Applied Occupational and Environmental Hygiene

ISSN: 1047-322X (Print) 1521-0898 (Online) Journal homepage: https://www.tandfonline.com/loi/uaoh20

Experimental Evaluation of a Mathematical Model for Predicting Transfer Efficiency of a High Volume?Low Pressure Air Spray Gun

Yu-Mei Tan & Michael R. Flynn

To cite this article: Yu-Mei Tan & Michael R. Flynn (2000) Experimental Evaluation of a Mathematical Model for Predicting Transfer Efficiency of a High Volume?Low Pressure Air Spray Gun, Applied Occupational and Environmental Hygiene, 15:10, 785-793, DOI: 10.1080/10473220050129428

To link to this article: https://doi.org/10.1080/10473220050129428

Applied Occupational and Environmental Hygiene
Volume 15(10): 785–793, 2000

1047-322X/00 $12.00 + .00

Experimental Evaluation of a Mathematical Model for Predicting Transfer Efficiency of a High Volume–Low Pressure Air Spray Gun

Yu-Mei Tan and Michael R. Flynn

Department of Environmental Sciences and Engineering, School of Public Health, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina

The transfer efficiency of a spray-painting gun is defined as the amount of coating applied to the workpiece divided by the amount sprayed. Characterizing this transfer process allows for accurate estimation of the overspray generation rate, which is important for determining a spray painter's exposure to airborne contaminants. This study presents an experimental evaluation of a mathematical model for predicting the transfer efficiency of a high volume–low pressure spray gun. The effects of gun-to-surface distance and nozzle pressure on the agreement between the transfer efficiency measurement and prediction were examined. Wind tunnel studies and non-volatile vacuum pump oil in place of commercial paint were used to determine transfer efficiency at nine gun-to-surface distances and four nozzle pressure levels. The mathematical model successfully predicts transfer efficiency within the uncertainty limits. The least squares regression between measured and predicted transfer efficiency has a slope of 0.83 and an intercept of 0.12 ($R^2 = 0.98$). Two correction factors were determined to improve the mathematical model. At higher nozzle pressure settings, 6.5 psig and 5.5 psig, the correction factor is a function of both gun-to-surface distance and nozzle pressure level. At lower nozzle pressures, 4 psig and 2.75 psig, gun-to-surface distance slightly influences the correction factor, while nozzle pressure has no discernible effect.

Keywords Spray Painting, Transfer Efficiency, High volume–Low pressure air spray gun

A number of techniques have been developed to increase transfer efficiency in the application of paints. One of the most prevalent methods is to atomize the paint into fine particles and subsequently transport it to the workpiece in an airflow from a compressed air spray gun. These spray guns can be categorized as either conventional or high volume–low pressure (HVLP) guns, according to the volume and pressure of the atomizing air. A conventional gun performs at pressures ranging from 25 to 100 psig, while an HVLP gun usually operates at 10 psig or less.(1) The low operating pressure of HVLP guns produces larger droplets, and results in a higher transfer efficiency.(2–7)

Commercial paints contain toxic materials such as lead, cadmium, chromium, and isocyanates.(1) Research has shown that long-term exposure to these and other agents among spray painters can induce respiratory, systemic, and possibly carcinogenic effects.(8–15) A spray booth is the most commonly used control technique. Spray guns with higher transfer efficiency are also introduced as control intervention devices to reduce worker exposure. Transfer efficiency is defined as the mass fraction of paint sprayed from the gun that is deposited onto the workpiece surface. It has become an index of both occupational and environmental exposure standards.(16–19) The National Institute for Occupational Safety and Health (NIOSH) recommends the use of HVLP guns,(20) which are said to have higher transfer efficiencies than conventional guns.(2–7)

Heitbrink et al. suggested that a physical model for overspray production would be a very useful tool in identifying how operational parameters influence the transfer efficiency of a spray gun.(21) This study evaluates an existing mathematical model(22) for predicting the transfer efficiency of an HVLP spray gun. This model provides fundamental knowledge on the transfer processes of a spraying operation. Transfer efficiency is directly related to the paint overspray generation rate, an important parameter in an empirical model(22–29) designed to estimate worker exposure. The goal of this study is to provide feasible and effective control interventions based on model predictions.

MODEL DESCRIPTION

Transfer Efficiency Prediction

The mathematical model evaluated in this study was developed by Flynn et al.(22) The model simulates the transfer process

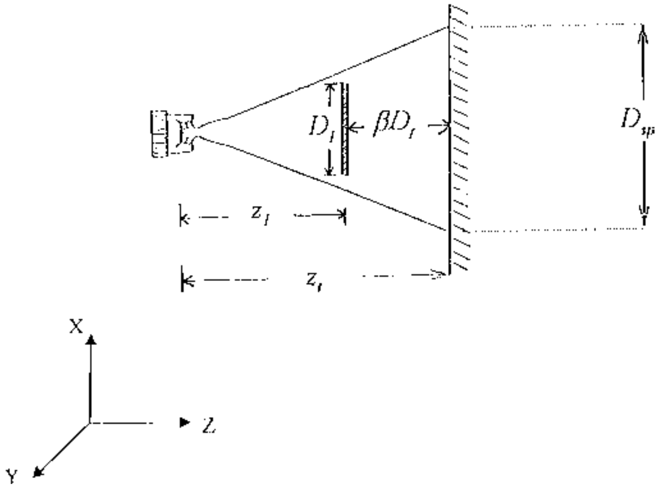

FIGURE 1
Impaction model for spray painting (not drawn to scale).

as an imaginary impactor with a circular or rectangular opening, depending upon the shape of spray pattern. The impaction plate, or workpiece, collects large particles with sufficient inertia. Small particles then follow the air streamlines and become overspray mist. Airflow through the two opposed horns on the air cap can be regulated to shape the spray into an elliptical pattern, which is employed in this study. Figure 1 illustrates the geometry of the imaginary impactor. The characteristic dimension is described below:

$$D_I = \frac{Z_t D_{sp}}{\beta D_{sp} + Z_t} \qquad [1]$$

where:

D_I = the characteristic dimension of the imaginary impactor, cm
Z_t = the gun-to-surface distance, cm
β = 1.5 when spray gun's fan air is on (elliptical spray pattern) or 1 when spray gun's fan air is off (circular spray pattern)
D_{sp} = the short dimension of the elliptical spray pattern or the diameter of the circular spray pattern, cm

To estimate the transfer efficiency of an HVLP spray gun, information on the droplet size distribution is required. Equation (2) is a cumulative mass droplet size distribution developed by Kim and Marshall(30) for a pneumatic nozzle. The reduced diameter, d^*, is the ratio of a specific diameter to the mass median diameter of the atomized droplets. In this study, d_{50}, the 50 percent collection efficiency cut size, is selected as the specific diameter to compare with the mass median diameter. Consequently, Φ_v represents the mass fraction of droplets that will not impact on the target. Equation (5) describes transfer efficiency as the mass fraction of droplets larger than d_{50}.

$$\Phi_v = \frac{1.15}{1 + 6.67\exp(-2.18d^*)} - 0.15 \qquad [2]$$

$$d^* = \frac{d_{50}}{MMD} \qquad [3]$$

$$d_{50} = 10000\sqrt{\frac{9(Stk)\mu D_I}{\rho_p V_I}} \qquad [4]$$

$$\eta = 1 - \Phi_v \qquad [5]$$

where:

Stk = 0.53, the critical Stokes number for 50 percent collection
μ = the air viscosity, poise
ρ_p = the particle density, g/cc
V_I = the air velocity from the spray gun, cm/s
η = the transfer efficiency of a spray gun

An empirical model developed by Kim and Marshall,(30) shown in Eq. (6), estimates the mass median diameter of the size distribution atomized by the spray gun. The average air velocity that carries the droplets was obtained based on Schlichting's work,(31) which is given in Eqs. (7)–(11).

$$MMD = \left\{5117\left[\frac{\sigma^{0.41}\mu_L^{0.32}}{(v^2\rho_n)^{0.57}A^{0.36}\rho_L^{0.16}}\right] + 18905\left[\left(\frac{\mu_L^2}{\rho_L\sigma}\right)^{0.17}\left(\frac{m_L}{m_a}\right)\frac{1}{v^{0.54}}\right]\right\} \qquad [6]$$

where:

MMD = the mass median diameter of the droplet size distribution, microns
ρ_L = the liquid density, g/cc
ρ_n = the air density at the nozzle, g/cc
σ = the liquid surface tension, dynes/cm
v = the relative velocity of air and liquid, cm/s
μ_L = the liquid viscosity, poise
A = the nozzle area for airflow, cm^2
m_L = the mass of liquid sprayed, g
m_a = the mass of air sprayed, g

$$V_I = \frac{Q}{A_{jet}} \qquad [7]$$

$$Q = 0.404 Z_I\sqrt{K} \qquad [8]$$

$$Z_I = Z_t - \beta D_I \qquad [9]$$

$$K = \frac{\rho_n A_n V_n^2 + (p_n - p_a)A_n}{\rho_a} + \frac{\rho_f A_f V_f^2 + (p_f - p_a)A_f}{\rho_a} \qquad [10]$$

$$A_{jet} = \pi Z_I^2 \tan^2(14.5^\circ) \qquad [11]$$

where:

Z_I = the distance between the imaginary impactor and the spray gun, cm
Q = the total air flow carried by the jet at Z_I, cm^3/s
K = the kinematic momentum flux, m^4/s^2
A_{jet} = the cross-sectional area of the air jet, cm^2

A = the exit area of air cap (subscript n) or fan air (subscript f), cm^2
V = the air velocity at cap air exit (subscript n), or at fan air exit (subscript f), cm/s
ρ = the air density at cap air exit (subscript n), or at fan air exit (subscript f), g/cc
p = the pressure at the air cap (subscript n), or at the horn (subscript f), g/cm
p_a = the ambient pressure, g/cm

For the subsonic airflow generated by HVLP spray guns, the pressure difference terms in Eq. (10) are zero. In Eq. (11), the airflow is assumed to pass through an expanding area with an included angle of 29 degrees.(32) The kinematic momentum flux, K, used to determine the total airflow carried by the jet from the imaginary impactor, is estimated by the isentropic compressible flow equations.(33)

Contaminant Exposure Estimation

The long-term objectives of the transfer efficiency model development are to characterize the transfer process of spray painting operations and to apply the knowledge to worker exposure estimation. Models developed by Flynn et al.(22) estimate the breathing zone concentration of airborne contaminants as a function of contaminant generation rate, air velocity field, and work practices during spray painting operations. Overspray generation rate is a function of the transfer efficiency of a spray gun, as shown in Eq. (14). The following equations determine a dimensionless breathing zone concentration in a side-draft spray booth when the workpiece is placed between the worker and the exhaust fan.

$$\log_{10}\left(\frac{CHUD}{m_o}\right)_{180} = -2.3 + 0.8\left(\frac{F_g}{F_m}\right)^{-1} \qquad [12]$$

$$\frac{F_g}{F_m} = \frac{K}{HDU^2} \qquad [13]$$

$$m_o = (1 - \eta) \times m_L \qquad [14]$$

where:

C = the total mass concentration in the breathing zone, mg/m^3
U = the average air velocity in the cross-flow spray booth, m/s
H = the height of the worker (or mannequin in this study), m
D = the breadth of the worker (or mannequin in this study), m
m_o = the overspray generation rate, mg/s
F_g = the momentum flux of the spray gun, kg m/s^2
F_m = the momentum flux through the projected area of the mannequin, kg m/s^2
K = the kinemetic momentum flux, m^4/s^2

METHODS

Experiments were conducted in a 1.5 m by 1.5 m by 2.45 m deep wind tunnel. The wind tunnel was used to simulate a cross-draft spray paint booth. A full-sized mannequin equipped with an electronically controlled trigger device on his right index finger was truncated at the knees to accommodate the size of the wind tunnel. The mannequin measures 1.30 m high and 0.36 m at the chest. A subsonic DeVilbiss HVLP spray gun (Model number: MSV-533-4-FF) was held in the mannequin's right hand, and was remotely activated from outside the wind tunnel. A 0.61 m by 1.22 m flat plate represents a simple workpiece to allow better experimental reproducibility among runs. The plate was placed between the mannequin and the exhaust fan of the wind tunnel. Inland #99 neutral parrafinic vacuum pump oil was chosen in place of commercial paint to simplify the problem because it is non-volatile. The primary assumption made when using non-volatile oil instead of volatile paint is that the transport processes in overspray vapor and solid particles are the same.

To measure the transfer efficiency of the HVLP gun, the flat metal plate was covered with 0.46 m by 1.27 m heavy-duty aluminum foil with the bottom end of the foil folded to collect oil drainage. Spraying time was between 20 to 30 seconds to prevent the vacuum pump oil from overflowing. Transfer efficiency was determined by calculating the ratio of the weight gain of aluminum foil to the difference in weight of the paint container before and after spraying. Gun-to-surface distances tested were six to fourteen inches with one-inch increments. This should represent the extreme spraying distances under normal operational procedures. The four nozzle pressures tested were 6.5, 5.5, 4, and 2.75 psig. This is within the normal range of nozzle pressures used in industrial spray painting operations. It was expected that neither gun-to-surface distance or nozzle pressure would have any effect on the predictive ability of the transfer efficiency model. For each nozzle pressure and distance setting, the experiment was repeated five times, yielding a total of 180 samples.

RESULTS

Results show good agreement between model predictions and experimental data. Figure 2 illustrates the comparison between the measured transfer efficiency and the predicted values. Error bars in both directions denote one standard deviation about the average transfer efficiencies. The physical properties of the vacuum pump oil and ambient air were determined empirically for model input. Random errors in these measurements introduce variation in the predicted transfer efficiency. Kim and Marshall's empirical model, Eq. (6), is used in place of a direct measurement to determine the mass median diameter of the particles atomized by the spray gun. An unknown particle size distribution introduces uncertainty into the transfer efficiency model. Kim and Marshall reported the error in mass median diameter as ±24% at a 95 percent confidence level.(30) The two dotted lines in Figure 2 reflect the uncertainties in the prediction of transfer efficiency given this error. All empirical data fell within these limits.

Figure 3 shows the effect of gun-to-surface distance on the percent difference in transfer efficiency prediction when nozzle pressure is varied. The percent difference in transfer efficiency

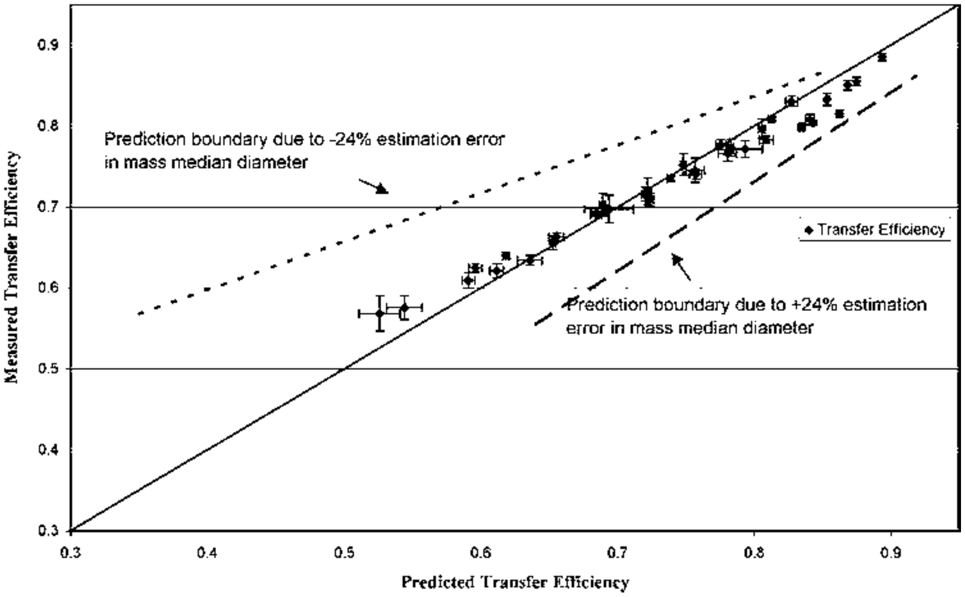

FIGURE 2
Measured transfer efficiency compared with predicted values.

prediction is calculated as the difference between the predicted and measured transfer efficiency divided by the measured transfer efficiency. It is observed that the predictive ability of the model varies with gun-to-surface distance. The model tends to overestimate the transfer efficiency at closer gun-to-surface distances, but underestimates it when the spray gun moves farther away from the surface. Higher nozzle pressures have slightly more influence on this relationship at extreme gun-to-surface distances. Yet, the differences between the measurement and prediction are small—less than eight percent. Predicted transfer efficiencies agree well with measured transfer efficiencies at gun-to-surface distances between nine to eleven inches, and nozzle pressure does not have a notable effect on the agreement. This is very encouraging because this is also the gun-to-surface distance range recommended in industry.

The least squares regression evaluates the association between the measured and predicted transfer efficiency. Ideally, a linear relationship with a slope of 1.0, intercept of 0.0, and an

FIGURE 3
Effect of gun-to-surface distance upon the percent difference in transfer efficiency prediction varied by nozzle pressure.

TABLE I

Regression analysis: Measured transfer efficiency versus predicted values

Least squares regression	Slope	95%C.I. for slope	Intercept	95%C.I. for intercept	R^2
M.T.E.^{A} vs. P.T.E.^{B}	0.83	(0.79, 0.87)	0.12	(0.09, 0.15)	0.98
M.T.E.^{A} vs. corrected^C P.T.E.^{B} at 6.5 and 5.5 psig	0.98	(0.95, 1.01)	0.01	(−0.01, 0.03)	0.99
M.T.E.^{A} vs. corrected^C P.T.E.^{B} at 4 and 2.75 psig	1.05	(0.98, 1.13)	−0.04	(−0.10, 0.01)	0.97

[A] M.T.E. = Measured transfer efficiency.

[B] P.T.E. = Predicted transfer efficiency.

[C] The corrected P.T.E. were determined using 70 percent of the data. The remaining 30 percent were used to validate the model, that is, estimate the slope, intercept, and R^2.

R^2 of 1.0 indicates perfect agreement. As shown in Table I, the linear regression yields a slope of 0.83 (95% C.I. 0.79–0.87) and an intercept of 0.12 (95% C.I.: 0.09–0.15) with an R^2 of 0.98. This indicates that the model overestimates transfer efficiency at higher levels but underestimates it at lower ones. Two correction factors were determined to improve the predictive power of the model, as listed in Table II. For each nozzle pressure setting, 70 percent of the data were used to determine the correction factors, while the remaining 30 percent of the data were used to validate the adjusted model. At higher nozzle pressure settings (6.5 psig and 5.5 psig) the correction factor is a function of both gun-to-surface distance and nozzle pressure. At lower pressures, gun-to-surface distance only slightly influences the correction factor. As shown in Table I, the 95 percent confidence intervals of slopes and intercepts of both nozzle pressure groups include the values 1.0 and 0.0, respectively. Thus, the corrected model is in excellent agreement with measured transfer efficiency.

The effects of gun-to-surface distance and nozzle pressure on transfer efficiency are examined with experimental data and model predictions. The results are shown in Tables IIIa and IIIb. Table IIIa shows that the transfer efficiency of an HVLP spray gun decreases as the gun-to-surface distance increases. Linear regression of the transfer efficiency with respect to the gun-to-surface distance shows a decreasing rate in transfer efficiency for every inch the spray gun is moved away from the target. The decreasing rates in predicted transfer efficiency, with gun-to-surface increment per inch, range from 2.57 percent to 4.24 percent, while they range from 2.25 percent to 3.30 percent in measured transfer efficiency. Experimental data show a lower rate of decrease than model predictions, given the same nozzle pressure. Our finding is consistent with Kwok's 3.44 percent decreasing rate when using a conventional spray gun to spray commercial paint.(34)

At lower nozzle pressures the rate of decrease in transfer efficiency is less than at higher nozzle pressures. Table IIIb shows that the transfer efficiency of an HVLP spray gun also decreases as the nozzle pressure increases. The reason is that the spray gun atomizes smaller droplets at higher nozzle pressure levels than at lower ones. The decreasing rates in predicted transfer efficiency per increment in unit nozzle pressure range from 1.22 percent to 4.39 percent, while they range from 1.76 percent to 3.55 percent in measured transfer efficiency.

DISCUSSION

To explain why the model overestimates transfer efficiency at small gun-to-target distances, the atomization process is examined. When a spray is formed at the outlet of an atomizer, it expands in the radial direction before developing a fully axial flow.(35) Larger particles penetrate farther in the radial direction than smaller ones and cause the formation of larger size distribution at the edge of the spray. To make the following discussion clear, a coordinate system is defined, as shown in Figure 1. The

TABLE II

Correction factors at various nozzle pressure levels

Nozzle pressure (psig)	Correction factor^A
6.5	$(0.0015 \times \text{pressure}^B + 0.00415) \times \text{distance}^B + 0.87$
5.5	$(0.0015 \times \text{pressure}^B + 0.00415) \times \text{distance}^B + 0.87$
4	$1.05 - (0.5/\text{distance}^B)$
2.75	$1.05 - (0.5/\text{distance}^B)$

[A] Correction factor at each air-cap pressure level is determined with 70 percent of the total data.

[B] Units in the correction factor: Pressure (psig); distance (inch).

TABLE IIIa
Effect of gun-to-surface distance upon the decreasing rate in transfer efficiency varied by nozzle pressure

	Predicted transfer efficiency		Measured transfer efficiency	
Nozzle pressure (psig)	Decreasing rate per inch gun-to-surface distance increment	R^2	Decreasing rate per inch gun-to-surface distance increment	R^2
6.5	4.24%	0.99	3.30%	0.98
5.5	3.43%	0.99	2.50%	0.99
4	3.18%	0.99	2.79%	0.99
2.75	2.57%	0.99	2.25%	0.99

origin is placed at the center of the nozzle exit. The Z-axis coincides with the centerline. The X- axis and Y-axis are parallel to the short and long dimensions of the elliptical spray pattern, respectively.

Kwok(34) defined a flow angle as the angle formed between the air streamline and the Z-axis. When Kwok plotted the flow angles against the X- and Y-axes at three distinct Z distances, each flow angle curve looked like a parabola with the starting point at the origin. This means that the flow angles increase as the aerosols expand in the radial directions, X- and Y-axes, and decline rapidly after reaching the peak values. The transfer efficiency model assumes all streamlines are parallel to the centerline and thus does not include this flow angle effect. Large particles, that the model predicts have enough inertia to impact on the surface, might be lost because in reality more larger particles are concentrated at the edges and impact at an angle other than 90 degrees, as the model assumes. Therefore, the model overestimates transfer efficiency at short gun-to-surface distances.

Observations from Kwok's study(34) provide a possible explanation for the improved model prediction as gun-to-surface distance increases over six inches. The peaks of the parabolic curves of the flow angle with respect to X- and Y-axes drop and the bases of the curve enlarge as the Z distance increases. This reflects air entrainment into the jet flow, and flow velocities in both X- and Y-axes become negative, that is, toward the Z-axis. As a result, the magnitude and the influence of the flow angle are reduced. As shown in Figure 3, larger errors in model prediction are evident at higher nozzle pressures. This might be caused by the tendency for bigger droplets to concentrate more in the outer region of the spray with increased nozzle pressure.(36)

The model underestimation at gun-to-surface distances greater than 12 inches may be caused by particle coagulation. Coagulation is a time-dependent process whereby aerosol droplets collide with one another and adhere, and the size distribution increases with time. This inter-particle phenomenon is evident as gun-to-surface distances increase from 10 inches to 14 inches.(34) Actual particle size distributions might be larger than estimated by Eq. (6), thus resulting in model underestimation at large gun-to-surface distances. Yet, the errors are less significant at lower nozzle pressures than at higher ones. Secondary atomization, also found at large gun-to-surface distances,(34) is more likely at lower nozzle pressures. Secondary atomization means large

TABLE IIIb
Effect of nozzle pressure upon the decreasing rate in transfer efficiency varied by gun-to-surface distance

	Predicted transfer efficiency		Measured transfer efficiency	
Gun-to-surface distance (in)	Decreasing rate per unit cap pressure increment	R^2	Decreasing rate per unit cap pressure increment	R^2
6	1.22%	0.93	2.20%	0.98
7	1.59%	0.92	1.76%	0.88
8	1.88%	0.94	1.88%	0.97
9	2.29%	0.97	2.52%	0.91
10	2.93%	0.99	2.57%	0.96
11	3.51%	0.98	3.42%	0.93
12	3.87%	0.96	3.55%	0.97
13	4.39%	0.96	3.45%	0.93
14	3.89%	0.92	3.08%	0.84

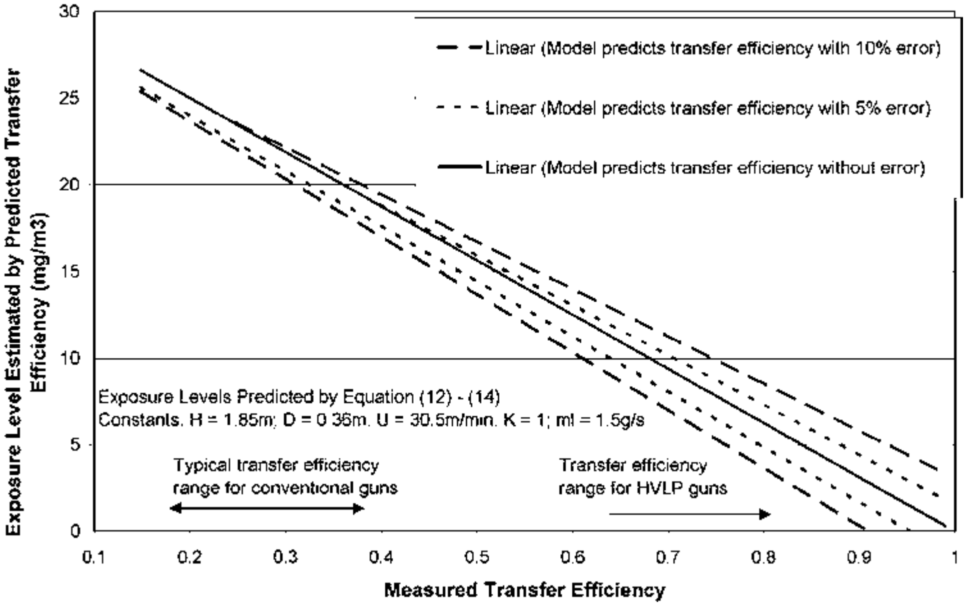

FIGURE 4

Effects of transfer efficiency prediction upon exposure estimation.

droplets are further atomized into smaller ones. It usually occurs with particles big enough to be broken down easily, as is the case at lower nozzle pressures. Therefore, the net result of secondary atomization and coagulation may be to produce better agreement between model and measurement at lower nozzle pressures.

Transfer efficiency is a function of gun-to-surface distance and nozzle pressure. The high decreasing rate in gun-to-surface distance suggests considerable variation in transfer efficiency under unsteady spraying operations. Cautious determination of transfer efficiency as a function of time is required when applying the model to a worker who is not capable of controlling the spray gun at a constant distance from the workpiece. Nozzle pressure can be precisely controlled in actual spray painting operations, and should not present a problem for applying the model to the real world.

The primary application of the transfer efficiency model is to estimate the overspray generation rate described by Eq. (12) and to determine the airborne contaminant concentration levels. To evaluate the effects of uncertainty in the transfer efficiency model on exposure estimation, a simple example is presented.

Let the following parameters be constants in Eqs. (12) to (14): the worker's dimensions are 1.85 m in height and 0.36 m in breadth; air velocity in the spray booth is 30.5 m/min; liquid flow rate is 1.5 g/s; and, K value is 1.0. Figure 4 shows the effect of transfer efficiency prediction upon the estimated exposure levels.

The important conclusions are:

a. Underestimation in transfer efficiency results in overestimation in exposure levels, and vice versa.
b. Overestimation in transfer efficiency causes a more significant error in exposure estimation than underestimation does. For example, if the actual transfer efficiency is 0.70, a 5 percent overestimation will result in underestimating exposure by 14.1 percent, but underestimating transfer efficiency by 5 percent results in overestimating exposure by 8.63 percent.
c. A small error in predicted transfer efficiency can result in a large uncertainty in estimating exposure, especially at high transfer efficiencies. For example, if the actual transfer efficiency is 0.80, with an error range of ±10 percent, the uncertainty in overspray generation rate, or exposure level will be a factor of 4, ±40 percent.

Despite the significant effects of the uncertainty in transfer efficiency on exposure estimation, the uncertainty in exposure measurements and other parameters in the exposure model might exceed the problem presented here. Further research in the field is required to evaluate the applicability of the transfer efficiency model for estimating the overspray generation rate.

CONCLUSIONS

Laboratory studies conducted here present an experimental evaluation of a mathematical model for predicting the transfer efficiency of an HVLP spray gun. Two operational parameters, gun-to-surface distance and nozzle pressure, were evaluated to examine their effects on transfer efficiency measurement and prediction. This study also evaluates the effects of uncertainty in the transfer efficiency model on estimating breathing-zone contaminants.

Experimental results suggest that the mathematical model successfully predicts the transfer efficiency of an HVLP gun within known uncertainties. Two correction factors were determined to improve the model; the results show excellent agreement between the modified model and experimental data. Gun-to-surface distance and nozzle pressure are two important factors in determining transfer efficiency. The decreasing rates in transfer efficiency with increasing gun-to surface distance range from

2 percent to 4 percent, depending on the nozzle pressure. This suggests that unsteady spraying, that is, non-uniform gun-to-surface distance, could result in considerable variation in transfer efficiency. Transfer efficiency was also found to decrease as the nozzle pressure increases. Because the nozzle pressure can be easily controlled in the real world, it should have little critical effect on model application in the field.

This study presents fundamental knowledge of the transfer processes of spray painting operations. Major limitations of the current model are the incapability to describe effects caused by solvent volatilization, worker's hand motion, and various size/shape/structure of the workpiece being coated. Further research is planned to extend the predictive power of the current transfer efficiency model to account for a more realistic situation. Field studies will be conducted in the near future to determine how transfer efficiency of a spray gun affects worker's exposure to airborne contaminants during spraying operations.

ACKNOWLEDGMENTS

This work was supported by grant number R01/OH02858 from the U.S. National Institute for Occupational Safety and Health (NIOSH). Its contents are solely the responsibility of the authors and do not necessarily represent the official views of NIOSH.

REFERENCES

1. Roobol, N.R.: Industrial Painting: Principles and Practices. Hanser-Gardner Publishers, Cincinnati, Ohio (1997).
2. Marg, K.: HVLP Spray Puts You into Compliance. Metal Finish 87(3):21–23 (1989).
3. Anon.: Gain More with Less. Finishing 14(1):28–29 (1990).
4. Anon.: Sonic Boom Bang. Finishing 14(2):30–32 (1990).
5. Anon.: DeVilbiss Reaches 1000. Finishing 14(9):40–42 (1990).
6. Triplett, T.: The HVLP Way to Spray. Ind Paint Powder 72(2):40–41 (1989).
7. DeVilbiss Industrial Coating Equipment: HVLP–All You Want to Know About High Volume Low Pressure Finishing. DeVilbiss Industrial Coating Equipment, Jackson, TN (1994). (pamphlet)
8. Husman, K.; Karli, P.: Symptoms of Car Painters with Long-Term Exposure to a Mixture of Organic Solvents. Scandi J Work Environ Health 6:19–32 (1980).
9. Cherry, N.; Hutchins, H.; Pace, P.; et al.: Neurobehavioral Effects of Repeated Occupational Exposure to Toluene and Paint Solvents. Br J Ind Med 42:291–300 (1985).
10. Valciukas, J.A.; Lilia, R.; Singer, R.M.; et al.: Neurobehavioral Changes Among Shipyard Painters Exposed to Solvents. Arch Environ Health 40:47–52 (1985).
11. Linz, D.H.; de Garmo, P.L.; Morton, W.E.; et al.: Organic Solvent-Induced Encephalopathy in Industrial Painters. J Occup Med 28:119–125 (1986).
12. Baker, E.L.; Letz, R.E.; Eisen, E.A.; et al.: Neurobehavioral Effects of Solvents in Construction Painters. J Occup Med 30:116–123 (1988).
13. Triebig, G.; Schaller, K.H.; Weltle, D.: Neurotoxicity of Solvent Mixtures in Spray Painters (I) Study Design, Workplace Exposure, and Questionnaire. Inter Arch Occup Environ Health 64:353–359 (1992).
14. Triebig, G.; Barocka, A.; Erbguth, E.; et al.: Neurotoxicity of Solvent Mixtures in Spray Painters (II) Neurologic, Psychiatric, Psychological, and Neuroradiologic Findings. Inter Arch Occup Environ Health 64:361–372 (1992).
15. Rosenberg, C.; Tuomi, T.: Airborne Isocyanates in Polyurethane Spray Painting: Determination and Respirator Efficiency. Am Ind Hyg Assoc J 45(2):117–121 (1984).
16. Regulation XI Source Specific Standards, Rule 1107, Coatings of Metal Parts and Products. South Coast Air Quality Management District, California (1991).
17. Regulation XI Source Specific Standards, Rule 1162, Polyester Resin Operations. South Coast Air Quality Management District, California (1994).
18. Regulation XI Source Specific Standards, Rule 1151, Motor Vehicle and Mobile Equipment Non-Assembly Line Coating Operations. South Coast Air Quality Management District, California (1996).
19. U.S. Environmental Protection Agency (EPA): Final Standards for Hazardous Air Pollutant Emissions from Wood Furniture Manufacturing Operations; Final Rule. Code of Federal Regulations Parts 9 and 63. EPA, Washington D.C. (1995).
20. National Institute for Occupational Safety and Health: Control of Paint Overspray in Autobody Repair Shops. DHHS (NIOSH) Publication No. 96-106. NIOSH, Cincinnati, Ohio (1996).
21. Heitbrink, W.A.; Verb, R.H.; Fischbach, T.J.; et al.: A Comparison of Conventional and High Volume–Low Pressure Spray-Painting Guns. Am Ind Hyg Assoc J 57:304–310 (1996).
22. Flynn, M.R.; Gatano, B.L.; McKernan, J.L.; et al.: Modeling Breathing-Zone Concentrations of Airborne Contaminants Generated During Compressed Air Spray Painting. Ann Occup Hyg 43(1):67–76 (1999).
23. Kim, T.; Flynn M.R.: Modeling a Worker's Exposure from a Hand-Held Source in a Uniform Freestream. Am Ind Hyg Assoc J 52(11):458–463 (1991).
24. Kim, T.; Flynn, M.R.: The Effect of Contaminant Source Momentum on a Worker's Breathing Zone Concentration in a Uniform Freestream. Amer Ind Hyg Assoc J 53(12):757–766 (1992).
25. Flynn, M.R.; Lackey, B.D.; Muthedath, P.: Experimental and Numerical Studies on the Impact of Work Practices Used to Control Exposures Occurring in Booth-Type Hoods. Amer Ind Hyg Assoc J 57:469–475 (1996).
26. Flynn, M.R.; George, D.K.: A Field Evaluation of a Mathematical Model to Predict Worker Exposure to Solvent Vapors. Appl Occup Environ Hyg 11(10):1212–1216 (1996).
27. Carlton, G.N.; Flynn, M.R.: A Model to Estimate Worker Exposure to Spray Paint Mists. Appl Occup Environ Hyg 12(5):375–382 (1997).
28. Carlton, G.N.; Flynn, M.R.: Field Evaluation of an Empirical-Conceptual Exposure Model. Appl Occup Environ Hyg 12(8):555–561 (1997).
29. Carlton, G.N.; Flynn, M.R.: Influence of Spray Painting Parameters on Breathing Zone Particle Size Distributions. Appl Occup Environ Hyg 12(11):744–750 (1997).
30. Kim, K.Y.; Marshall, W.R.: Drop-Size Distributions from Pneumatic Atomizers. AIChE J 17(3):575–584 (1971).
31. Schlichting, H.: Boundary Layer Theory. McGraw-Hill, Inc., New York (1979).

32. Baturin, V.V.: Fundamentals of Industrial Ventilation. Pergamon Press, Oxford, U.K. (1972).
33. White, F.W.: Fluid Mechanics. McGraw-Hill, Inc., New York (1986).
34. Kwok, K.: A Fundamental Study of Air Spray Painting. Ph.D. dissertation. University of Minnesota (1991).
35. Chin, J.S.; Nickolaus, D.; Lefebvre, A.H.: Influence of Downstream Distance on the Spray Characteristics of Pressure-Swirl Atomizers. J Eng Gas Turb Power 108:219–224 (1986).
36. Dominck, J.; Lindenthal, A.; Tropea, C.; et al.: Application of Phase Doppler Anemometry in Paint Sprays. Atomization and Sprays 4:437–450 (1994).