Transport of Welding Fume in Automotive Industry

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***Abstract*—Fumes are very harmful based on their particle size. Various chemical analysis techniques are presented and their applicability to airborne particles is described. The size of fume particles will affect the deposition region in lungs. Temperature, air velocity and relative humidity are the factors that affect the size fume particles as well as the motion of the fumes particle in air. Aim: This study was conducted in order to measure the environmental parameters, to evaluate the physical properties and to determine the transport of welding fumes in air. Method: This research was used several equipments to measure the factors of the source emission. The particle morphology and shape of fume particles were capture and analysed using FESEM (Field Emission Scanning Electron Microscope) . Then the transportation of fumes particles, were calculated based on their Reynolds Number, settling velocity, mechanical velocity and stopping distance. Result: The shape of the fumes particle is spherical and then it was form chain like agglomerate structure. The diameter of the particle was found to be in nano-particles. The aerodynamic diameter value was calculated and also found the deposition region might be in the deep region of the lung (alveoli). The data of the source emission was used to solve the equations of the particle transportation. The temperature, relative humidity and air velocity was compared with Industrial Code of Practise on Indoor Air Quality which pulished by Department of Occupational Safety and Health (2010). The Reynolds number proved that the particles moved in a laminar flow. The velocity was believed affected by the size of the particle. The smaller the fumes particle would be decreased the velocity as well as easier the movement of fume particle and the stopping distance will be nearest.**

Keywords— Fumes, Morphology, Settling Velocity, Nanoparticles, Mechanical Mobility.

I. INTRODUCTION

Workplace is an important place for person that called as workers. Workplace also becomes as second home for them. That's why workplace should be as comfortable as well as home. This is important for each worker to maintain their condition of health. In the United States, there are 360,000 workers are roughly categorize as full-time welders [1].

Malaysian industries faced many challenges that influence their competitiveness although they expand rapidly and their expansion was fast. One of the challenges that faced by the industries is about the scenario on occupational safety and health (OSH) awareness in workplace. The factors that influence the evidence are the occurrences of the industrial accidents and the non-conducive work environment [2]. Besides, welding operations is one of automotive manufacturing process.

Welding fumes produce via the welding process that are doing by an employee. Welding is a process to joint two metals to any purpose. Welding generally needs a heat source to form a high temperature zone to melt the material, or else it is possible to weld two metal pieces without much increase in the temperature. Hence, the fumes produce through the process of joining the metal when the metals are melting.

Size of the welding fumes cause most toxic airborne particulate matter and nano-particles can easily access to the body cells of the airway and even intracellular components [3]. Nano-particle is a central for pulmonary toxicity to be deposited in the alveolar spaces of the lung. Nano-particles have high efficiency to be deposited in a lung of individual. Besides, it also has high efficiency in individuals with asthma or chronic obstructive pulmonary disease [4].

The aim of this study are to characterize the environment parameters of welding fumes in automotive industry, to evaluate the physical properties of welding fumes in automotive industry and to determine the transport of welding fumes in automotive industry.

II. METHODOLOGY

The location of this study was conducted at automotive industry in Selangor, Malaysia.

A. Measurement of Environmental Parameters

There are three factors that related to the environmental parameters which are concentration of fumes particles, temperature, relative humidity and air velocity. These factors will be analysed by using the TSI Velocicalc. The Dusttrak Aerosol Monitor was used to evaluate the concentration of fume particles present in the welding area. These equipments will be locate at six sampling point which are spot welding area, fuel lid, robot line welding area, spot gun welding and MIG area and the entrance (door).

Reading for two slot which in the morning (between 8.00am to 1.00pm), and the afternoon (between 2.00pm to 5.00pm) were taken in average of 15 minutes for each locations.

B. Characterization of Physical Properties of Welding Fumes

To determine the morphology of welding fumes, a mixed cellulose ester (MCE) filter, 0.8 microns was used. The filter cassettes were attached to the collars of welder, same as the step of gaining personal sampling was conducted. The filter was placed near the employee's breathing zone.

Eight hours time weighted average exposures were usually used for task-based measurement. The samples for this study take for 8 hours, which started from 8.00am to 1.00pm and continue from 2.00pm to 5.00pm, there was an hour of rest time from 1.00pm to 2.00pm. According to OSHA Technical Manual (OTM) 2008, all cassettes needed to be sealed correctly by covering inlet and outlet parts in order to maintain the samples integrity with proper details for easy to be identifying during analysis.

C. Determination of Fume Morphology and Fume Particles Size

The microscopy study of glass ceramic produced was measured under the Field Emission Scanning Electron Microscope (FESEM, JEOL JSM- 7800F, Japan). Analysis was carried out to investigate the microstructural features on the surface of the fume produced and the particle size. The magnifications were used between 22kV to 70kV at the same area to view the microstructure more clearly.

The samples were analysed with an acceleration voltage of 3.0kV. The microscopes have the ability to produce images in magnifications from 5x to 1,000,000x, where particle size, particle shape and other morphological properties can be obtained.Fume particles on the impactor stages were imaged using high resolution field emission scanning electron microscopy (FESEM) able to identify the particles size and the presence of three fume particle morphologies including spherical, agglomerated, and irregular.

D. Determination of Transport of Welding Fumes in Air.

The diameter of welding fume particle is important for transport, collection and respiratory tract deposition of larger particles. The aerodynamic diameter is expressed an in (1).

$$d_p = d_a (\frac{p_p}{p_0})^{\frac{1}{2}} \tag{1}$$

Particle motion is caused primarily by external forces, such as gravity or forces from an electric field, and resistance forces from the surrounding gas. The relation between the force that pushes away the surrounding gas and the friction force between the particle and the gas is defined as the particle Reynolds number. Reynolds numbers:

$$(\mathrm{Re} = \frac{p_g v d_p}{\eta}) \tag{2}$$

Thus, Newton's assumption that *Cd* is a constant is only valid for high Reynolds numbers (Re > 1000). (While, d_p= diameter of the sphere, V: velocity of the sphere, ρ_g: density of the gas, η = dynamic viscosity coefficient of the gas). (For air at 1013 hPa and 293 K: η = 1.81x10-5 Pa s)
Drag Coefficient:

$$C_D = \frac{24\eta}{p_g V d_p} = \frac{24}{\mathrm{Re}} \tag{3}$$

Newton has drawn an equation for the force resisting the motion of a sphere passing through a gas. The projected area of the sphere times the travelled distance is equivalent by the sphere pushes aside a volume of gas. This derivation is based only on the inertia of the gas and does not take into account molecular viscous friction. FD = Drag Force. (While, *r* = particles radius, V = Velocity of the sphere, η = dynamic viscosity coefficient of the gas).

(For air at 1013 hPa and 293 K: η = 1.81x10-5 Pa s)
Drag Force:

$$F_D = 6\pi\eta r V \tag{4}$$

When a particle is discharged into air, it quickly arrive at its terminal settling velocity, a situation with constant velocity wherein the drag force of the air on the particle, F_D, is exactly equivalent but opposite to the force of gravity, F_G. (While, m: Mass, g: acceleration of gravity, ρ_p: particle density, d_p: Diameter of the sphere, C_C: Cunningham slip correction, η = dynamic viscosity coefficient of the gas. (For air at 1013 hPa and 293 K: η = 1.81x10-5 Pa s)).

1) Settling Velocity

a) Force of Gravity:

$$F_G = mg = \frac{\pi}{6}\rho_p d_p^3 g \tag{5}$$

b) Terminal Settling Velocity:

$$V_{TS} = \frac{\rho_p d_p^2 g C_c}{18\eta} \tag{6}$$

2) Mechanical Mobility

Since in Stokes' law the resistance force is proportional to the particle velocity, the particle mobility can be defined below. (While, V: Velocity of the sphere, F_D: Drag force, d_p: Diameter of the sphere, C_C: Cunningham slip correction, η = dynamic viscosity coefficient of the gas. (For air at 1013 hPa and 293 K: η = 1.81x10-5 Pa s).

$$B = \frac{V}{F_D} = \frac{C_C}{3\pi\eta d_p} \tag{7}$$

3) Stopping Distance

Stopping distance of a particle is an initial velocity towards the critical surface, i.e., the distance over which the particle is decelerated by the different forces acting on it, before it stops and turns around. In other words, the stopping distance is the total distance traveled by the particle.

$$S = \frac{p_p d^2 p\, V_0}{18\eta} \tag{8}$$

III. RESULT AND DISCUSSION

A. The Environmental Parameters

The environmental parameters were tabulated in Table 1. It shows the average level on the particular temperature, air velocity and relative humidity. As tabulated on Table I, during Slot 1, the temperature was higher at sampling point 5 (Spot Gun Welding) which is 30.5˚C while the lowest temperature was at sampling point 6 (Door) which is 25.6˚C. However during Slot 2, the temperature was higher at sampling point 2 (Assy Robot Line) which is 33.6˚C and lower at sampling point 5 (Spot Gun Welding) which is 29.9˚C. From the result, the temperatures at sampling point 2 (Assy Robot Line) were slightly higher during slot 2 which is 33.6˚C due to the high temperature in the afternoon. Furthermore, the temperature might be lower may be because of the stop of welding operation including the stop using of fan as ventilation during that time. Besides, sampling point 5 was nearest to the window that is why the temperature was highest during Slot 1 and lowest during Slot 2.The temperature in all sections excluding sampling point 6 (door) have exceeded those recommended by the standard Industry Code of Practice on Indoor Air Quality (ICOP IAQ) [5] which are supposed in the range of 23°C – 26°C.

In temperature climates the window is possibly the most thermal control device in any building. The window opening is not only useful for energy saving, by reducing the need for mechanical cooling but also provides for beneficial interaction between the indoor and the outdoor environments [6]. In Ismail and colleagues (2010) studies states that Malaysia is considered as a hot and humid tropical country that has a yearly mean temperature of between 26˚C to 27˚C and has high daytime temperatures of 29˚C to 34˚C and relative humidity of 70% to 90% throughout the year. Result of their studies suggest a wider thermal comfort range for these regions that are proposed by international standards, i.e., ASHRAE Standard 55, which indicates that Malaysians are acclimatized to much higher environmental temperatures.

On the other hand, for the relative humidity, the averages for all six sampling locations are between 67.7% - 71.7%. During Slot 1, the relative humidity was higher which 73.1% in the sampling point 1 (MIG) and 2 (Assy Robot Line). The relative humidity was low at sampling point 5 (Spot Gun Welding) which is 71.7%. During Slot 2, the relative humidity was higher at sampling point 3 (Fuel Lid Assy) which is 71.7% and the lowest relative humidity in slot 2 was 67.7 at sampling point 2 (Assy Robot Line). Relative humidity varies significantly when the temperature changes, even when the actual amount of water vapor is held constant, then if there is reduction in the temperature, the relative humidity will be increased [7]. From the results shows that the relative humidity at certain time have exceed the DOSH standard limit which are in supposed to be in between 40% - 70%. However, in a tropical country, [8] the outdoor air is usually very hot (air temperature 30 °C) and humid (90% RH) throughout the year .Thus, Singapore NEA Standard [9] has recommended 70% as the maximum allowable RH for indoor air. Since Malaysia is a tropical country and very near to Singapore, therefore, the relative humidity in all the six sampling point taken is still in the acceptable range.

TABLE I. THE AIR VELOCITY, TEMPERATURE AND RELATIVE HUMIDITY OF SIX SAMPLING POINT

Sampling Point	**Parameter**	**Slot 1 (Morning)**	**Slot 2 (Afternoon)**
		Average	**Average**
1 (MIG)	**Air Velocity (m/s)**	0.39	0.2
	Temperature (Celsius)	28.4	33
	Relative Humidity (%)	73.1	69
2 (Assy Robot Line)	**Air Velocity (m/s)**	0.46	0.07
	Temperature (Celsius)	28.9	33.6
	Relative Humidity (%)	73.1	67.7
3 (Fuel Lid Assy)	**Air Velocity (m/s)**	0.23	0.07
	Temperature (Celsius)	27.8	31.0
	Relative Humidity (%)	73	71.7
4 (Spot Weld)	**Air Velocity (m/s)**	0.34	0.30
	Temperature (Celsius)	28.7	31.9
	Relative Humidity (%)	73	68.5
5 (Spot Gun Welding)	**Air Velocity (m/s)**	0.48	0.25
	Temperature (Celsius)	30.5	29.9
	Relative Humidity (%)	71.7	70.1
6 (Door)	**Air Velocity (m/s)**	0.18	0.17

The relative humidity indicates that the averages for all six sampling locations are between 67.7% - 71.7%. During Slot 1, the relative humidity was higher which 73.1% in the sampling point 1 (MIG) and 2 (Assy Robot Line). The relative humidity was low at sampling point 5 (Spot Gun Welding) which is 71.7%. During Slot 2, the relative humidity was higher at sampling point 3 (Fuel Lid Assy) which is 71.7% and the lowest relative humidity in slot 2 was 67.7 at sampling point 2 (Assy Robot Line). Relative humidity varies significantly when the temperature changes, even when the actual amount of water vapor is held constant, then if there is reduction in the temperature, the relative humidity goes up [7]. From the results shows that the relative humidity at certain time have exceed the ICOP IAQ standard limit which are in supposed to be in between 40% - 70%. However, in a tropical country, [8] the outdoor air is usually very hot (air temperature 30 °C) and humid (90% RH) throughout the year .Thus, Singapore NEA Standard [9] has recommended 70% as the maximum allowable RH for indoor air. Since Malaysia is a tropical country and very near to Singapore, therefore, the relative humidity in all the six sampling point taken is still in the acceptable range.

For the air velocity, during Slot 1, Table I shows the highest air velocity was 0.48m/s at sampling point 5 (Spot Gun Welding) and the lowest air velocity is 0.18/s at sampling point 6 (Door). During Slot 2, the highest air velocity was 0.30m/s at sampling point 4 (Spot Weld) while the lowest air velocity was 0.07m/s at sampling point 2 (Assy Robot Line) and 3 (Fuel Lid Assy). The air velocity was important in order to help the distribution of the fumes particles, prevent from inhale by the welders. The air velocity was lower may be because the fan was off. Besides, the used of fan could control the temperature at the welding area. It was believe that the temperature also might influence the size of welding fume transport in air. Because of the sampling point 5 was nearest to the window that is why the air velocity was higher during Slot 1. This might happen because of the interaction between the indoor and outdoor environment. The standard limit of air velocity as stated in ICOP on IAQ which published by DOSH 2010 are in between 0.15 – 0.50 m/s. Most of the air velocity does not exceed the recommended limit.

Based on the observation, the employer only installed the fan for ventilation without installing any hood to suck out the fumes production. It also identified that the level of fumes concentration particles are above the allowable limit. The fume minimization guidelines from standard guidelines ACGIH and ASHRAE should be used to ensure the controlling the fumes and gases from welding process keep under the allowable concentration depended on the types of welding process [10]. Mechanical ventilation must be proposed and design properly and the LEV system must be put in certain area especially welding area [11].

B. The Concentration of Fumes Particles

The result of the particles fumes concentration will be compare with OSHA PEL-TWA which state fumes concentration limit, are supposed to be 0.50mg/m^3. Table II shows the concentration of fumes particles at six sampling point area. Results shows that the fume particles concentrations was not exceed the concentration limit in the four sampling point including both slot while exceed for sampling point 2 and 6 during slot 1. As tabulated in Table II, sampling point 6 produces highest concentration in slot 1 which is 0.543 mg/m^3 while during slot 2, sampling point 2 (Assy Robot Line) area produces highest concentration of particles (0.486 mg/m^3). The concentration of fumes particles was lowest in sampling point 5 during slot 1 (0.392mg/m^3) and during slot 2, sampling point 6 produce the lowest particles concentration (0.213 mg/m^3).

The observation results shows that most of welding areas have been installed with the fan ventilation, but the result shows that the used of that mechanical ventilation were not really effective. In between the sampling point 2 (Assy Robot Line) and 3 (Fuel Lid Assy), there are a curtain was design purposely to control the distribution of welding fumes. This is one reasonable cause which leads the highest concentration of fumes produce as well as it traps in sampling point 2 (Assy Robot Line) areas. For sampling point 5, the concentration was low during slot 1 because of the stop using fan ventilation. This shows that the air velocity might reflect the fume concentration reading. For sampling point 6 (door), which forms the highest concentration of particles during slot 1, may be because of the effect of outdoor environment parameters.

TABLE II. THE CONCENTRATION OF PARTICLES AT SIX SAMPLING POINT

Sampling Point	**Slot 1 (Morning)**	**Slot 2 (Afternoon)**
	Average (mg/m^3)	**Average(mg/m^3)**
1 (MIG)	0.439	0.432
2 (Assy Robot Line)	0.54	0.486
3 (Fuel Lid Assy)	0.453	0.336
4 (Spot Weld)	0.465	0.292
5 (Spot Gun Weld)	0.392	0.249
6 (Door)	0.543	0.213

C. The Physical Characteristics of Welding Fume

The physical characteristics of welding fumes were evaluated in terms of morphology, size and aerodynamic diameter. The sizes of welding fumes affect the deposition of welding fumes in welders' lungs. The aerodynamic diameter was calculated in presenting the particles size of welding fumes.

1) Morphology of Welding Fumes

The morphology of the particles collected on the two area been analysed by FESEM for MIG and Assy Robot Line welding. Figure 1 and Figure 2 shows selected, representative images of the particles found. The FESEM images confirm that the fumes from MIG and certainly Assy Robot Line welding are dominated by clusters of primary particles. The fumes diameter in MIG area found in the range of 52.2 nm, 68.0nm, 74.9nm and 81.5nm. In Figure 2, there is spherical particles with a diameter of up to 2.38μm were found among the agglomerates. These particles are probably formed from molten metal transfer. However, very few large particles were collected. Some particles with a size of towards 61.0 nm, 76.6 nm, 91 nm and 105 nm were found in MIG fumes.

The initial particle characterization was performed by using FESEM analysis because particle morphology is most easily obtained with these techniques, respectively. Magnifications of the image is approximately 70,000× were readily obtainable with FESEM, allowing for imaging of particles at the larger end of the ultrafine region (diameters < 100 nm). In Figure 1, most of the aerosols generated for MIG were arranged in homogeneous, chain-like agglomerates of primary particles. In Figure 2, there are particles morphology spherical was sometimes observed among the agglomerates.

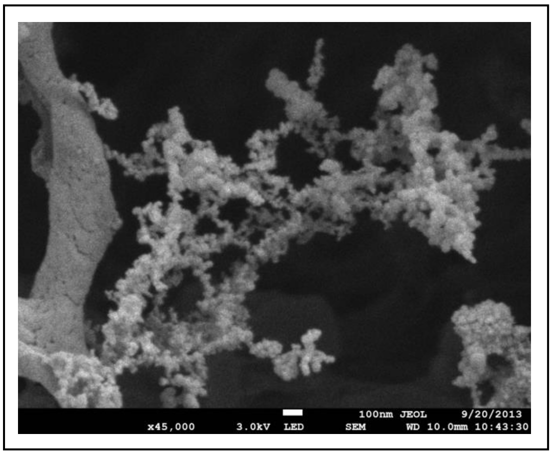

Fig. 1. SEM image of Assy Robot Line Welding at 45Kx magnifications

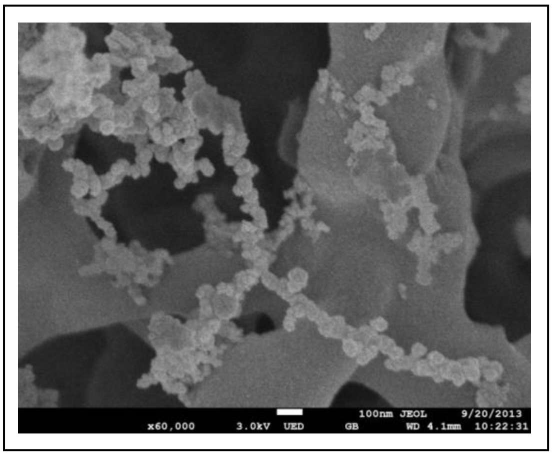

Fig. 2. SEM image for MIG Welding at 60Kx magnifications

Three distinct particle morphologies were observed, namely spherical and agglomerated. Spherical particles were the most abundant type of individual particle. Agglomerates were found to consist of anywhere from several to hundreds of spherical and irregular particles bound together [12]. A schematic representation of the types of particles observed is shown along with a schematic of the core-shell structure, which was observed during FESEM analysis. A large number of agglomerates are found on all the stages for the samples in Figure 2, though they were quite different from the agglomerates as shown in Figure 1. These agglomerates were generally well packed together, and in some cases formed large consolidated round agglomerates consisting of multiple fume particles of different sizes. These round agglomerates were most prevalent on magnification of 22,000×. However, during analyse fume morphology for sample in Figure 1, most of the agglomerates were generally observed to be spherical in shape and apparently consolidated.

Formation of aerosols exists including with nucleation, which a process of high temperature metal vapors are transformed into primary particles [13]. Then it was followed by coagulation form. Dynamic aerosols were growth by which the mechanism occurs when small particles collide to become larger agglomerate. After collide to form large agglomerates, likely to hold together by van der Waals and other attractive interactions, such as electrostatic and magnetic forces [13]. The strength of these forces is importance toxicologically because the individual primary particles are in the ultrafine size range which is in between 0.01µm to–0.10µm. If these attractive forces were to be disrupted by interactions with lungs cells and biological fluids after inhalation, the primary particles could possibly dissociate from the larger agglomerates. Studies have indicated that the adverse effects of particles in the lungs may be due in part to particle size [14].

The shape of fumes particles might be affects the transport of fume particles in air. Neopane and colleagues (2012) studies determined that spherically shaped particles had higher settling velocities than particles with other shapes [15]. However, non-spherical shape of the particles will tend to have lower settling velocities because both decreases in spheroid and increases in angularity tend to decrease velocities. Moreover, larger cross-sectional areas tend to be directed perpendicular to the transport path.

2) The Aerodynamic Diameter

The aerodynamic diameter of a particle whatever its shape and density is defined as the diameter of a sphere with the density 1 (ρ_0 = 1.0 g/cm^3) which settles at the same velocity as the particle in calm or laminar flowing air. Aerodynamic diameter has been developed in order to categorize the sizes of particles that have different shapes and densities with a single dimension [16]. It was defined as the diameter of a spherical particle having a density of 1 gm/cm3 that has the same inertial properties i.e. terminal settling velocity in the gas as the particle of interest [17].

TABLE III. THE PARTICLE DIAMETER AND AERODYNAMIC DIAMETER IN MIG AND ROBOT WELDING AREA

	Particle Diameter*(da)*	**AED(*dp*)**
MIG	34.6nm	7.22×10^{-7} µm
Robot Welding	41.7nm	9.44×10^{-7} µm

As demonstrated in Table III, the aerodynamic diameter (AED) of a particle mainly depends upon the equivalent volume diameter of that particle and density of particles. Normalized particle mobilities with an aspect ratio of 0.1 are characterized by an exponential decrease with increasing particle diameter dp that is, small particles (dp<0.1µm) exhibit significant mobilities, whereas for large particles (dp> 1µm) may be evaluated as nearly negligible. The calculated diameters dp and da are summarized in Table III. Based upon the respective geometry, calculated diameters of fume particles are commonly lower than related values for dp. This result bears a significant consequence concerning the transport and deposition behavior of non-spherical particles in the human respiratory tract.

The deposition efficiency of generated particles was identified by aerodynamic diameter [16]. This was because of the mass and the size of generated particles contributed to deposition efficiency especially when they fall in the respirable range. The respirable particles deposited deeper in the respiratory system. Based on the Table III above, shown the diameter of particles and aerodynamic diameter of fumes particles that produce between two areas which are MIG area and robot welding area. The particles diameter shows the average of four reading of particle diameter. The result shows that both welding fumes produce the size of nano-particles which are 7.22×10^{-7} µm for MIG area and 9.44×10^{-7} µm for robot welding area.

As particles travel through air, gravitational forces and air resistance eventually overcome their buoyancy (the tendency for the particle to stay up). The result is that the particles will settle on a surface of the lung. This type of deposition is most common in the bronchi, and the bronchioles. Sedimentation is not an important factor when the aerodynamic diameter of the particle is less than 0.5 µm. The random motion of particles is similar to gas molecules in the air when particles are smaller than 0.5 µm. When particles are in random motion, they deposit on the lung walls mostly by chance. The smaller the particle size, the more vigorous the movement is. Diffusion is the most important mechanism for deposition in the small airways and alveoli. Very fine particles 001 µm or smaller are also trapped in the upper airway.

Smaller particles with an aerodynamic diameter of about 0.003 to 5 µm are deposited in the trachea bronchial and alveolar regions [18]. When the air gets to the alveolar region (the lower lung area), it has slowed even more. The air is essentially calm. Particulates that make it this far into the lungs are usually 0.5 µm or smaller.

D. Transport Of Welding Fumes In Air

Since a fume is a particle in air, it is important to understand how air moves before we can characterize the motions of a fume in air. These motions include the type of motion, the suitable Law apply, the drag force, the settling velocity, the terminal settling velocity, the mechanical velocity and the stopping distance of fumes particle in air.

1) The Type of Fume Particles Motion

Reynolds number (Re) is one index had used. The fume Reynolds number (Re) is a dimensionless parameter to characterize the type of flow of particles either laminar, turbulent or transition. It is the ratio of inertial forces to viscous forces acting on the fume particle.

TABLE IV. THE REYNOLD NUMBER (RE) VERSUS DRAG COEFFICIENT (CD) VALUE

	Re	**C_D**
MIG Welding		
Slot 1 (Morning)	0.0012	2.0×10^4
Slot 2 (Afternoon)	0.0006	3.93×10^4
Robot Welding		
Slot 1 (Morning)	0.0017	1.41×10^4
Slot 2 (Afternoon)	0.0002	9.23×10^4

This Newton's resistance equation is valid in the turbulent flow regime (i.e. Re > 1000), where inertial forces are much larger than viscous forces. The drag coefficient CD has a nearly constant value of 0.44. On the other hand, when small fume particle size and low air velocity are involved, the Reynolds number is small and the flow is laminar. Under this condition, inertial forces are negligible compared to viscous forces. Newton's Law is no longer valid and Stokes's Law shall be used.

Table IV shows the value of Reynolds Number and Drag Coefficient value of welding fumes in MIG area and Assy Robot Line Area. When the Re value was smaller than 1, so that the fume particles is believed move in laminar flow.

There are several assumption associated with the Stokes's Law:

1. The fluid is incompressible.
2. There is no other particle nearby that would affect the flow pattern.
3. The motion of the particle is constant / laminar.
4. The particle is spherical and rigid.
5. The air velocity right at the particle surface is zero.

Figure 3 shows the relationship between Aerosols Reynolds number and Drag Coefficient. This figure proved that the result obtain in Table IV was still correspond to the previous research by Boss and Jumars, 2003.

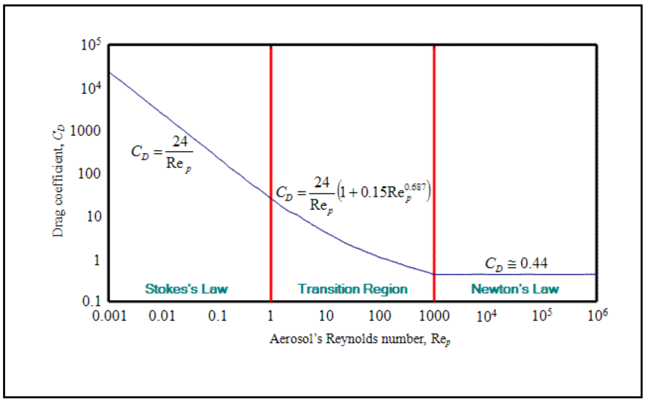

Fig 3. The relationship between Aerosols Reynolds number and Drag Coefficient [19]

2) The Velocity of the Fumes Particle

Once the force acting on the fume was determined, and then investigates how the fume particle moves. When a fume particle is released in air, it settles due to gravity and the velocity increases. As the velocity increases, the drag also increases which counter balances the gravitational force. Eventually, when these two forces are equal to each other, i.e. the net force is zero, there is no more acceleration and the velocity reaches a constant value. This is called terminal settling velocity.

TABLE V. THE VALUE OF DRAG FORCE (FD), SETTLING VELOCITY (SV), TERMINAL SETTLING VELOCITY (VTS) AND MECHANICAL VELOCITY (MV) OF FUME PARTICLE IN MIG AND ASSY ROBOT LINE AREA

	FD(N)	**FG (g.m/s^2)**	**VTS(m/s)**	**MV (mN^{-1}s^{-1})**
MIG Area				
Slot 1 (Morning)	$2.3019x 10^{-12}$	9.34×10^{-26}	1.1131×10^{-16}	1.1917×10^{12}
Slot 2 (Afternoon)	1.1805×10^{-12}	9.1014×10^{-26}	1.0954×10^{-16}	1.1917×10^{12}
Assy Robot Line				
Slot 1 (Morning)	3.2801×10^{-12}	2.0113×10^{-25}	1.6782×10^{-16}	8.3438×10^{11}
Slot 2 (Afternoon)	$4.9914x10^{-13}$	$1.8101x10^{-25}$	1.5103×10^{-16}	8.3438×10^{11}

Table V above shows the calculated value of Drag Force, Settling Velocity, Terminal Settling Velocity and Mechanical Velocity of the fume particles in two areas. Settling is the process by which particle settle to the bottom of a gas. Particles that experience an applied force, either due to gravity or due to centrifugal motion will tend to move in a uniform manner in the direction exerted by that force. The applied force is usually not affected by the particle's velocity, whereas the drag force is a function of the particle velocity. From the table V, the Drag Force of fume particle in MIG area was higher during Slot 1 which is 2.3019×10^{-12}N while fume particle in Assy Robot Line was lowest during Slot 1 which is $4.9914x10^{-13}$ N.

For the force of gravity and Terminal Settling Velocity, obviously the velocity of fume particles in Assy Robot Line Area (Slot1: 2.0113×10^{-25} g.m/s^2 and; 1.6782×10^{-16} m/s. Slot 2: $1.8101x10^{-25}$ g.m/s^2 and 1.5103×10^{-16} m/s) is faster compared to MIG area (Slot 1: 9.34×10^{-26} g.m/s^2 and 1.1131×10^{-16} m/s; Slot 2: 9.1014×10^{-26} g.m/s^2 and 1.0954×10^{-16} m/s). This might be influence by the diameter of the fume particles itself (refer Table III). Therefore, the larger the size of fumes particles might increase the settling velocity value. Figure 4 proved that the increase of the particle size directly increase the settling velocity of particles.

Then, mechanical velocity is the value calculated in order to know the movement of particles to have a constant motion in air either more easily or not. The smaller the fume particle, the larger the mechanical mobility and consume to the easier the particle to move. Based on Table III, the fume particle size for MIG area is $34.6x10^{-9}$m while for Assy Robot Line area is $41.7x10^{-9}$m. Based on Table V, the mechanical velocity was higher in Assy Robot Line area (8.3438×10^{11} mN^{-1}s^{-1}) and lower in MIG Area (1.1917×10^{12} ms^2). From these results, conclude that the movements of fume particles are easier to move in Assy Robot Line area compares to the movement of fume particles in MIG area.

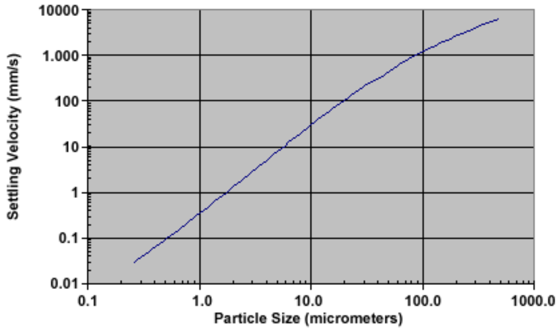

Fig 4: The particle size versus settling velocity of particles [20]

Furthermore, particle deposition velocity increases with air relative humidity [21]. His studies also state that it is not clear that whether particle deposition is affect by the temperature and relative humidity. However, the results show in Table V is vice versa to the Han studies. This might happen because of other factors such as the particle diameter as well as other environmental parameters.

3) Stopping Distance of Fume Particles

To determine the maximum distance a particle with an initial velocity will travel in the still air without any external forces (i.e. only drag force is acting on the particle), stopping distance is introduced. Table VI shows the calculated stopping distance of fume particle in between two areas which are MIG area and Assy Robot Line Area. Stopping distance for fume particle in MIG area during slot 1 (morning) is 6.29612×10^{-19}m, while during Slot 2 (afternoon) is 3.1748×10^{-19}m. In the Assy Robot Line area, stopping distance during slot 1 (morning) is 1.3258×10^{-18}m, while during Slot 2 (afternoon) is 1.8157×19^{-19}m. Based on the Table VI, proved that the larger the diameter of fume particle, the longer the stopping distance of the particle transport. Besides, the stopping distance for fumes in robot welding was longer in the morning because of the higher of air velocity compared to the air velocity in the afternoon. It is shows that the air velocity also affects the stopping distance. The larger the fume particles diameter, the higher the air velocity, the longer the fume particle travels.

TABLE VI: THE STOPPING DISTANCE (S) BASED ON DIAMETER OF FUME PARTICLE (DP)

	Diameter of Fume (Dp), nm	**Stopping Distance (S), m**
MIG Welding		
Morning	34.6	$6.29612x10^{-19}$
Afternoon	34.6	$3.1748x10^{--19}$
Assy Robot Line Welding		

Morning	41.7	$1.3258x10^{-18}$
Afternoon	41.7	$1.8157x19^{-19}$

The result are in parallel with the study conducted by Loffler and colleagues [22]. They found that the stopping distance decreases rapidly with the increase of particle diameter. However, it might be other factors that influence their result. Besides, their result also corresponds to the result studies by Kulkarni [23]. Kulkarni studies shows air velocity and particle diameter are other factors affect the stopping distance.

IV. CONCLUSION

Safety and health issues must be addressed in all applications to provide a safe work environment for employees and the community they live in. Environmental setting might influence on the production of welding fumes either in size or the concentration and directly might be inhaled by the welders. From this result study shows that the welders might expose in unhealthy working condition. The temperature and relative humidity in this welding area are the important factors that should be control so that the welders will be more comfort as well as working in healthy condition.

In order to achieve the second objective, which are about the physical properties of welding fumes, the sample collected have been analysed using the FESEM machines. From the analysis results, found that fumes particles produces in this industry are in nano-particles size which is tiny. It is too hazardous because, when inhaled, it will diffuse into the deep of welder lungs (alveoli region). Nano-sized particles also can penetrate the skin and find their way into the lymph nodes and channels [4]. Besides, from the analysis, found that the shape of the fume particle are mostly is chain like agglomerate. Sometimes, the larger spherical also was found in between the agglomerate. Agglomerates are the bounding of the spherical and irregular shape. Furthermore, the spherically shaped particles had higher settling velocities than particles with other shapes.

Particle size is the greatest factor when determining the transportation of welding fumes in this industry. After being calculate the value of Reynolds number, it is conclude that the motion of particle are move in laminar flow. The law applied was Stoke's Law. The velocities of the fume particles are depended on the size of fume particles. The larger the size of the particle might increase the velocity of the fume particles. Besides, the smaller the size of fumes particles, as well as higher air velocity, the longer distance of fumes particles being transport.

Acknowledgment

This work was supported by the grants from Universiti Malaysia Pahang under Grant (RDU 1303220).

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