Simplified Procedure for Calculating Exhaust/Intake Separation Distances

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ABSTRACT

The purpose of this research project is to provide a simple yet accurate procedure for calculating the minimum distance required between the outlet of an exhaust system and the outdoor air intake to a ventilation system to avoid reentrainment of exhaust gases. The new procedure addresses the technical deficiencies in the simplified equations and tables that are currently in ANSI/ASHRAE Standard 62.1-2016, Ventilation for Acceptable Indoor Air Quality *(ASHRAE 2016a), and model building codes. This new procedure makes use of the knowledge provided in Chapter 45 of the 2015* ASHRAE Handbook—HVAC Applications *(ASHRAE 2015), and was tested against various physical modeling and full-scale studies.*

The study demonstrated that the new method is more accurate than the existing Standard 62.1 equation, which underpredicts and overpredicts observed dilution more frequently than the new method. In addition, the new method accounts for the following additional important variables: stack height, wind speed, and "hidden" intake. The new method also has theoretically justified procedures for addressing heated exhaust, louvered exhaust, capped heated exhaust, and horizontal exhaust that is pointed away from the intake.

INTRODUCTION

ANSI/ASHRAE Standard 62.1-2016 (ASHRAE 2016a) has air intake minimum separation distances specified for various types of exhaust sources in Table 5.5-1 of the standard. Other codes and standards (e.g., *Uniform Mechanical Code* [IAPMO 2015a], *International Mechanical Code* [ICC 2012], *Uniform Plumbing Code* [IAPMO 2015b], and ANSI/ASHRAE Standard 62.2 [ASHRAE 2016b]) also specify minimum separation distances, all of which appear to be rule-of-thumb based with 1 to 3 m (3 to 10 ft) being the magic numbers for most exhaust types. The separation distances can be both far too lenient and far too restrictive depending on the type of exhaust and exhaust and intake configurations.

Both code and Standard 62.1 requirements are overly simplistic and fail to account for significant variables such as the exhaust airflow rate, the enhanced mixing caused by high exhaust discharge velocity, the orientation of the discharge, or the height of the exhaust relative to intake. Standard 62.1 includes an Informative Appendix F that outlines a procedure to account for exhaust airflow rate, velocity, and exhaust orientation to achieve target dilution levels. The appendix is not mandatory but is given as an example of how to use analytical techniques to show that separation distances other than those in Table 5.5-1 are acceptable.

The purpose of this research project is to provide a simple yet accurate procedure for calculating the minimum distance required between the outlet of an exhaust system and the outdoor air intake to a ventilation system to avoid reentrainment of exhaust gases. The procedure addresses the technical deficiencies in the simplified equations and tables currently in Standard 62.1. This new procedure makes use of the knowledge provided in Chapter 45 of the 2015 *ASHRAE Handbook—HVAC Applications* (ASHRAE 2015) and various wind tunnel and full-scale studies discussed herein.

The new methodology is suitable for standard HVAC engineering practice and has exhaust outlet velocity, exhaust air volumetric flow rate, exhaust outlet configuration (capped/

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uncapped and position/orientation relative to intake), desired dilution ratio, and ambient wind speed as independent variables. The current Standard 62.1 Informative Appendix F method includes some of these factors but does not include variable wind speed, stack height, plume rise effect caused by exhaust velocity, or hidden intake reduction factors. The new method discussed herein takes into account all of these variables. The new method also has theoretically justified procedures for addressing heated exhaust, louvered exhaust, capped heated exhaust, and horizontal exhaust that is pointed away from the intake.

The research started out with an objective to develop two new procedures from existing and new research with the following characteristics:

- **Procedure 1.** A general procedure suitable for standard HVAC engineering practice that has exhaust outlet velocity, exhaust air volumetric flow rate, exhaust outlet configuration (capped/uncapped/horizontal/louvered) and position (vertical separation distance), exhaust direction, desired dilution ratio, hidden intakes (building sidewall), and ambient wind speed as independent variables. Other factors, such as location relative to walls and edge of building, geometry of the exhaust discharge and inlets, etc., are reduced to fixed assumptions that are reasonable yet somewhat conservative.
- **Procedure 2.** A regulatory procedure suitable for Standard 62.1, Standard 62.2, and model building codes that has only exhaust outlet velocity, exhaust air volumetric flow rate, desired dilution ratio, and a simple way to account for orientation relative to the inlet as independent variables. All other variables are reduced to fixed assumptions that are reasonable yet conservative.

In the end, one simple procedure was developed that met the overall objectives of the study and is appropriate for the following exhaust types:

- Toilet exhaust from rain-capped vents or dome exhaust fans
- Grease and other kitchen fan exhausts
- Combustion flues and vents with either forced or natural draft discharge in horizontal or vertical direction, with and without flue caps (this includes diesel generators)
- Diesel vehicle emissions
- Building exhaust at indoor air temperature through louvered or hooded vents
- Plumbing vents
- Cooling towers

The method does not address laboratory and industrial ventilation process exhausts; large, industrial-sized combustion flues and stacks; or packaged units that have integral exhaust and intake locations.

A secondary objective of this project is to address dilution targets, a necessary parameter for calculating the separation distance calculation. Accordingly, minimum dilution factors were reviewed and updated for various types of exhausts as appropriate, especially those with known emissions and health impacts such as combustion exhaust. The results of that research are not discussed herein but can be found in the research by Petersen et al. (2015). Table 1 provides a summary of the minimum recommended dilution factors from that research.

The following sections provide a review of the Standard 62.1 equation, discussion of databases that were used to test and compare the Standard 62.1 equation and the new equation, development of the new equation, an evaluation of the new and Standard 62.1 equations against observations, and a discussion of the new methodology.

EVALUATION OF EXISTING STANDARD 62.1 EQUATION

The development of the Standard 62.1 equation can be found in Appendix N of the August 1996 Public Review Draft of ASHRAE Standard 62, which will be referred to as *62-1989R* (ASHRAE 1996). The equation development begins with the minimum dilution equation D_{min} found in the 1993 *ASHRAE Handbook—Fundamentals*, Chapter 14 (ASHRAE 1993) and in the research by Wilson and Lamb (1994):

Table 1. Summary of Recommended Minimum Dilution Factors

Exhaust Type	Minimum Dilution Factor (DF)
Class 1 air exhaust/relief outlet	5
Class 2 air exhaust/relief outlet	10
Class 3 air exhaust/relief outlet	50
Class 4 air exhaust/relief outlet	300
Wood-burning kitchen exhaust	700
General boilers, natural gas and fuel oil, based on NO_x* ppm factor, *p* in percent†	2.8 × *p*
Garage entry, automobile loading area, or drive-in queue (light-duty gasoline vehicles)	50
Diesel generators, diesel truck loading area or dock, diesel bus parking/idling area‡	2000 × *e*
Cooling tower exhaust (based on chemicals used for treatment)	10

* NO_x = nitrous oxides (NO and NO_2)
† If the NO_x ppm is 10, *p* = 10 and DF = 28.
‡ *e* = 1 – efficiency of the odor filter. For example, if the filter is 80% efficient, e = 0.2 and DF = 400.

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$$D_{min} = [D_o^{0.5} + D_s^{0.5}]^2 \quad (1)$$

$$D_o = 1 + C_1\beta\left(\frac{V_e}{U_H}\right)^2 \quad (2)$$

$$D_s = \beta_1\left(\frac{s^2 U_H}{Q_e}\right) \quad (3)$$

where

D_o = initial jet dilution

D_s = dilution that occurs versus separation distance

s = "stretched string" distance measured along a trajectory

U_H = wind speed at the roof level

V_e = discharge velocity

Q_e = volume flow rate

β = factor that relates the nature of discharge outlet; β equals 1 for the vertical discharge and 0 for a capped (or downward) discharge

62-1989R states that C_1 ranges from 1.6 to 7 and β_1 ranges from 0.0625 to 0.25 (C_2 in 62-1989R).

The minimum separation distance is defined as the shortest "stretched string" distance from the closest point of the outlet opening to the closest point of the outdoor air intake opening or operable window, skylight, or door opening along a trajectory as if a string were stretched between them.

To develop the Standard 62.1 equation, Equations 1, 2, and 3 were first rearranged to solve for s (L in the Standard 62.1 equation), which results in

$$s = \left[\frac{Q_e}{\beta_1 U_H}\right]^{0.5}\left[D^{0.5} - \left(1 + C_1\beta\left(\frac{V_e}{U_H}\right)^2\right)^{0.5}\right] \quad (4)$$

The equation is then simplified by assuming (ASHRAE 1996) the following:

- The 1 term is insignificant
- $V_e = 0$ for capped or non-vertical stacks
- $U_H = 2.5$ m/s (500 fpm) average wind speed
- $C_1 = 1.7$ (on the low end of the range, giving less credit for dilution due to the discharge velocity, which tends to increase the separation distance)
- $\beta_1 = 0.25$ (on the high end of the range, giving maximum credit for dilution due to separation, and tends to reduce separation distance, and is non-conservative)

Using the above assumptions, the Standard 62.1 equation then results, or

$$s = 0.04Q_e^{0.5}\left[D^{0.5} - \frac{V_e}{2}\right] \text{ (in metres)} \quad (5)$$

$$s = 0.09Q_e^{0.5}\left[D^{0.5} - \frac{V_e}{400}\right] \text{ (in feet)} \quad (6)$$

where

Q_e = exhaust air volume, L/s (cfm)

D = dilution factor for the exhaust type of concern

V_e = exhaust air discharge velocity, m/s (fpm)

V_e is positive when the exhaust is directed away from the outdoor air intake at a direction that is greater than 45° from the direction of a line drawn from the closest exhaust point to the edge of the intake.

V_e has a negative value when the exhaust is directed toward the intake bounded by lines drawn from the closest exhaust point the edge of the intake.

V_e is set to 0 for other exhaust air directions regardless of actual velocity. V_e is also set to 0 for vents from gravity (atmospheric) fuel-fired appliances, plumbing vents, and other nonpowered exhausts, or if the exhaust discharge is covered by a cap or other device that dissipates the exhaust airstream.

For hot gas exhausts such as combustion products, an effective additional 2.5 m/s (500 fpm) upward velocity is added to the actual discharge velocity if the exhaust stream is aimed directly upward and unimpeded by devices such as flue caps or louvers.

Equation 4, from which Equations 5 and 6 were developed, has the following problems:

- The equation is only valid for flush vents and does not account for stack height or height difference between the stack and the air intake.
- Even though an exit velocity term is included, it does not adequately account for high-velocity exhaust systems. The velocity term accounts for the added dilution due to a higher exit velocity but does not account for the additional plume rise.
- The assumed value for the constant C_1 (1.7), while conservative, is not supported by the research. According to Wilson and Chui (1994) and ASHRAE (1993, 1997), values of 7 and 13 are more appropriate.
- The assumed value for the constant β_1 (0.25) is non-conservative and is not supported by the research. According to Wilson and Chui (1994) and ASHRAE (1993, 1997), values ranging from 0.04 to 0.08 are more appropriate.
- For vertical stacks, a wind speed higher than 2.5 m/s (500 fpm) may be critical because plume rise will decrease as wind speed increases, while at low wind speed the plume rise will be very large. For flush vents and capped stacks, a wind speed lower than 2.5 m/s (500 fpm) will most likely be the critical case. Speeds as low as 1 m/s (200 fpm) can occur a significant fraction of the time (Perkins 1974).
- Setting V_e equal to a negative number when the exhaust is directed away from the intake, while intuitively correct, cannot be derived from the original equation used to develop the Standard 62.1 approach.

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To evaluate the Standard 62.1 equation, it needs to be rearranged so dilution can be predicted for comparison with the dilution values recorded in the databases discussed the "Dilution Databases" section. The rearranged equation is provided as follows:

$$D(s) = \left(\frac{11.1s}{Q_e^{0.5}} + \frac{V_e}{400}\right)^2 \quad \text{(I-P)} \quad (7)$$

$$D(s) = \left(\frac{25s}{Q_e^{0.5}} + \frac{V_e}{2}\right)^2 \quad \text{(SI)} \quad (8)$$

Overall, this section shows some of the problems with the current 62.1 equation and confirms the need for an improved equation.

DILUTION DATABASES

In order to evaluate the existing Standard 62.1 equation and New4, existing wind tunnel and full-scale data were assembled and reviewed. Only those wind tunnel databases that meet the criteria outlined in the Environmental Protection Agency's (EPA) *Guideline for Fluid Modeling of Atmospheric Diffusion* (Snyder 1981) were used in this study. Some of the important criteria considered are as follows: a boundary-layer wind profile representative of the atmosphere was established, the approach turbulence profile was representative of the atmosphere, and Reynolds number independent flow was established.

For the relevant databases, data were entered into a Microsoft® Excel spreadsheet in a form that would expedite comparisons with Standard 62.1 Informative Appendix F equations and the new method. The following subsections discuss each database.

Database 1—Wilson and Chui (1994)

The following summarizes the important aspects of this database:

- 1:500 and 1:2000 scale model tests were conducted
- Building Reynolds numbers exceeded 104 to meet the Reynolds number independence criterion by Snyder (1981)
- A wind power law exponent of 0.25 was established and wind speeds at building heights of 5.9 to 12.1 m/s (1200 to 2400 fpm) were set

Eleven model building configurations were tested at six different exhaust velocity ratios ($M = V_e/U_H$). Exhaust parameters were a flush circular vent with exhaust density ratio varying from 0.14 to 0.38. Velocity ratios varied from 0.8 to 1.5. Building height to width ratios varied from 1 to 12. Wilson and Chui (1994) showed that Equations 1, 2, and 3 with $\beta_1 = 0.625$ and $C_1 = 7$ provided a lower bound to the observed dilution values for several building configurations. This database is not used directly to evaluate the performance of the new equation; rather, the predicted lower bound using Equations 1, 2, and 3 with recommended constants are used as a lower bound prediction for comparison purposes.

Wilson and Chui (1994) show comparisons of predicted (Equations 1, 2, and 3) and observed dilution versus normalized distance.

Database 2—Wilson and Lamb (1994)

This is a very unique database in that it is based on a full-scale study that was conducted using tracer gas released from stacks and exhaust vents on Washington State University chemistry laboratory buildings "Fulmer Building" and "Annex Building."

The following summarizes the important aspects of this database:

- Each test took place on a different day between January 14 and March 11, 1994.
- Hourly meteorological data (wind speed, wind direction, temperature, and the standard deviation of wind direction flucturations σ_θ) were collected from an 8 m (26.25 ft) mast erected on the penthouse roof on the Annex Building. This represents the tallest point of the test buildings, which minimizes building wake effects. Wind speeds during the testing period varied from 2.2 to 8.1 m/s (440 to 1600 fpm). Crosswind turbulence indicated by σ_θ ranged from 6.5° to 24.8°.
- Tracer gas dilution measurements were carried out by releasing sulfur hexafluoride (SF_6) from the uncapped fume hood exhaust vents and collecting four sequential hourly average air samples from 44 locations. The distances ranged from s = 5 m (16.4 ft) to s = 270 m (886 ft). Sufficient data were collected to ensure that the minimum dilution could be documented.
- Stack heights ranged from 0 to 3.66 m (0 to 12 ft) and average velocity ratios M ranged from 0.83 to 8.3.

Wilson and Lamb (1994) provide figures showing that Equations 1, 2, and 3 with $\beta_1 = 0.04$ and $C_1 = 13$ provide a lower bound estimate of dilution when compared to observations. This confirms the validity of these equations for flush vents with low plume rise. As with the research by Wilson and Chui (1994), this database is not used directly to evaluate the performance of the new equation; rather the predicted lower bound using Equations 1, 2, and 3 with the recommended constants from this study are used as a second lower bound prediction for comparison purposes.

Database 3—ASHRAE Research Project 805 (Petersen et al. 1997)

This study was initially commissioned in 1997 as an ASHRAE research project to determine the influence of architectural screens on exhaust dilution. Wind tunnel experiments were performed with generic building geometry to generate a database of concentrations to document the effects of several screen wall configurations. Baseline exhaust concentrations obtained without the presence of a screen wall were also included in the wind tunnel assessment.

The following summarizes the important aspects of this database:

- 1:50 scale model tests were conducted in a boundary layer wind tunnel with velocity profile power law exponent of 0.28
- Building Reynolds number >11,000 to meet Reynolds number independence criterion by Snyder (1981)
- Concentration data for various different exhaust configurations:
  - Building measurements of 15.2 × 30.48 × 15.2 m (50 × 100 × 50 ft) ($H_b \times W \times L$)
  - Stack heights (h_s) of 0, 0.3, 0.9, 1.5, 2.1, and 3.7 m (0, 1, 3, 5, 7, and 12 ft)
  - Volumetric flow rates of 0.25, 2.4, and 9.4 m^3/s (500, 5000, and 20,000 cfm)
  - Exhaust velocity ratios ($M = V_e/U_H$) ranging from ~1 to 4
- Receptors were placed on rooftop and leeward walls
- Wind azimuths of 0°, 45°, and 90°
- Reference wind speeds of U_{ref} = 3.7 and 11.1 m/s (728 and 2185 fpm) in the wind tunnel

For this study, data were used only for results obtained in the wind tunnel for cases with no screen wall on the test building. Only data collected at receptor locations on the test building were used, and no downwind or off-building exhaust concentrations were considered. Data for multiple stack heights, multiple velocity ratios, and wind azimuths of 0° and 45° were considered in this evaluation.

Concentration measurement data from the original wind tunnel study were entered in tablature format into a spreadsheet. Plots of the measured dilution values versus string distance are provided in Figures 1 and 2 for selected data. The figures show a solid line as a baseline case, with each shade representing a fixed volume flow rate and velocity ratio *M*. The figures show that the observed dilution increases as stack height is increased for a fixed volume flow rate and velocity ratio. The figures also both show the expected trend that as volume flow rate increases, the dilution decreases for a fixed stack height.

For the 0° orientation, the furthest rooftop receptor location was located approximately 15 m (49 ft) from the stack. Data taken at distances greater than 15 m (49 ft) indicate concentrations obtained at a receptor in a “sidewall” location. As expected, a noticeable increase in dilution is observed at sidewall receptor locations.

For the 45° data set, the furthest rooftop receptor location is located approximately 13 m (42.7 ft) from the stack. Receptors at a distance greater than 13 m (42.7 ft) were located on the leeward wall of the building (sidewall receptors). As expected, dilution values were observed to increase at the sidewall intake locations.

Database 4—Hajra and Stathopoulos (2012)

This study was performed to determine the impact of pollutant reentrainment affecting downstream buildings of different geometries. However, a baseline configuration without downstream buildings was also evaluated. Receptors were placed on rooftop, windward, and leeward walls.

The following summarizes the important aspects of this database:

- 1:200 scale model tests were conducted in a boundary layer wind tunnel 12.2 m (40 ft) long with a 3.2 m^2 (34.4 ft^2) cross section
- Power law exponent of 0.31 with wind speed at building height U_H of 6.2 m/s (1220 fpm) in the wind tunnel
- Building Reynolds number >11,000 to meet Reynolds number independence criterion by Snyder (1981)
- Concentration (dilution) data were obtained for the following different exhaust configurations:
  - Stack heights h_s of 1, 3, and 5 m (3.28, 9.84, and 16.4 ft)
  - Exhaust velocity ratios ($M = V_e/U_H$) of 1, 2, and 3
  - Wind azimuths of 0° and 45°

For this evaluation, concentration data for the low-rise building model configuration were used. Data from the configurations with multiple buildings were not used, which included several downwind buildings of various sizes and distances from the test building. Configuration 1 was considered for this database, and has $H_b \times W \times L$ characteristics of 15 × 50 × 50 m (49.2 × 164 × 164 ft).

For the purposes of this evaluation, data were used for the lowest stack heights (i.e., h_s = 1 and 3 m (3.28 and 9.84 ft). Only exhaust velocity ratios of M = 1 were considered. These are the cases of most interest because they apply directly to the Standard 62.1 equation.

Concentration measurement data were extracted from the database plots using a plot digitizer and entered in tablature format into a spreadsheet. Plots of the measured dilution values versus string distance for each configuration considered for this study are provided in Figure 3.

Figure 3 shows that the observed dilution versus distance was about the same for the cases with low velocity ratio (M = 1), regardless of stack height. In cases with similar plume rise (i.e., equal stack height and *M*), the dilution values should be similar. As expected, the taller stack height provides slightly higher dilution at distances greater than 20 m (66 ft) from the stack.

Database 5—Schulman and Scire (1991)

This study was performed to determine the effect of stack height, exhaust plume momentum, and wind direction on downwind exhaust concentrations from a rooftop exhaust source. The results of this database were taken from previous wind tunnel findings from the work by Hoydysh and Schulman (1987). Various stack heights and velocity ratios were

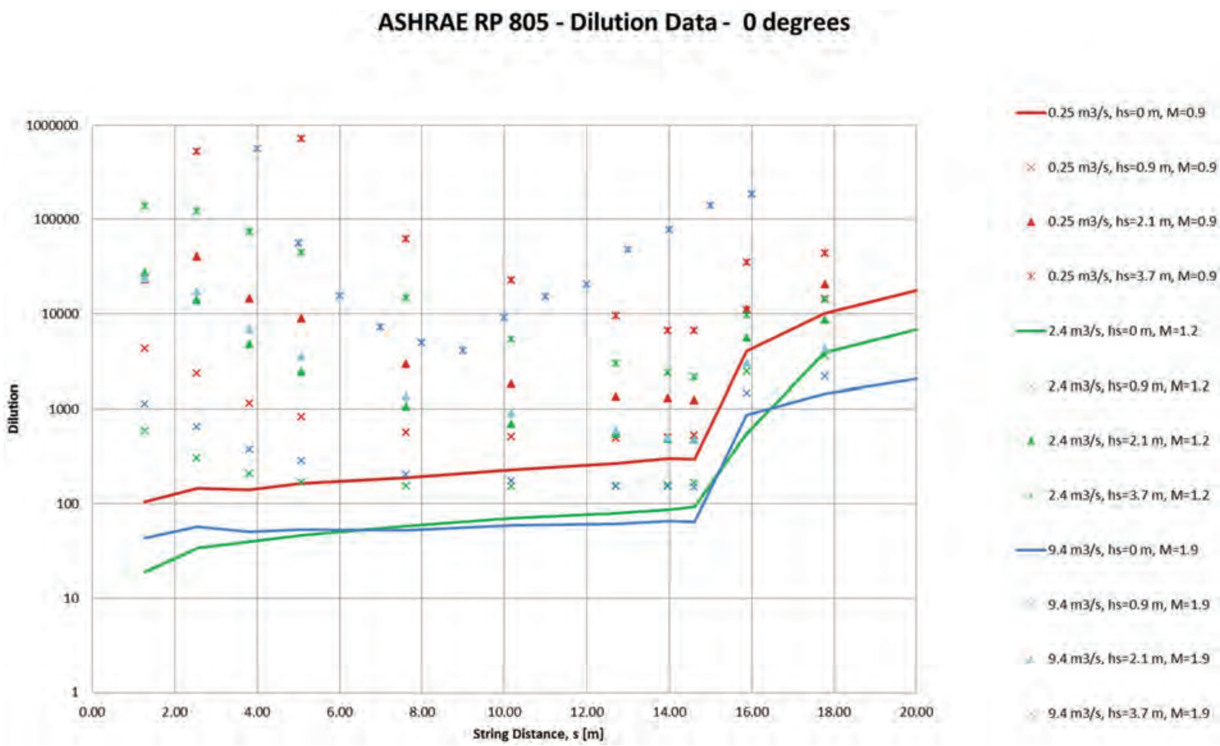


Figure 1 *Observed dilution versus string distance for the 0° wind direction (Petersen et al. 1997).*

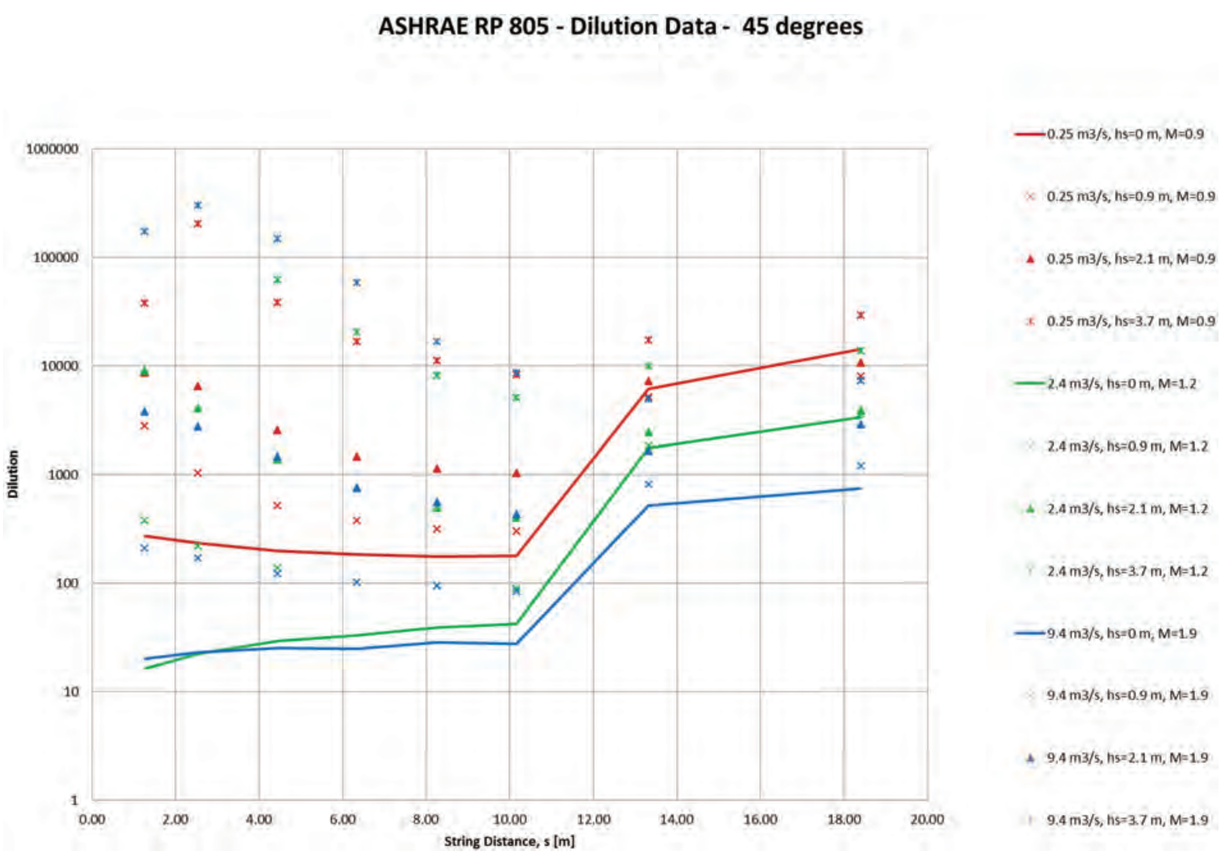


Figure 2 *Observed dilution versus string distance for the 45° wind direction (Petersen et al. 1997).*

evaluated at both 0 and 45°, with receptor locations downwind of the exhaust stack on the test building rooftop and façades.

The following summarizes the important aspects of this database:

- 1:100 scale model in wind tunnel with power law profile with exponent 0.20
- Building Reynolds number of 14,000
- Measurements obtained from flame ionization hydrocarbon analyzer, with claimed concentration repeatability of 10%
- Concentration (dilution) data for the following different exhaust configurations were obtained:
    - building measurements of 15.2 × 76 × 76 m (50 × 250 × 250 ft) ($H_b \times W \times L$)
    - stack heights h_s of h_s/H_b= 1.0, 1.1, 1.3, and 1.5
    - exhaust velocity ratios of ($M = V_e/U_H$) of 1.0, 1.1, 3.0, and 5.0
    - receptors on rooftop and leeward walls, in direct line downwind of stack
    - wind azimuths of 0° and 45°
    - reference wind speed of 1.37 m/s (270 fpm)

For this study, only stack heights of h_s/H_b = 1 and 1.1 were considered, as they are the stack heights to which Standard 62.1 is most likely to be applied. Dilution values from this database were used for azimuths of 0° and 45° at both rooftop and hidden receptors.

Concentration measurement data were extracted from the database plots using a plot digitizer and entered in tablature format into a spreadsheet. Plots of the measured dilution values versus string distance for each configuration considered for this study are provided in Figure 4.

Figure 4 shows a solid line as a baseline case, with each symbol representing a stack height and azimuth. The various symbols are increases in exhaust stack velocity ratios. As expected, increased dilution occurs with increased stack height and increased velocity ratio *M*. The abrupt increase in dilution represents a transition from a rooftop to hidden intake on a building sidewall and occurs at approximately 40 m (131 ft) for 0° azimuth and approximately 50 m (164 ft) for 45° azimuth.

NEW STANDARD 62.1 EQUATION DEVELOPMENT

New Basic Equation

A new general equation was developed by first starting with the basic Gaussian dispersion equation from Chapter 45 of the 2015 *ASHRAE Handbook—HVAC Applications* (ASHRAE 2015) as follows:

$$D(s) = \frac{4U_H\sigma_y\sigma_z}{V_e d_e^2}\exp\left(\frac{h_p^2}{2\sigma_z^2}\right) \quad (9)$$

= Nonexponential term (NET) × Exponential term (ET)

The equation was simplified using the following identities or approximations:

$$\sigma_y = \sigma_z \approx (i^2 s^2 + \sigma_o^2)^{0.5}$$

$$Q = \pi V_e\, d_e^2/4$$

i = average lateral (i_y) and vertical (i_z) turbulence intensity (assume the plume is symmetrical for simplification purposes)

σ_o^2 = 0.123 d_e^2 (ASHRAE 2015)

The nonexponential term (NET) can be written as:

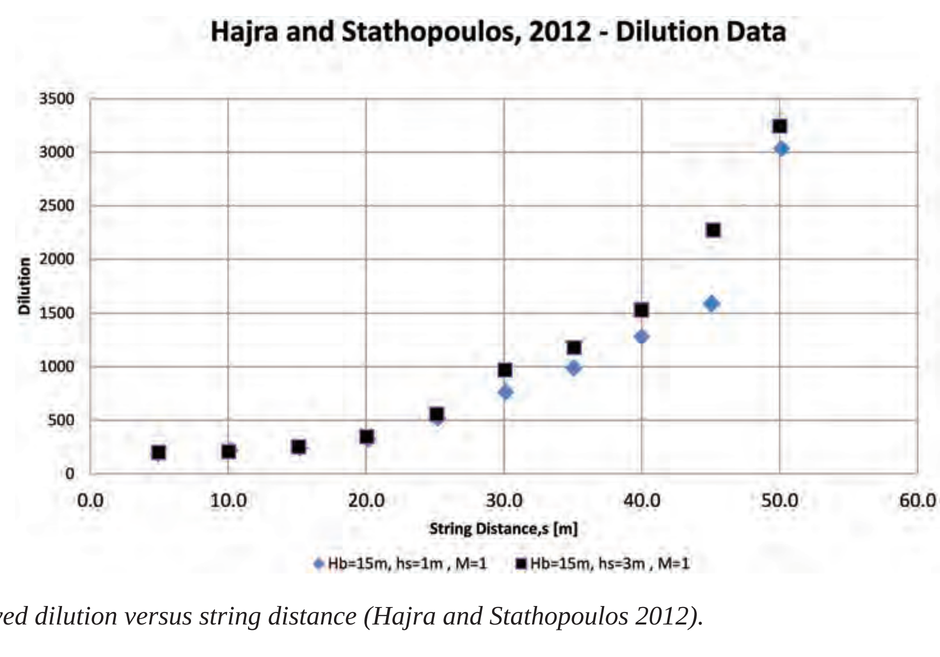


Figure 3 *Observed dilution versus string distance (Hajra and Stathopoulos 2012).*

$$\text{NET} = \frac{\pi U_{H}\sigma_y\sigma_z}{Q_e} = \frac{\pi U_H}{Q_e}[i^2 s^2 + 0.123 d_e^2] = As^2 + B \quad (10)$$

where

$$A = \frac{\pi i^2 U_H}{Q_e};\ B = \frac{0.385 d_e^2 U_H}{Q_e} \quad (11)$$

Now consider the plume rise, ET:

$$\text{ET} = \exp\left(\frac{h_p^2}{2\sigma_z^2}\right) = 1 + \left(\frac{h_p^2}{2\sigma_z^2}\right) + \frac{1}{2!}\left(\frac{h_p^2}{2\sigma_z^2}\right)^2 + \frac{1}{3!}\left(\frac{h_p^2}{2\sigma_z^2}\right)^3 \quad (12)$$

+ Higher order terms

The plume rise can then be approximated as follows:

$$h_p = (h_s + h_f \approx h_s) + \lambda d_e M \quad (13)$$

then

$$\text{ET} = \ \leq 1 + \left(\frac{\{h_s + \lambda d_e M\}^2}{2 i_z^2 s^2}\right) \quad (14)$$

which is still conservative (will underestimate dilution). An early approximation to final plume rise (ASHRAE 2007) had $\lambda = 3.0$, which is the value used in this work. The term i_z is equal to 0.5 times the longitudinal turbulence intensity, i_x, from the work by Snyder (1981). Because $i = (i_y + i_z)/2$, which, from the work by Snyder (1981) is equal to $(0.75\ i_x + 0.5\ i_x)/2$, it can be shown that $i_z = 0.8\ i$. Substituting into Equation 14 results in:

$$\text{ET} = \ \leq 1 + \left(\frac{\{h_s + 3 d_e M\}^2}{2(0.8i)^2 s^2}\right) = 1 + \left(\frac{\{h_s + 3 d_e M\}^2}{1.28 i^2 s^2}\right) \quad (15)$$

Expanding:

$$\text{ET} \leq \left(1 + \frac{1}{1.28 i^2 s^2}\{h_s^2 + 6\beta h_s d_e M + 9\beta d_e^2 M^2\}\right) = 1 + \frac{C}{s^2} \quad (16)$$

where

$$C = \frac{1}{1.28 i^2}\{h_s^2 + 6\beta h_s d_e M + 9\beta d_e^2 M^2\} \quad (17)$$

Combining the NET and ET terms results in

$$D(s) = (As^2 + B)\left(1 + \frac{C}{s^2}\right) = \left(As^2 + B + AC + \frac{BC}{s^2}\right) \quad (18)$$

This form of the equation was originally evaluated against the databases but was found to be too complex for use as a "simple" equation. With the conservative assumption that $B = 0$ (no initial dilution due to the size of the release, that is, σ_o is assumed to be small), the equation simplifies to

$$D = As^2 + AC \quad (19)$$

which is a form of the quadratic equation from which s can be solved for as follows:

$$s^2 = -C + \frac{D}{A} \quad (20)$$

Substituting and simplifying, the following "new" equation results:

$$s = [F1 - F2]^{0.5}$$

where

$$F1 = 13.6\frac{DQ_e}{U_H} \quad (21)$$

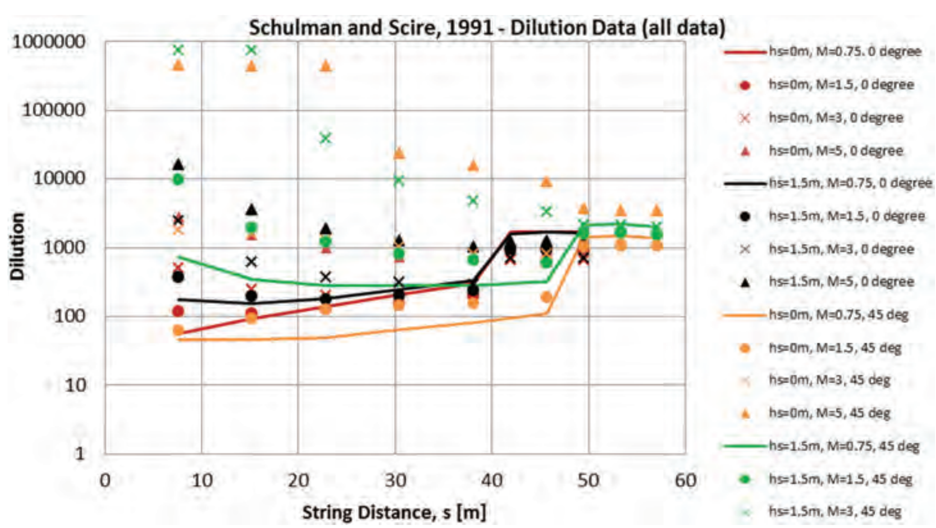


Figure 4 *Observed dilution versus string distance (Schulman and Sicre 1991).*

$$F2 = 33.37 h_s^2 + 254.9\beta \frac{h_s Q_e}{d_e U_H} + 486.9\beta \left[\frac{Q_e}{d_e U_H}\right]^2 \quad (22)$$

Then s is determined by finding the maximum difference between $F1$ and $F2$ by varying the wind speed. If the maximum difference is less than zero, the separation distance is zero. The new equation (referred as *New4* to be consistent with the work by Petersen et al. [2015]) will compute minimum separation distances that will account for all important variables (i.e., stack height, wind speed, volume flow rate, capped or noncapped, and dilution criteria). To account for special cases, the factors discussed in the following subsections are applied.

Special Cases—Horizontal Exhaust

When an exhaust is pointed away from an intake and the wind is blowing toward the intake, the exhaust travels some direction upwind and then turns around. The upwind distance traveled depends upon the ratio of exhaust velocity to wind speed (velocity ratio). An integral plume model (Petersen 1987) was used to estimate the dilution and travel distance versus velocity ratio. The plume is also diluted as it travels upwind. For small velocity ratios, the exhaust turns around quickly (within 0.5 d_e for a velocity ratio of 0.5) and for high velocity ratios, the plume travels upwind for a larger distance (6 d_e for a velocity ratio of 5). From this analysis, the following rules were developed when an exhaust is pointed away from an intake:

- "Pointed away" includes cases where the direction of the exhaust is oriented 180° away from the intake ± 45°
- Set $U_H = V_e$
- Decrease the minimum dilution factor by 1.7
- Decrease the separation distance by 1.75 d_e

Special Cases—Upblast and Downblast Exhaust

For upblast exhaust (typically used for kitchen exhaust), the effective exhaust velocity is computed using the dimension A for d_e in Figure 5 and the exhaust volume flow rate and the following equation:

$$V_e = Q_e / (\pi d_e^2 / 4) \quad (23)$$

Downblast exhaust (e.g., "mushroom" exhausters) are treated the same as a capped exhaust stack and the input exhaust diameter is A in Figure 5. If the downblast stack is heated, the heated exhaust method can be used.

Special Cases—Hidden Intakes

A hidden intake is defined as one that cannot be seen if one is standing at the exhaust location. Typically, hidden intakes are on building sidewalls or on the side of a large mechanical penthouse or unit. Chapter 45 of the 2015 *ASHRAE Handbook—HVAC Applications* (ASHRAE 2015) specifies that dilution is enhanced by at least a factor two for a hidden intake. Hence, for hidden intakes the minimum dilution factors in Table 1 are divided by 2. It should be noted that a hidden intake should meet one of the following criteria: 1) not be on the same roof as the exhaust and on a building sidewall or 2) be on the same roof as the exhaust but on the other side of a significant obstruction.

A significant obstruction is defined as one that would increase the size of the plume by at least a factor of two that would result in a dilution increase of at least a factor of two. The minimum obstruction height and width can be estimated for a flush vent with insignificant plume rise using initial plume spread estimates σ_{yo} and σ_{zo} defined as follows:

$$\sigma_{yo} = \frac{W}{4.3}; \sigma_{zo} = \frac{H}{2.15} \quad (24)$$

The dilution increase can be determined by using the following equation:

$$\text{Dilution increase factor} = \frac{(\sigma_{yo} + \sigma_y)(\sigma_{zo} + \sigma_z)}{\sigma_z \sigma_y} \quad (25)$$

where

$$\sigma_y = 0.75 i_x x; \sigma_z = 0.5 i_x x \quad (26)$$

and i_x is the longitudinal turbulence intensity and x is the distance from the stack to the windward side of the barrier. A reasonable value for i_x on a building roof is 0.35 and a reasonable maximum downwind distance, x, for a barrier wall from a stack is 10 m (33 ft). This gives values of 2.4 and 1.6 m (8 and 5 ft) for σ_y and σ_z and an estimated dilution increase of about a factor of two for a wall that is 10 m (33 ft) wide and

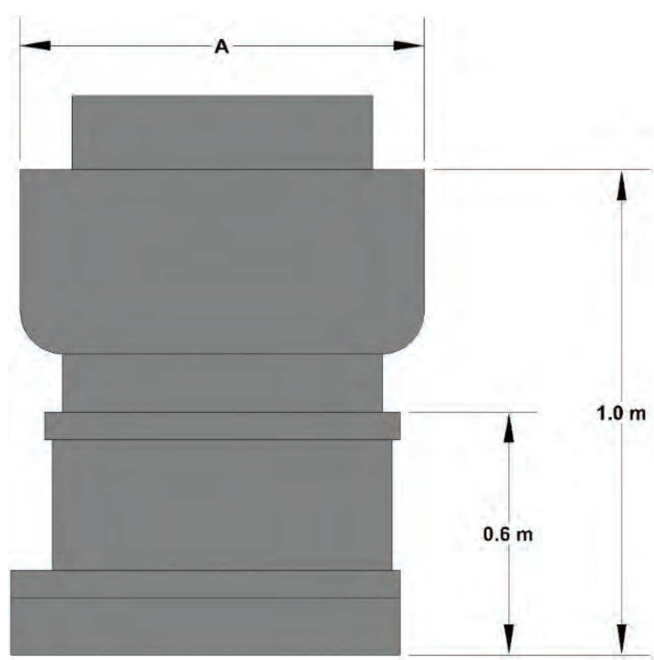


Figure 5 *Typical upblast exhaust.*

4.6 m (15 ft) high, which equates to a vertical plane square footage of 46 m^2 (500 ft^2). Therefore, a significant obstacle for a flush vent is defined as follows:

- it is located no farther than 10 m (33 ft) from the stack, and
- it has a vertical plane square footage of at least 46 m^2 (500 ft^2),
- it has a height that is greater than one σ_z, or 1.6 m (5.2 ft), which accounts most of the plume above the release point, and
- it has a width that is greater than two σ_y, or 4.8 m (16 ft), which accounts for most of the plume in the lateral direction.

Alternative larger dilution enhancement factors may be justified in some cases if additional analysis is carried out using the method outline above for barriers and as outlined by Petersen et al. (2002, 2004) for building sidewall intakes. Larger downwind distances for the barrier may also be justified using the method outlined above. For taller stacks and/or exhaust with significant plume rise, the required obstacle height can be estimated using the same method but by adding the stack height or plume rise to the σ_z value.

Special Cases—Heated Exhaust

New4 assumes plume buoyancy effects are not significant for plume rise. Therefore, some method needed to be developed to provide some plume rise enhancement for hot exhaust. To develop the method, we started with the following plume rise equation due to momentum and buoyancy (EPA 1995, 2004):

$$\Delta h = [Mo + Bo]^{1/3} = \left[\left(\frac{3T_a r^2 V_e^2 x}{T_s \beta U_H^2}\right) + \left(\frac{3g(T_s - T_a) r^2 V_e x^2}{2T_a \beta U_H^3}\right)\right]^{1/3} \quad (27)$$

where

$$Mo = \text{momentum rise} = \left(\frac{3Tr^2 V_e^2 x}{T_s \beta U_H^2}\right)^{1/3} \quad (28)$$

$$Bo = \text{buoyant rise} = \left(\frac{3(T_s - T_a) r^2 V_e x^2}{2T_a \beta U_H^3}\right)^{1/3} \quad (29)$$

Because New4 was developed assuming all plume rise is due to momentum, an equivalent momentum, *Mo, equivalent*, needs to be computed that gives the same plume rise as that caused by momentum and buoyancy effect combined, or

$$Mo, equivalent = [Mo + Bo] \quad (30)$$

Expanding and simplifying the following equation can be developed by setting x = 3.05 m (10 ft) and g = 9.8 m/s^2 (115,718 ft/min^2):

$$(Q_{e,b}) = Q_e\left[1 + \left(\frac{30.5(T_s - T_a)T_s}{T_a^2 U_H V_e}\right)\right]^{0.5} = Q_e * B_{fac} \quad \text{(SI)} \quad (31)$$

$$(Q_{e,b}) = Q_e\left[1 + \left(\frac{1180800(T_s - T_a)T_s}{T_a^2 U_H V_e}\right)\right]^{0.5} = Q_e * B_{fac} \quad \text{(I-P)} \quad (32)$$

where B_{fac} is the correction factor for heated exhaust. Equations 31 and 32 show B_{fac} is highest for low winds and low exit velocities. It tends toward a value of 1 for high wind speeds and high exit velocities.

Special Cases—Capped Heated Exhaust

Capped stacks that are heated will still have plume rise because of buoyancy effects. To account for this additional plume rise, a method similar to that recommended by the EPA will be used. Brode (2015) suggested two alternative methods from which the following method is recommended: multiply diameter by 10 and maintain the actual volume flow rate, which decreases the exit velocity by a factor of 100. This method results in more reasonable exit velocities (much greater than 0.001 m/s [0.2 fpm]) and exhaust diameters than the EPA recommended method. For this calculation β is set equal to 1. An example calculation is found in the work by Petersen et al. (2015).

EVALUATION OF NEW AND EXISTING STANDARD 62.1 EQUATIONS

Dilution Equation Performance Metrics

When evaluating models for measurements and predictions paired in space and time, such as for this evaluation, the following model performance measures are often used (Hanna et al. 2004):

$$\text{FB} = 2\left[\frac{\bar{D}_o - \bar{D}_p}{\bar{D}_o \bar{D}_p}\right] \quad (33)$$

$$\text{NMSE} = \left[\frac{\overline{[D_o - D_p]^2}}{\bar{D}_o \bar{D}_p}\right] \quad (34)$$

where

FB	=	fractional bias
NMSE	=	normalized mean-square error
D_o	=	observed dilution
D_p	=	model prediction of dilution
overbar	=	average over the date set

These statistics were initially used for the performance evaluation but were found to provide little useful information since a conservative model is desired, or one that will underpredict dilution most of the time with some overpredictions occurring. Therefore, more relevant statistics were developed.

The ratio R of predicted to observed dilution was computed as was the percent time that the ratio met the following criteria:

- % time $R > 1.5$ (percent time dilution predictions are a factor of 1.5 or more high): the best model will have a low percentage.
- % time $0.5 \le R \le 1.5$ (percent time dilution predictions are between a factor of 0.5 low to 1.5 high): the best model will have a high percentage.
- % time $0.5 \le R \le 1$ (percent time dilution predictions are between a factor of 0.5 low to perfect agreement): the best model will have a high percentage.

Another performance measure is a scatter plot of predicted divided by observed dilution with a one-to-one line. Again, the ideal model in this case will have almost all predicted dilution values equal to the observed dilution with a few values greater than observed and most values less than observed. The goal is that New4 over- and underpredicts less than the current Standard 62.1 equation.

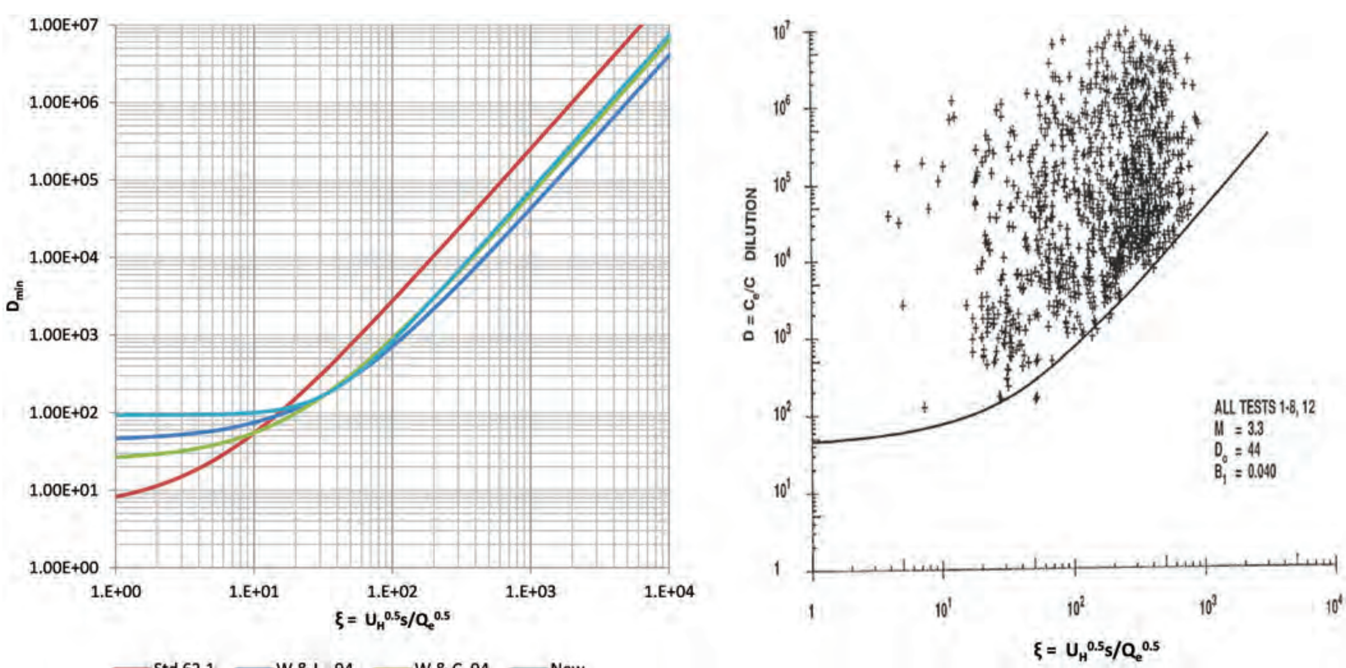
Wilson and Chui (1994) and Wilson and Lamb (1994) Database Comparison

Actual data from the Wilson and Chui (1994) and Wilson and Lamb (1994) databases were not obtained, but the equations developed from those databases did bound the measured data and provide a standard from which to evaluate the Standard 62.1 equation and New4. Figure 6a shows the predicted minimum dilution using the Standard 62.1 equation versus normalized string distance compared with predictions obtained using Equations 1, 2, and 3 with $V_e / U_H (M) = 3.3$, per Wilson and Lamb (1994), and using the following:

- $C_1 = 7.0$ and $\beta_1 = 0.0625$ as recommended by Wilson and Chui (1994 [hereon *W&C 94]*) and
- $C_1 = 13.0$ and $\beta_1 = 0.04$ as recommended by Wilson and Lamb (1994 [hereon *W&L 94*]).

These constants were found to bound all observed dilution values in W&C 94 and W&L 94 and should be considered the most conservative. Inspection of Figure 6a shows that all minimum dilution equations (except Standard 62.1) produce similar results for normalized distances (ξ) greater than about 20, while the Standard 62.1 and W&C 94 equations provided the lowest dilution estimates for $\xi < \sim 10$.

New4 was then tested against the W&C 94 and W&L 94 equations and an *i* value of 0.153 was determined to provide a best fit with W&C 94 for $20 < \xi < 1000$. Figure 6a shows New4 dilution equation estimates versus those obtained using W&C 94 and W&L 94 with the graph from W&L 94 on the right (Figure 6b), which includes the measured data. The solid line in Figure 6b corresponds with the W&L 94 line in Figure 6a. By comparing the two figures it can be seen that New4 does provide a lower bound for the observed dilution values for normalized distance $\xi > 20$ and also shows that dilution is approximately constant closer to the stack. This is the effect of the plume rise, which is not included in the Standard 62.1 equation. For $\xi < 10$, New4 approximately bounds the limited observations.



(a) (b)

Figure 6 *Comparison of predicted dilution using the Standard 62.1, Wilson and Lamb (1994), Wilson and Chui (1994), and New4.*

Other Databases—Rooftop

Figure 7 shows a scatter plot of predicted versus observed dilution for the existing Standard 62.1 equation and New4 for all databases. Several solid lines are included in the plots to help interpret the results (1:1 line; factor of ±10; factor of –100). Ideally, all data would fall on the 1:1 line (solid black), which would indicate an exact match for predicted and measured dilution. The dark grey lines indicate predicted dilution with a factor of ±10 and the light grey lines indicate a factor of –100. The figures clearly show that New4 captures a significantly higher amount of data near the 1:1 line. In addition, New4 does a much better job of bounding the data, so that overpredictions in dilution occur much less frequently. The result is that New4 provides a more accurate dilution prediction while also maintaining a higher frequency of conservatively underpredicted dilution values.

Table 2 shows the statistical quantities used to evaluate the model performance. The table shows that New4 is an improvement over the Standard 62.1 equation for the following reasons:

- Smaller percentage of *R* values greater than 1.5 (less overprediction)
- Greater percentage of *R* values between 0.5 and 1.0 (less underprediction)
- Greater percentage of *R* values between 0.5 and 1.5 (more frequent predictions that have a reasonable degree of uncertainty)

Other Databases—Sidewall

Configurations when an intake is not in the line of sight of the exhaust should also be considered. An example of such a configuration is a building with rooftop exhaust sources and intakes located on the building façade. Such sidewall intakes are considered “hidden” from the exhaust source. Significant additional plume dilution is associated with this type of exhaust/intake configuration due to the plume having to “turn the corner” to reach the intake. Currently, Standard 62.1 does not have specific guidelines for such a case, other than the slight benefit of increased string distance. For hidden intake cases, New4 dilution estimates are increased by a sidewall concentration reduction factor of 2 (dilution increase factor) to account for the additional dilution provided by the sidewall orientation. Figure 8 compares predicted values for Standard 62.1 and New4 for cases where the intake is located along the building sidewall. The two databases used for this evaluation are from the research by Petersen et al. (1997) and Schulman and Scire (1991).

Table 2. Statistical Evaluation of Standard 62.1 Equation and New4 Equation—Rooftop Intakes

Statistical Criteria	Standard 62.1 Equation	New4
% time $R > 1.5$	15%	4%
0.5 < % time $R < 1.5$	25%	35%
0.5 < % time R <1	15%	25%

From Figure 8 it can be seen that New4 generally provides better predictions for sidewall dilution, with fewer predictions varying greater than a factor of 10 from the measured dilution. In addition, based on the Schulman and Scire (1991) database, the Standard 62.1 equation has the potential to underpredict dilution, which can result in a potentially unsatisfactory design. For both databases, New4 bounds the data and is much more likely to prevent an overprediction in dilution. For practical applications, predicted dilution values greater than 2000 are of little interest because all target dilution factors in Table 1 are less than 2000.

Table 3 shows the statistical quantities used to evaluate the model performance. The table shows that New4 is an improvement over the Standard 62.1 equation for the following reasons:

- Smaller percentage of *R* values greater than 1.0 (less overprediction)
- Greater percentage of *R* values between 0.5 and 1.0 (less underprediction)
- Greater percentage of *R* values between 0.5 and 1.5 (more frequent predictions that have a reasonable degree of uncertainty)

NEW SEPARATION DISTANCE CALCULATION METHODOLOGY

Calculated Separation Distances (General and Regulatory Procedures)

The stated purpose of this research project is to provide a simple yet accurate procedure for calculating the minimum distance required between the outlet of an exhaust system and the outdoor air intake to a ventilation system to avoid reentrainment of exhaust gases. Two new procedures were originally thought to be needed. One, a general procedure suitable for standard HVAC engineering practice that has exhaust

Table 3. Statistical Evaluation of Standard 62.1 Equation and New4 Equation—Sidewall Intakes

Statistical Criteria	Standard 62.1 Equation	New4
% time R > 1.0	24%	1%
0.5 < % time R < 1.5	17%	21%
0.5 < %time R < 1	20%	47%

outlet velocity, exhaust air volumetric flow rate, exhaust outlet configuration (capped/uncapped) and position (vertical separation distance), desired dilution ratio, ambient wind speed, and exhaust direction as independent variables. The second method was to be a regulatory procedure suitable for Standard 62.1, Standard 62.2, and model building codes that has only exhaust outlet velocity, exhaust air volumetric flow rate, desired dilution ratio, and a simple way to account for orientation relative to the inlet as independent variables The recommended equation (New4) meets both requirements. New4 accounts for all the important variables yet is simple enough to be used as a regulatory method.

The methodology for computing minimum separation distances using New4 along with example calculations and additional documentation is found in the ensuing sections.

General Equation and Method

To compute the minimum separation distance *s*, first set up a spreadsheet as shown in Table 4. The values in the medium dark shading are input, and all other values are computed using the equations below. The details on the special cases (i.e., hidden intake, exhaust pointed away from intake, heated exhaust, and upblast exhaust) were discussed previously.

The equations and method are provided as follows:

$$F1 = 13.6\frac{DQ_e}{U_H} \quad (35)$$

$$F2 = 33.37h_s^2 + 254.9\beta\frac{B_{fac}h_sQ_e}{d_eU_H} + 486.9\beta\left[\frac{B_{fac}Q_e}{d_eU_H}\right]^2 \quad (36)$$

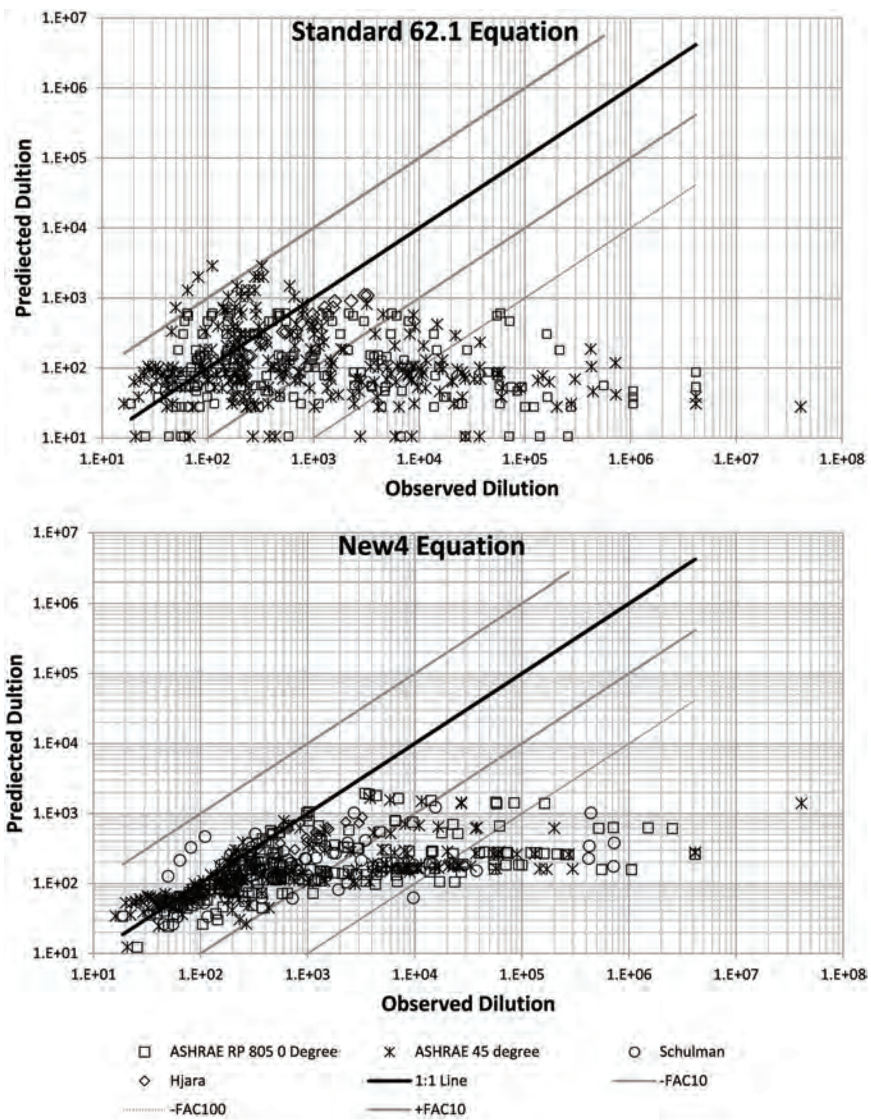


Figure 7   Predicted versus observed dilution for Standard 62.1 and new (New4) equations—Rooftop intakes.

$$B_{fac} = \left[1 + \left(\frac{387302(T_s - T_a)T_s}{T_a^2 U_H V_e}\right)\right]^{0.5} \quad \text{(SI)} \quad (37)$$

$$B_{fac} = \left[1 + \left(\frac{10(T_s - T_a)T_s}{T_a^2 U_H V_e}\right)\right]^{0.5} \quad \text{(I-P)} \quad (38)$$

Find the maximum of $[F1 - F2]$ by varying U_H between 1.5 and 10 m/s (300 and 2000 fpm)

$$\text{if } \max[F1 - F2] > 0;\ s = [F1 - F2]^{0.5} \quad (39)$$

$$\text{if } \max[F1 - F2] \le 0;\ s = 0 \quad (40)$$

where

s = minimum separation (string) distance, m (ft)

U_H = wind speed, m/s (fpm)

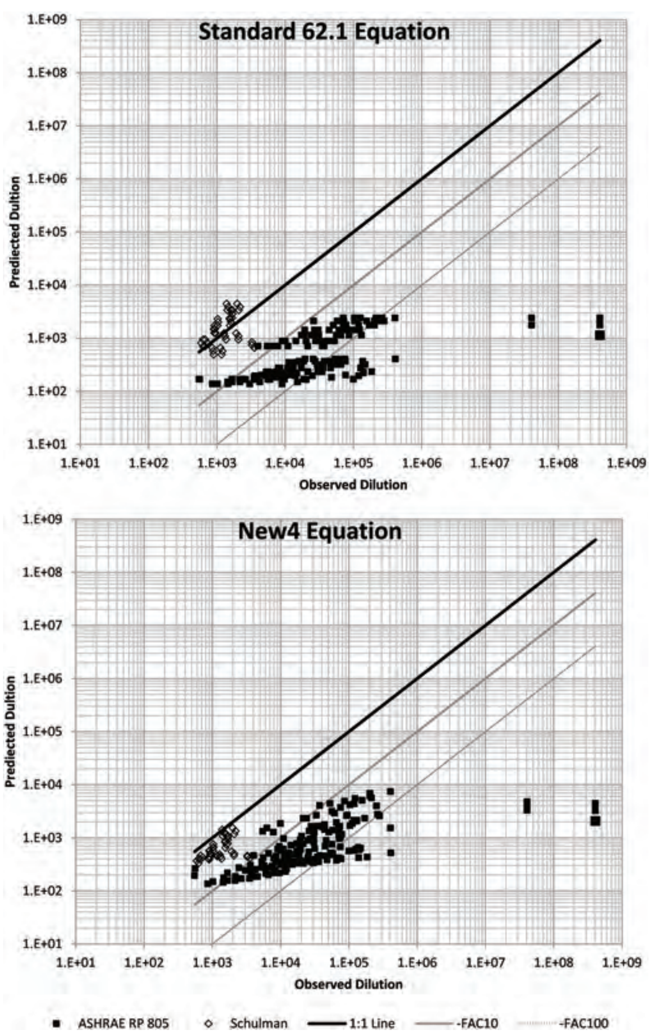


Figure 8 *Predicted versus observed dilution for Standard 62.1 and New4—Sidewall intakes.*

D = dilution factor (taken from Table 1)

T_s = exhaust temperature, K (°R)

T_a = ambient temperature, K (°R)

h_s = stack height above the top the air intake, m (ft)

Q_e = volume flow rate, m^3/s (cfm)

d_e = exhaust diameter, m (ft)

β = 1 for uncapped stacks and 0 for capped stacks

Note that for these calculations, absolute temperature units are required (i.e., Kelvin and Rankine).

The following describes the calculations and information that is input into Table 4:

- **Row 1:** The exhaust type first needs to be specified from Table 1, taken from Petersen et al. (2015), and then the appropriate dilution factor from the table is input. For Class 1 exhaust, the dilution factor is 5, which is the value in the table.
- **Row 2:** If the intake is on a building sidewall or on the opposite side of a roof top obstacle (hidden), the dilution factor can be decreased by a factor of 2, which is then input into the table. If the intake is not hidden, the value should be set to 1.
- **Row 3:** If the exhaust is horizontal and pointed away from the intake as described previously, the dilution factor can be decreased by an additional factor of 1.7 and that value is input into the table. For all other cases, a value of 1 is input.
- **Row 4:** The final dilution factor is computed by dividing the dilution factor in Row 1 by the factors in Rows 2 and 3.
- **Row 5:** The height of the stack above the top of the intake is input. For intakes on a building sidewall or behind a rooftop obstacle, the height of the stack above the roof or obstacle top where the intake is located should be used. If the intake is above the stack height, the height difference is negative and the stack height input is also negative.
- **Row 6:** For capped or horizontal exhaust (including louvered), a value of 0 is entered. For all other exhaust types, including heated capped or horizontal exhaust pointed away from the input, the value should be 1.0.
- **Row 7:** The exhaust diameter is entered using the methods described above. For rectangular exhaust (capped, horizontal, or vertical), an equivalent round stack diameter should be calculated using the following equation:

$$d_{e,\,eff} = [\text{exhaust area} \times 4/\pi]^{0.5}$$

For louvered round or rectangular exhaust (capped, horizontal, or vertical), an equivalent round stack diameter should be calculated as follows:

$$d_{e,\,eff} = [\text{exhaust area} \times \text{open fraction} \times 4/\pi]^{0.5}$$

For heated capped or horizontal (including louvered) exhaust, the exhaust diameter is the actual or effective diameter multiplied by 10, as discussed previously.

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Table 4. Example Spreadsheet for Calculating Minimum Separation Distance

Exhaust Type: Class 1			**SI Units**
1	Input dilution factor from Table 1	5	
2	Hidden intake (yes/no)	2	If yes, set equal to 2; if no, set equal to 1
3	Exhaust pointed away from intake (yes/no)	1.7	If yes, set equal to 1.7; if no, set equal to 1
4	Final dilution factor	1.5	Divide line 1 by row 2 and row 3
5	h_s (m)	0.31	Height above the top of intake
6	β	0	Set equal to 0 for capped or horizontal; equal to 1 for vertical and noncapped or heated/capped
7	d_e (m)	1.2	For upblast/downblast or heated capped exhaust, see discussion
8	Q_e (m^3/s)	2.0	
9	Exhaust temperature (K)	294.3	Default is set to ambient, K = °C + 273.14
10	Ambient temperature (K)	294.3	Default is 21.1°C, K = °C + 273.14
11	Heated exhaust factor, B_{fac}	1.00	Equation 37 or 38
12	V_e (m/s)	1.8	$V_e = Q_e / (\pi d_e^2 / 4)$
13	$F1$	22.6	Equation 35
14	$F2$	3.2	Equation 36
15	U_H (m/s)	1.8	Vary unless pointed away or capped—If pointed, always set $U_H = V_e$; if capped, set equal to 1.5 m/s
16	F1 – F2	19.5	Maximize by changing U_H between 1.5 and 10 m/s, unless pointed away or capped
17	$s_{initial}$ (m)	4.4	Equals 0 if max[$F1 - F2$] is negative
18	s_{final} (m)	2.3	$s_{final} = s_{initial}$ unless pointed away; then $s_{final} = s_{initial} - 1.75 d_e$

Exhaust Type: Class 1			**I-P Units**
1	Input dilution factor from Table 1	5	
2	Hidden intake (yes/no)	1.0	If yes, set equal to 2. If no, set equal to 1.
3	Exhaust pointed away from intake (yes/no)	1.7	If yes, set equal to 2. If no, set equal to 1.
4	Final dilution factor	1.5	Divide line 1 by line 2 and line 3
5	h_s (ft)	1.0	Height above the top of intake
6	β	0	Set = 0 for capped or horizontal, = 1 for vertical and noncapped or heated/capped
7	d_e (ft)	3.94	For upblast/downblast or heated capped exhaust, see discussion
8	Q_e (cfm)	4235	
9	Exhaust temperature (°R)	529.7	Default is set to ambient, °R = °F + 459.67
10	Ambient temperature (°R)	529.7	Default is 70°F, °R = °F + 459.67
11	Heated exhaust factor, B_{fac}	1.00	Equation 37 or 38
12	V_e (fpm)	348.0	$V_e = Q_e / (\pi d_e^2 / 4)$
13	$F1$	243.3	Equation 35
14	$F2$	34.1	Equation 36
15	U_H (fpm)	348	Vary unless pointed away or capped—If pointed, aways set U_H equal to V_e; if capped, set equal to 295 fpm
16	$F1 - F2$	209.3	Maximize by changing U_H between 300 and 2000 fpm
17	$s_{initial}$, ft	14.5	Equals 0 if max[$F1 - F2$] is negative
18	s_{final}, ft	7.6	$s_{final} = s_{initial}$ unless pointed away; then $s_{final} = s_{initial} - 1.75 d_e$

Shade gradation key:
Darkest: Final result
Medium dark: Input
Medium light: Calculation
Lightest: Varies

- **Row 8:** The exhaust volume flow rate is entered. For gravity vents, such as plumbing vents, use an exhaust rate of 75 L/s (150 cfm). For flue vents from fuel-burning appliances, assume a value of 0.43 L/s per kW (250 cfm per million Btu/h) of combustion input (or obtain actual rates from the combustion appliance manufacturer).
- **Row 9:** The exhaust temperature is entered. Unless the exhaust is heated, this temperature should be the same as the ambient temperature.
- **Row 10:** Enter the ambient temperature. Default values of 294.3 K (21.1°C) or 529.7°R (70°F) should typically be used.
- **Row 11:** The heated exhaust factor is computed using Equations 37 or 38.
- **Row 12:** The exhaust velocity is computed using the equation in the table.
- **Row 13:** $F1$ is computed using Equation 35.
- **Row 14:** $F2$ is computed using Equation 36.
- **Row 15:** For noncapped or heated horizontal exhaust and heated capped exhaust, the wind speed is varied between 1.5 and 10 m/s (300 and 2000 fpm) and the difference between $F1$ and $F2$ is maximized. If the maximum value is negative, the minimum separation distance is zero. If the difference is positive, then the initial separation distance is computed using Equation 39. For capped stacks or horizontal exhaust not pointed away from the intake, a wind speed of 1.5 m/s (300 fpm) should be used. For horizontal exhaust pointed away from the intake, the wind speed should be set equal to the exit velocity.
- **Row 16:** $F1 - F2$ is computed.
- **Row 17:** $s_{initial}$ is computed using Equations 39 or 40.
- **Row 18:** s_{final} is the same as $s_{initial}$ for all exhaust except horizontal exhaust that is pointed away. For the latter case, s_{final} is computed using the equation in the table.

CONCLUSIONS

The purpose of this research project was to provide a relatively simple yet accurate procedure for calculating the minimum distance required between the outlet of an exhaust system and the outdoor air intake to a ventilation system to avoid reentrainment of exhaust gases. Accordingly, a new procedure was developed that addresses the technical deficiencies in the simplified equations and tables that are currently in ANSI/ASHRAE Standard 62.1 (ASHRAE 2016a). The new procedure makes use of the knowledge provided in Chapter 45 of the 2015 *ASHRAE Handbook—HVAC Applications* (ASHRAE 2015) and various wind tunnel and full-scale studies discussed herein.

The updated methodology is suitable for standard HVAC engineering practice, and for regulatory use suitable for ASHRAE Standard 62.1, ASHRAE Standard 62.2, and model building codes. The new method has exhaust diameter (velocity), exhaust air volumetric flow rate, exhaust outlet configuration (capped/uncapped), position relative to intake orientation and position (horizontal and pointed away), desired dilution ratio, ambient wind speed, temperature of the exhaust, and hidden versus visible intakes as independent variables.

The updated method was tested against several databases (field and wind tunnel), which demonstrated that the new method is more accurate than the existing Standard 62.1 equation in that it underpredicts and overpredicts observed dilution less frequently. In addition, the new method accounts for the following additional important variables: stack height, wind speed, and hidden versus visible intakes. The new method also has theoretically justified procedures for addressing heated exhaust, louvered exhaust, capped heated exhaust, and horizontal exhaust that is pointed away from the intake.

ACKNOWLEDGMENTS

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REFERENCES

ASHRAE. 1993. Chapter 14 in *ASHRAE handbook—Fundamentals*. Atlanta: ASHRAE.

ASHRAE. 1996. *ASHRAE Standard* 62-1989R. *Ventilation for acceptable indoor air quality—Public review draft*. Atlanta: ASHRAE.

ASHRAE. 1997. Chapter 15 in *ASHRAE handbook—Fundamentals*. Atlanta: ASHRAE.

ASHRAE. 2015. Chapter 45 in *ASHRAE handbook—HVAC applications*. Atlanta: ASHRAE.

ASHRAE. 2016a. ANSI/ASHRAE Standard 62.1-2016, *Ventilation for acceptable indoor air quality*. Atlanta: ASHRAE

ASHRAE. 2016b. ANSI/ASHRAE Standard 62.2-2016, *Ventilation and acceptable indoor air quality in low-rise residential buildings*. Atlanta: ASHRAE.

Brode, R.W. 2015. Proposed updates to AERMOD modeling system. 11th Modeling Conference Presentation, Research Triangle Park, NC. www.epa.gov/ttn/scram/11thmodconf/presentations/1-5_Proposed_Updates_AERMOD_System.pdf.

EPA. 1995. *User's guide for the Industrial Source Complex (ISC3) dispersion models, vol. 2: Description of model algorithms*. EPA-454/B-95993B. Research Triangle Park, NC: U.S. Environmental Protection Agency.

EPA. 2004. *AERMOD, Description of model formulation*. EPA-454/R-03-004. Research Triangle Park, NC: U.S. Environmental Protection Agency.

Hajra, B., and T. Stathopoulos. 2012. A wind tunnel study of the effect of downstream buildings on near-field pollutant dispersion. *Building and Environment* 52:19–31.

Hanna, S.R., O.R. Hansen, and S. Dharmavaram. 2004. FLACS CFD air quality model performance evaluation with Kit Fox, MUST, Prairie Grass, and EMU observations. *Atmospheric Environment* 38:4675–87.

Hoydysh, W.G., and L.L. Schulman. 1987. Fluid modeling study of the contamination of fresh air intakes from rooftop emissions. Paper 87-82A.9, 80th Annual Meeting of APCA, New York, NY.

IAPMO. 2015a. *Uniform mechanical code*. Ontario, Canada: International Association of Plumbing and Mechanical Officials.

IAPMO. 2015b. *Uniform plumbing code*. Ontario, Canada: International Association of Plumbing and Mechanical Officials.

ICC. 2012. *International mechanical code*. Country Club Hills, IL: International Code Council.

Perkins, H.C. 1974. *Air pollution*. New York: McGraw-Hill Book Company. p. 152.

Petersen, R.L. 1987. Performance evaluation of integral and analytical plume rise algorithms. *Journal of the Air Pollution Control Association* 37(11):1314–19.

Petersen, R.L., J.J. Carter, and M.A. Ratcliff. 1997. *The influence of architectural screens on exhaust dilution*. Final Report, ASHRAE 805-TRP. Atlanta: ASHRAE.

Petersen, R.L., B.C. Cochran, and J.J. Carter. 2002. Specifying exhaust and intake systems. *ASHRAE Journal* 44(8):30–5.

Petersen, R.L., J.J. Carter, and J.W. LeCompte. 2004. Exhaust contamination of hidden vs. visible air intakes. *ASHRAE Transactions* 110(1):130–42.

Petersen, R.L, J.D. Ritter, A.S. Bova, and J.J. Carter. 2015 *Simplified procedure for calculating exhaust/intake separation distance*s. Final Report, ASHRAE RP 1635-TRP.

Schulman, L.L, and J.S. Scire. 1991. The effect of stack height, exhaust speed, and wind direction on concentrations from a rooftop stack. *ASHRAE Transactions* 97(2): 573–85.

Snyder, W.H. 1981. *Guideline for fluid modeling of atmospheric diffusion*. Report No. EPA600/8–81–009. Research Triangle Park, NC: U.S. Environmental Protection Agency, Environmental Sciences Research Laboratory, Office of Research and Development.

Wilson, D.J., and B.K. Lamb. 1994. Dispersion of exhaust gases from roof-level stacks and vents on laboratory building. *Atmospheric Environment* 28(19):3099–111.

Wilson, D.J., and E.H. Chui. 1994. Influence of building size on rooftop dispersion of exhaust gas. *Atmospheric Environment* 28(14):2325–34.

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