrix composities in wind power generation [10].
- One of the important application of cold spray is the coating of copper powder on the aluminium tips of the electric mains to prevent the electrochemical oxidation of contacting elements of copper wire of the transformer and aluminium tip of the cable . The presence of different material results in circuit breakdown and can be prevented by this method.[10]
- The process for applying a kinetic spray coating of powder particles into a substrate that covers a plastic – type material without first removing of plastic – type material is useful . The process finds special use in forming electrical connectors or solder able pads anywhere along the length of flexible circuit, which is electrically isolate them from each other [4].

7- Conclusions

Cold spray technology is an emerging technology and it should be clear that it is not for replacement of the well established thermal spray methods . Instead , cold spray technology is expected to supplement and expand the range of application for thermal spray processes as a greener alternative according to stringent environmental and health safety regulations. Extensive research is required to design the optimum parameters like nature of gas such as mono atomic gases are better than diatomic gases , as carrier gas , and for performed supersonic condition in cold spray. Also the total temperature , nozzle design which affect the exit velocity of the gas, furthermore the stagnation pressure which affected the initial acceleration of solid particle. The research area of mathematical modeling to optimize various design parameters is still open to expand this process to more non- traditional applications.

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تكنولوجيا الطلاء بواسطة الجريان الثنائي الطوري (غاز بارد – جسيمات صلبة)

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ان عملية طلاء السطوح والمعروفة بالرش البارد لجسيمات صلبة يتم تحقيقه او انجازه عن طريق تعجيل هذه الجسيمات الصلبة , لمعدن معين (المراد طلاءه) الى سرعات فوق مستوى سرعة الصوت وذلك من خلال جريان غاز في نفاث , وبالتعاقب تترسب هذه الجسيمات الصلبة بارتطامها على السطح المراد طلاءه . ايضا في هذا البحث تم تقديم موديل رياضي تحليلي لعملية الرش البارد وذلك بفرض جريان ايسنتروبي احادي البعد , لغرض توضيح ديناميكية الجريان الثنائي الطوري (جسيمات المسحوق زائدا الغاز الحامل لهذه الجسيمات) علاوة على ذلك ايضا تم تقديم المعادلات الخاصة بالجسيمات الصلبة في حالة افتراض حدوث انتقال بالحرارة بين الجسيمات الصلبة والغاز .

ان سرعة الجسيمات الصلبة يجب ان تصل الى القيمة الحرجة من اجل تامين وضمان كفاءة ترسيب مثالية وجودة طلاء عالية , ايضا ان هناك بارامترات عدة اخرى تتضمن ظروف الغاز مثل , ضغط الركود للغاز , درجة الحرارة , كثافة الغاز , فضلا عن خصائص الجسيمات وهندسية النفاث المستخدم, والتي تؤثر بدورها هي الاخرى على سرعة جسيمات المعدن المراد طلاءه , وبالتالي تأثيرها على جودة الطلاء .