Standard Test Method for Measuring Air Performance Characteristics of Central Vacuum Cleaning Systems[1]

This standard is issued under the fixed designation F820; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers procedures for determining air performance characteristics of household central vacuum cleaning systems, which use a flexible cleaning hose assembly and incorporates a series universal motor(s). This test method does not apply to the carpet cleaning mode of operation where dirt or debris is involved.

1.2 These tests and calculations include determination of suction, airflow, air power, maximum air power, and input power under standard operating conditions (see Note 1).

NOTE 1—For more information on air performance characteristics, see Refs (**1-6**).[2]

1.3 The values stated in inch-pound units are to be regarded as the standard. The values given in parentheses are provided for information only.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* A specific precautionary statement is given in Note 4.

2. Referenced Documents

2.1 *ASTM Standards:*[3]

E1 Specification for ASTM Liquid-in-Glass Thermometers

E177 Practice for Use of the Terms Precision and Bias in ASTM Test Methods

E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

E2251 Specification for Liquid-in-Glass ASTM Thermometers with Low-Hazard Precision Liquids

F431 Specification for Air Performance Measurement Plenum Chamber for Vacuum Cleaners

2.2 *AMCA Standard:*[4]

210–85 Laboratory Methods of Testing Fans for Rating

2.3 *IEC Standard:*[5]

IEC 60312 Ed 3.2 Vacuum Cleaners for Household Use—Methods of Measuring the Performance

3. Terminology

3.1 *Definitions:*

3.1.1 *air power, AP, W, n*—in a vacuum cleaner, the net time rate of work performed by an air stream while expending energy to produce an airflow by a vacuum cleaner under specified air resistance conditions.

3.1.2 *automatic bleed valve, n*—any device a part of a vacuum cleaner's design, which automatically introduces an intentional leak within the vacuum cleaner's system when manufacturer specified conditions are met.

3.1.3 *corrected airflow, Q, cfm, n*—in a vacuum cleaner, the volume of air movement per unit of time under standard atmospheric conditions.

3.1.4 *input power, W, n*—the rate at which electrical energy is absorbed by a vacuum cleaner.

3.1.5 *model, n*—the designation of a group of vacuum cleaners having the same mechanical and electrical construction with only cosmetic or nonfunctional differences.

3.1.6 *population, n*—the total of all units of a particular model vacuum cleaner being tested.

3.1.7 *repeatability limit (r), n*—the value below which the absolute difference between two individual test results obtained under repeatability conditions may be expected to occur with a probability of approximately 0.95 (95 %).

3.1.8 *reproducibility limit (R), n*—the value below which the absolute difference between two test results obtained under

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[2] The boldface numbers in parentheses refer to the list of references at the end of this standard.

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[4] Available from Air Movement and Control Association, Inc., 30 West University Dr., Arlington Heights, IL 60004–1893.

[5] Available from the IEC Web store, webstore.iec.ch, or American National Standards Institute (ANSI), 25 W. 43rd St., 4th Floor, New York, NY 10036.

reproducibility conditions may be expected to occur with a probability of approximately 0.95 (95 %).

3.1.9 *repeatability standard deviation* (S_r), *n*—the standard deviation of test results obtained under repeatability conditions.

3.1.10 *reproducibility standard deviation* (S_R), *n*—the standard deviation of test results obtained under reproducibility conditions.

3.1.11 *sample, n*—a group of vacuum cleaners taken from a large collection of vacuum cleaners of one particular model, which serves to provide information that may be used as a basis for making a decision concerning the larger collection.

3.1.12 *standard air density,* ρ_{std}, *lb/ft*^{3}, *n*—atmospheric air density of 0.075 lb/ft^3 (1.2014 kg/m^3).

3.1.12.1 *Discussion*—This value of air density corresponds to atmospheric air at a temperature of 68 °F (20 °C), 14.696 psi (101.325 kPa), and approximately 30 % relative humidity.

3.1.13 *suction, inch of water, n*—in a vacuum cleaner, the absolute difference between ambient and subatmospheric pressure.

3.1.14 *test run, n*—the definitive procedure that produces the singular result of calculated maximum air power.

3.1.15 *test station pressure,* B_t, *inch of mercury, n*—for a vacuum cleaner, the absolute barometric pressure at the test location (elevation) and test time.

3.1.15.1 *Discussion*—It is not the equivalent mean sea level value of barometric pressure typically reported by the airport and weather bureaus. It is sometimes referred to as the uncorrected barometric pressure (that is, not corrected to the mean sea level equivalent value). Refer to 5.4 for additional information.

3.1.16 *unit, n*—a single vacuum cleaner of the model being tested.

4. Significance and Use

4.1 The test results allow the comparison of the maximum air power available when no dirt has been introduced into the vacuum cleaning system, that is, a completely clean filter or an empty, clean dirt container.

5. Apparatus

5.1 *Plenum Chamber*—See Specification F431 or IEC 60312, Section 5.2.8.2 (Figure 13c).

5.2 *Water Manometers,* or equivalent instruments. One to measure from 0 to 6 in. (152.4 mm) in increments of 0.01 in. (0.254 mm), and one with increments of 0.1 in. (2.54 mm) for use in making measurements above 6 in. (152.4 mm). A single instrument having a resolution of 0.01 in. (0.254 mm) over the entire required range may be used instead of two separate instruments.

5.3 *Power analyzer,* to provide measurements accurate to within ±1 %.

5.4 *Barometer,* with an accuracy of ±0.05 in. (1.27 mm) of mercury, capable of measuring and displaying absolute barometric pressure, scale divisions 0.02 in. (0.51 mm) or finer.

5.4.1 Mercury barometers, in general, measure and display the absolute barometric pressure. Some corrections may be needed for temperature and gravity. Consult the owner's manual.

5.4.2 When purchasing an aneroid or electronic barometer, be sure to purchase one which displays the absolute barometric pressure, not the mean sea level equivalent barometric pressure value. These types of barometers generally have temperature compensation built into them and do not need to be corrected for gravity.

5.5 *Sharp-Edge Orifice Plates*—See Specification F431.

5.6 *Thermometer*—Solid-stem, ambient thermometer having a range from 18 to 89°F (or –8 to +32°C) with graduations in 0.2°F (0.1°C), conforming to the requirements for thermometer 63°F (17°C) as prescribed in Specification E1. As an alternative, thermometers S63F or S63C, as prescribed in Specification E2251, may be used. In addition, thermometric devices such as resistance temperature detectors (RTDs), thermistors, or thermocouples of equal or better accuracy may be used.

5.7 *Psychrometer*—Thermometers graduated in 0.2 °F (0.1 °C).

5.8 *Voltage-Regulator System,* to control the input voltage to the vacuum cleaner. The regulator system shall be capable of maintaining the vacuum cleaner's rated voltage ±1 % and rated frequency ±1 Hz having a wave form that is essentially sinusoidal with 3 % maximum harmonic distortion for the duration of the test.

5.9 *Orifice Adapter Tube*—See Fig. 1.

6. Sampling

6.1 A minimum of three units of the same model vacuum cleaner selected at random in accordance with good statistical practice, shall constitute the population sample.

6.1.1 To determine the best estimate of maximum air power for the population of the vacuum cleaner model being tested, the arithmetic mean of the maximum air power of the sample from the population shall be established by testing it to a 90 % confidence level within ±5 %.

6.1.2 Annex A2 provides a procedural example for determining the 90 % confidence level and when the sample size shall be increased.

NOTE 2—See Annex A2 for method of determining 90 % confidence level.

7. Test Vacuum Cleaners

7.1 *New Test Vacuum Cleaner*—Run the vacuum cleaner in at rated voltage ±1% and rated frequency with filters in place for 1 h with a wide-open inlet (without hose).

7.2 *Used Test Vacuum Cleaners*—Recondition a used test vacuum cleaner; prior to the initial test run as follows:

7.2.1 Thoroughly remove excess dirt from the vacuum cleaner. Without using tools for disassembly, clean the entire outer surface, brushes, nozzle chamber, ductwork, inside of the chamber surrounding the primary filter, and inside hose and wands.

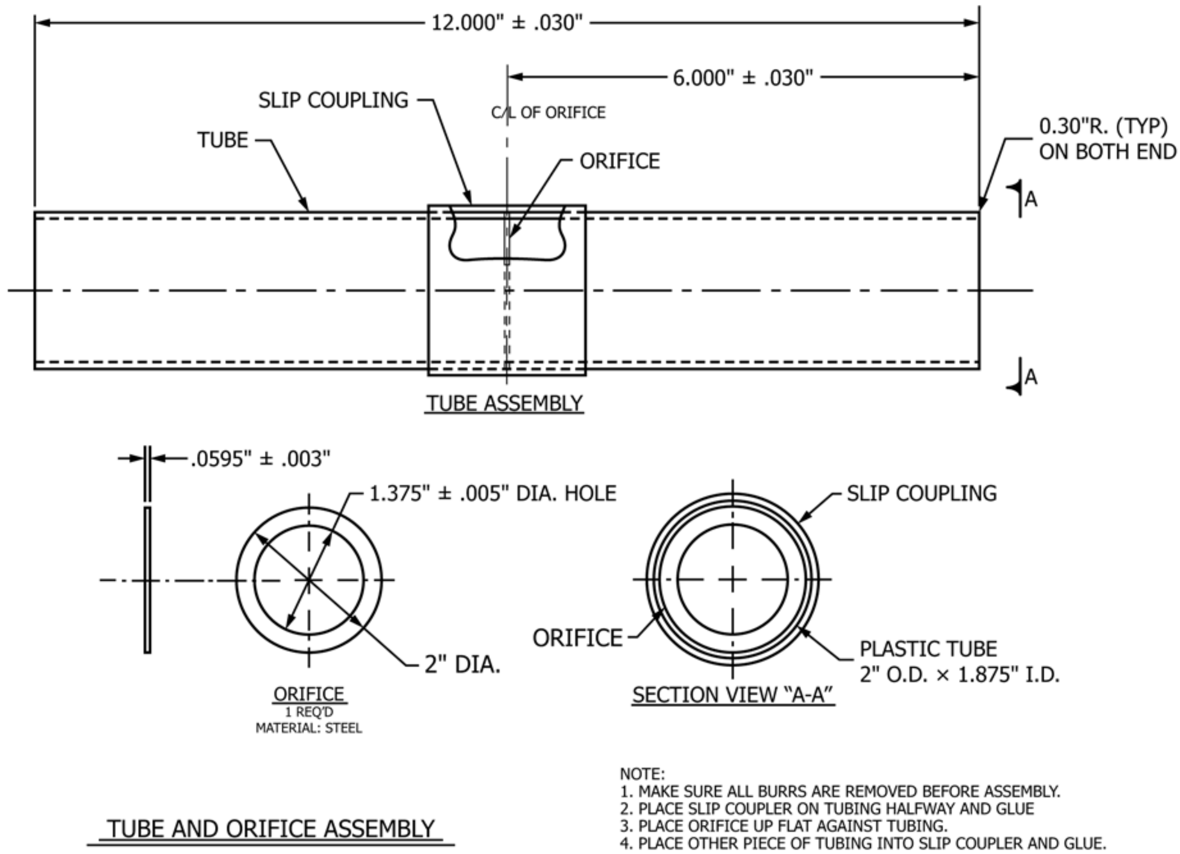


FIG. 1 Orifice Adapter Tube

7.2.2 For vacuum cleaners using disposable filters as the primary filters, use a new disposable primary filter from the manufacturer for each test. Install it as recommended by the vacuum cleaner manufacturer.

7.2.3 For vacuum cleaners using non-disposable dirt receptacles, empty in accordance with the manufacturer's instructions and clean the receptacle until its weight is within 0.07 oz (2 g) of its original weight and install it as recommended by the vacuum cleaner manufacturer.

7.2.4 For vacuum cleaners using non-disposable dirt receptacles, empty in accordance with the manufacturer's instructions and clean the receptacle until its weight is within 0.07 oz (2 g) of its original weight and install it as recommended by the vacuum cleaner manufacturer.

NOTE 3—It is preferable to conduct this test method on new test vacuum cleaners prior to any other ASTM test methods to avoid contamination that could cause performance variations.

7.3 *Test Vacuum Cleaner Settings*—If various settings are provided, set the motor speed setting or suction regulator using the manufacturer's specifications as provided in the instruction manual for normal operation. If a different setting is used, make a note of the deviation in the test report.

8. Procedure

8.1 *Preparation for Test:*

8.1.1 Prepare the test unit in accordance with Section 7. Set-up the test system as shown in Fig. 2. On the intake side, use an adapter terminating with the wall inlet valve. This wall inlet is to be the one specified for installation with the power unit being tested. All joints should be made in accordance with the manufacturer's specifications and be free of leaks. Insert into the wall valve a flexible cleaning hose as provided with the system. The hose assembly should be that which is offered normally with the particular unit being tested. For those systems, which provide for an external exhaust, connect 2 ft (0.6 m) of exhaust comprised of tubing and exhaust muffler, if a muffler is provided as part of the system.

8.1.2 Set the manometers to zero and check all instruments for proper operation.

8.1.3 Record the test station pressure and the dry-bulb and wet-bulb temperature readings within 6 ft of the test area. Read the barometric pressure to the nearest 0.02 in. (0.51 mm) of mercury, and the dry-bulb and wet-bulb temperatures to the nearest 0.2 °F (or 0.1 °C).

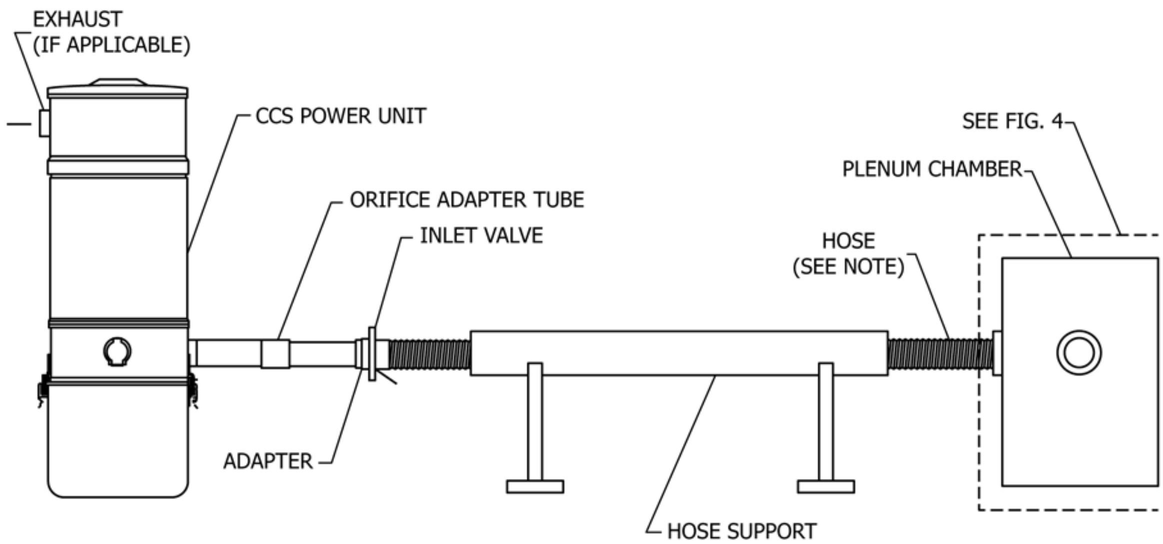
8.1.3.1 The test area shall be free of major fluctuating temperature conditions due to air conditioners or air drafts that would be indicated by a thermometer at the immediate test area.

8.1.4 Connect the manometer or equivalent instrument to the plenum chamber.

8.1.5 Connect a power analyzer.

8.2 *Test Procedure:*

8.2.1 Connect the hose assembly to the plenum chamber hose adapter and seal only this connection (see Fig. 3).



NOTE 1—Hose is to be supported in a straight line.

FIG. 2 Vacuum Cleaning System Test Set-up

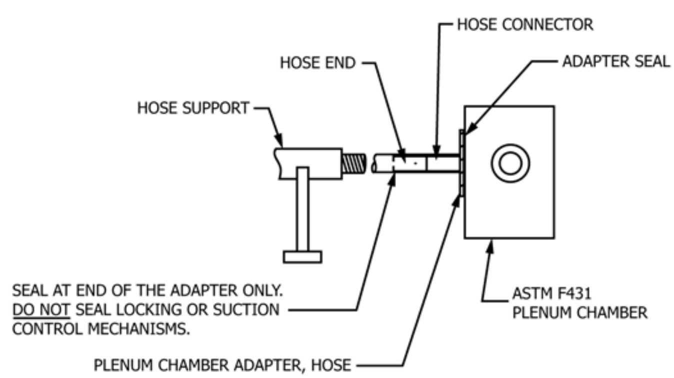


FIG. 3 Diagram of Hose and Adapter Connection

8.2.1.1 The end of the hose assembly should be inserted inside the hose connector adapter and be perpendicular to the plenum chamber.

8.2.1.2 The end of the hose assembly shall not project into the plenum chamber.

8.2.1.3 Any automatic bleed valve, which affects the air performance of the vacuum cleaner, shall not be defeated.

8.2.2 The hose should be supported and kept straight and horizontal over its entire length. Allowance should be made for the foreshortening of the hose assembly under the vacuum. Maintain the power unit and dirt canister in their normal operating orientation.

8.2.3 Operate the vacuum cleaner with no orifice plate inserted in the plenum chamber inlet at nameplate rated voltage ±1 % and frequency ±1 Hz prior to the start of the test run to allow the unit to reach its normal operating temperature. For vacuum cleaners with dual nameplate voltage ratings, conduct testing at the highest voltage. Allow the unit to reach its normal operating temperature before each test run.

8.2.4 The vacuum cleaner is to be operated at its nameplate rated voltage ±1 % and frequency ±1 Hz throughout the test. For vacuum cleaners with dual nameplate voltage ratings, conduct the test at the highest voltage.

8.2.4.1 Allow the vacuum cleaner to operate at the open orifice for 1 to 2 min between test runs.

8.2.5 While operating the vacuum cleaner in accordance with 8.2.4, insert orifice plates sequentially into the orifice plate holder of the plenum chamber starting with the largest size orifice and following it with the next smaller orifice plate. Use the following orifice plates: 2.0, 1.5, 1.25, 1.0, 0.875, 0.75, 0.625, 0.5, 0.375, 0.25, 0.0 in. (50.8, 38.1, 31.7, 25.4, 22.2, 19.0, 15.8, 12.7, 9.5, 6.3 mm). The following optional orifice plates also may be used: 2.5, 2.25, 1.75, 1.375, 1.125 in. (63.5, 57.2, 44.5, 34.9, 28.6 mm).

8.2.6 For each orifice plate, record the suction, *h*, and input power, *P*, in that order. All readings should be taken within 10 s of the orifice insertion. For orifices less than 0.750 in. allow the vacuum cleaner to operate at the open orifice for 1 to 2 min before inserting the next orifice.

8.2.6.1 Read the suction to the nearest graduation of the instrument. Readings should be taken as soon as the manometer reaches a true peak. When using a fluid type manometer, the liquid level may peak, drop, and peak again. The second peak is the true peak reading. A person conducting the test for the first time shall observe at least one run before recording data. See Specification F431 for instructions on how to minimize the overshoot (first peak) of the liquid level.

9. Calculation

9.1 *Correction of Data to Standard Conditions:*

9.1.1 *Air Density Ratio*—The density ratio, D_r, is the ratio of the air density at the time of test ρ_{test}, to the standard air density, ρ_{std} = 0.075 lb/ft^3 (1.2014 kg/m^3). It is used to correct the vacuum and wattage readings to standard conditions. Find ρ_{test} (lb/ft^3 or kg/m^3) from standard psychometric charts or ASHRAE tables and calculate D_r as follows:

$$D_r = \frac{\rho_{test}}{\rho_{std}} \quad (1)$$

where:

ρ_{test} = the air density at the time of test, lb/ft^3, and
ρ_{std} = the standard air density, 0.075 lb/ft^3.

9.1.1.1 As an alternative, the following equation is intended to be used for correcting ambient conditions where the barometric pressure exceeds 27 in mercury and the dry-bulb and wet-bulb temperatures are less than 100°F (37.8°C); and, may be used as an alternate method of calculating D_r (see Appendix X1 for derivation and accuracy analysis).

$$D_r = \frac{\left[\begin{array}{c}17.68\,B_t - 0.001978\,T_w^2 + 0.1064\,T_w + \\ 0.0024575 B_t(T_d - T_w) - 2.741\end{array}\right]}{T_d + 459.7} \quad (2)$$

where:

B_t = test station pressure at time of test, inch of mercury,
T_d = dry-bulb temperature at time of test, °F, and
T_w = wet-bulb temperature at time of test, °F.

9.1.2 *Corrected Suction*—Corrected suction, h_s, is the manometer reading, h, times the correction factor, C_s, as follows:

$$h_s = C_s h \quad (3)$$

9.1.2.1 For series universal motors (**6**) the correction factor, C_s, is calculated as follows:

$$C_s = 1 + 0.667(1 - D_r) \quad (4)$$

9.1.2.2 This test method does not have any formulas available for correcting input power for any other type of motor (permanent magnet, induction, etc.).

9.1.3 *Corrected Input Power*—Corrected input power, P_s, expressed in watts, is the wattmeter reading, P, times the correction factor, C_p, as follows:

$$P_s = C_p P \quad (5)$$

9.1.3.1 For series universal motors the correction factor, C_p, is calculated as follows:

$$C_p = 1 + 0.5(1 - D_r) \quad (6)$$

9.1.3.2 This test method does not have any formulas available for correcting input power for any other types of motor (permanent magnet, induction, etc.).

9.2 *Corrected Airflow*—Calculate the corrected airflow, Q, expressed in cubic feet per minute (see Note 4 and Appendix X2) as follows:

$$Q = 21.844\,D^2\,K_1\sqrt{h_s} \quad (7)$$

TABLE 1 Orifice Flow Coefficient Equations (K_1)

NOTE 1—K_1 was determined experimentally using an ASTM Plenum Chamber (see Specification F431) and an ASME Flowmeter (**1**).

NOTE 2—Equations for K_1 in terms of B_t and h, are given in Appendix X6.

Orifice Diameter, in. (mm)	Orifice Flow Coefficient Equation[A]
0.250 (6.3)	$K_1 = \frac{0.5575r - 0.5955}{r - 1.0468}$
0.375 (9.5)	$K_1 = \frac{0.5553r - 0.5754}{r - 1.0263}$
0.500 (12.7)	$K_1 = \frac{0.5694r - 0.5786}{r - 1.0138}$
0.625 (15.8)	$K_1 = \frac{0.5692r - 0.5767}{r - 1.0104}$
0.750 (19.0)	$K_1 = \frac{0.5715r - 0.5807}{r - 1.0138}$
0.875 (22.2)	$K_1 = \frac{0.5740r - 0.5841}{r - 1.0158}$
1.000 (25.4)	$K_1 = \frac{0.5687r - 0.5785}{r - 1.0146}$
1.125 (28.6)	$K_1 = \frac{0.5675r - 0.5819}{r - 1.0225}$
1.250 (31.7)	$K_1 = \frac{0.5717r - 0.5814}{r - 1.0152}$
1.375 (34.9)	$K_1 = \frac{0.5680r - 0.5826}{r - 1.0235}$
1.500 (38.1)	$K_1 = \frac{0.5719r - 0.5820}{r - 1.0165}$
1.750 (44.5)	$K_1 = \frac{0.5695r - 0.5839}{r - 1.0235}$
2.000 (50.8)	$K_1 = \frac{0.5757r - 0.5853}{r - 1.0157}$
2.250 (57.2)	$K_1 = \frac{0.5709r - 0.5878}{r - 1.0279}$
2.500 (63.5)	$K_1 = \frac{0.5660r - 0.59024}{r - 1.0400}$

[A] $r = \frac{B_t\,(0.4912) - h(0.03607)}{B_t\,(0.4912)}$

where:

B_t = test station pressure at time of test, in. of mercury, and
h = uncorrected suction (manometer reading), in. of water.

where:

Q = corrected flow, cfm,
D = orifice diameter, in.,
K_1 = constant (dimensionless) orifice flow coefficients for orifices in the plenum chamber. See Table 1 for values for each orifice. See Ref (**1**) for the derivation of these flow coefficients, and
h_s = corrected suction, water, in.

NOTE 4—For the corrected airflow expressed in liters per second, use the following equation:

$$Q = 10.309 D^2 K_1 \sqrt{h_s} \quad (8)$$

where:

Q = corrected flow, L/s,
D = orifice diameter, m,
K_1 = constant (dimensionless),

h_s = corrected suction, Pa.

9.3 *Air Power*—Calculate the air power, *AP*, in watts, as follows:

$$AP = 0.117354\,(Q)(h_s) \tag{9}$$

where:

AP = air power, *W*,
Q = corrected flow, cfm, and
h_s = corrected suction, inch of water (see Appendix X3 for derivation).

9.4 *Maximum Air Power*—Determine the maximum air power using the method in Annex A1.

10. Report

10.1 For each vacuum cleaner sample from the population being tested, report the following information:

10.1.1 Manufacturer's name and product model name or number, or both.

10.1.2 Type of filtration; that is, paper bag, cloth bag, foam filter, centrifugal, etc.

10.1.3 The corrected input power, corrected vacuum, corrected airflow, and air power for each orifice.

10.1.4 Manufacturer's parts, catalog, or model number of the ductwork, fittings, and flexible cleaning hose assembly used in the test.

10.1.5 Calculated maximum air power.

11. Precision and Bias

11.1 The following precision statements are based on interlaboratory tests involving nine laboratories and four units.

11.2 The statistics have been calculated as recommended in Practice E691.

11.3 The following statements regarding repeatability limit and reproducibility limit are used as directed in Practice E177.

11.4 The Coefficients of Variation of repeatability and reproducibility of the measured results have been derived from nine sets of data, where each set has been performed by a single analyst within each of the nine laboratories on two separate days using the same unit test.[6]

11.5 *Repeatability (Single Operator and Laboratory; Multiday Testing)*—The ability of a single analyst to repeat the test within a single laboratory.

11.5.1 The expected coefficient of variation of the measured results within a laboratory, CV $\%_r$, has been found to be the respective values listed in Table 2.

TABLE 2 Repeatability and Reproducibility

Coefficient of Variation, CV $\%_r$	Repeatability Limit, *r*	Coefficient of Variation, CV $\%_R$	Reproducibility Limit, *R*
1.5	4.3	9.0	25.1

11.5.2 The 95 % repeatability limit within a laboratory, *r*, has been found to be the respective values listed in Table 2, where $r = 2.8$ (CV $\%_r$).

11.5.3 With 95 % confidence, it can be stated that within a laboratory a set of measured results derived from testing a unit should be considered suspect if the difference between any two of the three values is greater than the respective value of the repeatability limit, *r*, listed in Table 2.

11.5.4 If the absolute value of the difference of any pair of measured results from three test runs performed within a single laboratory is not equal to or less than the respective repeatability limit listed in Table 2, that set of test results shall be considered suspect.

11.6 *Reproducibility (Multiday Testing and Single Operator Within Multilaboratories)*—The ability to repeat the test with multiple laboratories.

11.6.1 The expected coefficient of variation of reproducibility of the average of a set of measured results between multiple laboratories, CV $\%_R$, has been found to be the respective values listed in Table 2.

11.6.2 The 95 % reproducibility limit within a laboratory, *R*, has been found to be the respective values listed in Table 2, where $R = 2.8$ (CV $\%_R$).

11.6.3 With 95 % confidence, it can be stated that the average of the measured results from a set of three test runs performed in one laboratory, as compared to a second laboratory, should be considered suspect if the difference between those two values is greater than the respective values of the reproducibility limit, *R*, listed in Table 2.

11.6.4 If the absolute value of the difference between the average of the measured results from the two laboratories is not equal to or less than the respective reproducibility limit listed in Table 2, the set of results from both laboratories shall be considered suspect.

11.7 *Bias*—No justifiable statement can be made on the bias of this test method for testing the properties listed. The true values of the properties cannot be established by acceptable referee methods.

12. Keywords

12.1 airflow; air performance; air power; residential central vacuum cleaners; suction; suction power; vacuum cleaners

[6] Complete data on the round-robin test is available from ASTM Headquarters. Request RR:F11-1003.

ANNEXES

(Mandatory Information)

A1. MATHEMATICAL METHOD FOR DETERMINING MAXIMUM AIR POWER POINT

A1.1 The following, second degree polynomial equation, is assumed to provide the best mathematical approximation of the air power versus airflow relationship (see Ref **(4)** for additional information).

$$Y = A_1 + A_2X + A_3X^2 \quad (A1.1)$$

where:

Y	=	air power (AP),
X	=	airflow (Q), and
A_1, A_2, and A_3	=	arbitrary constants.

A1.1.1 Use X and Y values obtained from only five specific orifices selected as follows:

A1.1.1.1 Using the test data, determine the orifice size that produced the highest air power value.

A1.1.1.2 Use the air power and airflow values at this orifice, and the next two smaller and the next two larger orifices in the following computations.

A1.1.1.3 If the highest air power value calculated from the observed data is at the 2.0 in. (50.8 mm) orifice or larger, then use the air power and airflow values from the five largest orifices.

A1.2 To determine the values of A_1, A_2, and A_3, use the X and Y values obtained from the five specified orifices and solve the following set of normalized equations:

$$\sum Y_i = NA_1 + A_2 \sum X_i + A_3 \sum X_i^2 \quad (A1.2)$$

$$\sum X_iY_i = A_1 \sum X_i + A_2 \sum X_i^2 + A_3 \sum X_i^3 \quad (A1.3)$$

$$\sum X_i^2Y_i = A_1 \sum X_i^2 + A_2 \sum X_i^3 + A_3 \sum X_i^4 \quad (A1.4)$$

where:

N	=	5 (number of orifices selected),
I	=	1 to N, and
X_i and Y_i	=	the values obtained during testing (X_1Y_1, X_2Y_2, ... X_NY_N) at the five orifices specified in A1.1.1.

A1.3 Setting the derivative of Eq A1.1 equal to zero and solving for X will determine the value of X_m where Y is at its maximum value (Y_{max}) as follows:

$$\frac{dy}{dx} = \frac{d}{dx}[A_1 + A_2X + A_3X^2] = 0 \quad (A1.5)$$

$$\frac{dy}{dx} = A_2 + 2A_3X = 0$$

Substitute X_m as the value of X at Y_{max} and solve for X_m:

$$X_m = -\frac{A_2}{2A_3} \quad (A1.6)$$

Substituting this value of X_m, and A_1, A_2, and A_3, into Eq A1.1 will determine the value of Y_{max} (AP_{max}) as follows:

$$Y_{max} = A_1 + A_2X_m + A_3X_m^2 \quad (A1.7)$$

A1.4 Calculate the goodness of fit, R (correlation coefficient), as follows:

$$R = 1 - \frac{\sum (Y_{i\ OBS} - Y_{i\ CAL})^2}{\sum (Y_{i\ OBS} - Y_{OBS})^2} \quad (A1.8)$$

where:

$$Y_{i\ CAL} = A_1 + A_2X_{i\ OBS} + A_3X^2_{i\ OBS} \quad (A1.9)$$

and:

$$Y_{OBS} = \frac{1}{N} \sum Y_{i\ OBS} \quad (A1.10)$$

and:

i	=	1 to N orifices used in 8.2,
OBS	=	observed data,
CAL	=	calculated data, and
$Y_{i\ OBS}$	=	is the air power (AP) obtained from the calculations in 9.3 for the corresponding value $X_{i\ OBS}$ (airflow, Q) at any of the N orifices selected.

A1.4.1 If R is not greater than or equal to 0.900, the test must be performed again and the new set of data used.

A2. DETERMINATION OF 90 % CONFIDENCE INTERVAL

A2.1 *Theory*:

A2.1.1 The most common and ordinarily the best estimate of the population mean, μ, is simply the arithmetic mean, $\bar{x}$, of the individual scores (measurements) of the units comprising a sample taken from the population. The average score of these units will seldom be exactly the same as the population mean; however, it is expected to be fairly close so that in using the following procedure it can be stated with 90 % confidence that the true mean of the population, μ, lies within 5 % of the calculated mean, $\bar{x}$, of the sample taken from the population as stated in Section 6.

A2.1.2 The following procedure provides a confidence interval about the sample mean which is expected to bracket μ, the true population mean, 100(1-α) % of the time where α is the chance of being wrong; therefore, 1-α is the probability or level of confidence of being correct.

TABLE A2.1 Percentiles of the *t* Distribution

df	$t_{0.95}$
1	6.314
2	2.920
3	2.353
4	2.132
5	2.015
6	1.943
7	1.895
8	1.860
9	1.833
10	1.812
11	1.796
12	1.782
13	1.771
14	1.761
15	1.753

A2.1.3 The desired level of confidence is 1-α = 0.90 or 90 % as stated in Section 11; therefore, α = 0.10 or 10 %.

A2.1.4 Compute the mean, $\bar{x}$, and the standard deviation, *s*, of the individual scores of the sample taken from the population:

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i \quad (A2.1)$$

$$s = \sqrt{\frac{n\sum_{i=1}^{n} X_i^2 - \left(\sum_{i=1}^{n} X_i\right)^2}{n\,(n-1)}} \quad (A2.2)$$

where:

n = number of units tested, and
X_i = the value of the individual test unit score of the *i*th test unit. As will be seen in the procedural example to follow, this is the average value of the results from three test runs performed on an individual test unit with the resulting set of data meeting the repeatability requirements of Section 11.

A2.1.5 Determine the value of the *t* statistic for *n* – 1 degrees of freedom, df, from Table A2.1 at a 95 % confidence level.

NOTE A2.1—The value of *t* is defined as $t_{1\text{-}\alpha/2}$ and is read as "*t* at 95 % confidence."

$$t\ \text{statistic} = t_{1-\alpha/2} = t_{0.95} \quad (A2.3)$$

where:

1-α/2 = 1 – 0.10/2 = 1 – 0.05 = 0.95 or 95 %.

A2.1.6 The following equations establish the upper and lower limits of an interval centered about $\bar{x}$ that will provide the level of confidence required to assert that the true population mean lies within this interval:

$$CI_U = \bar{x} + ts/\sqrt{n} \quad (A2.4)$$

$$CI_L = \bar{x} - ts/\sqrt{n} \quad (A2.5)$$

where:

CI = Confidence Interval (*U* - upper limit; *L* - lower limit),
$\bar{x}$ = mean score of the sample taken from the population,
t = *t* statistic from Table A2.1 at 95 % confidence level,
s = standard deviation of the sample taken from the population, and
n = number of units tested.

A2.1.7 It is desired to assert with 90 % confidence that the true population mean, *μ*, lies within the interval, CI_U to CI_L, centered about the sample mean, $\bar{x}$; therefore, the quantity $ts/\sqrt{n}$ shall be less than some value, *A*, which shall be 5 % of $\bar{x}$ in accordance with the sampling statement of 6.1.

A2.1.8 As $n \to \infty$, $ts/\sqrt{n} \to 0$. As this relationship indicates, a numerically smaller confidence interval may be obtained by using a larger number of test units, *n*, for the sample; therefore, when the standard deviation, *s*, of the sample is large and the level of confidence is not reached after testing three units, a larger sample size, *n*, shall be used.

A2.2 *Procedure (A graphical flow chart for the following procedure is shown in Fig. A2.1.):*

A2.2.1 Select three units from the population for testing as the minimum sample size.

A2.2.2 Obtain individual test unit scores by averaging the results of three test runs performed on each of the three individual test units. The data set resulting from the three test runs performed on each individual test unit shall meet the respective repeatability requirement found in Section 11.

A2.2.3 Compute $\bar{x}$ and *s* of the sample.

A2.2.4 Compute the value of *A* where *A* = 0.05 (*X*).

A2.2.5 Determine the statistic *t* for *n* – 1 df from Table A2.1, where *n* = the number of test units.

A2.2.6 Compute $ts/\sqrt{n}$ for the sample and compare it to the value to *A*.

A2.2.7 If the value of $ts/\sqrt{n} > A$, an additional unit from the population shall be selected and tested, and the computations of steps A2.2.2 – A2.2.6 repeated.

A2.2.8 If the value of $ts/\sqrt{n} < A$, the desired 90 % confidence level has been obtained. The value of the final $\bar{x}$ may be used as the best estimate of the air power rating for the population.

A2.3 *Example*—The following data is chosen to illustrate how the value of air power for the population of a vacuum cleaner model is derived. The measured test results from three test runs on each unit are required to have a repeatability limit not exceeding the value as indicated in Section 11.

A2.3.1 Select three test units from the vacuum cleaner model population. A minimum of three test runs shall be performed using each test unit.

A2.3.2 Test run scores for test unit No. 1:

Test Run No. 1 = 146.0
Test Run No. 2 = 136.5
Test Run No. 3 = 142.5

A2.3.3 Maximum spread = 146.0 – 136.5 = 9.5

$$\%\ \text{difference} = \text{maximum spread/maximum score} = \frac{9.5}{146.0} = 6.51\,\% \quad (A2.6)$$

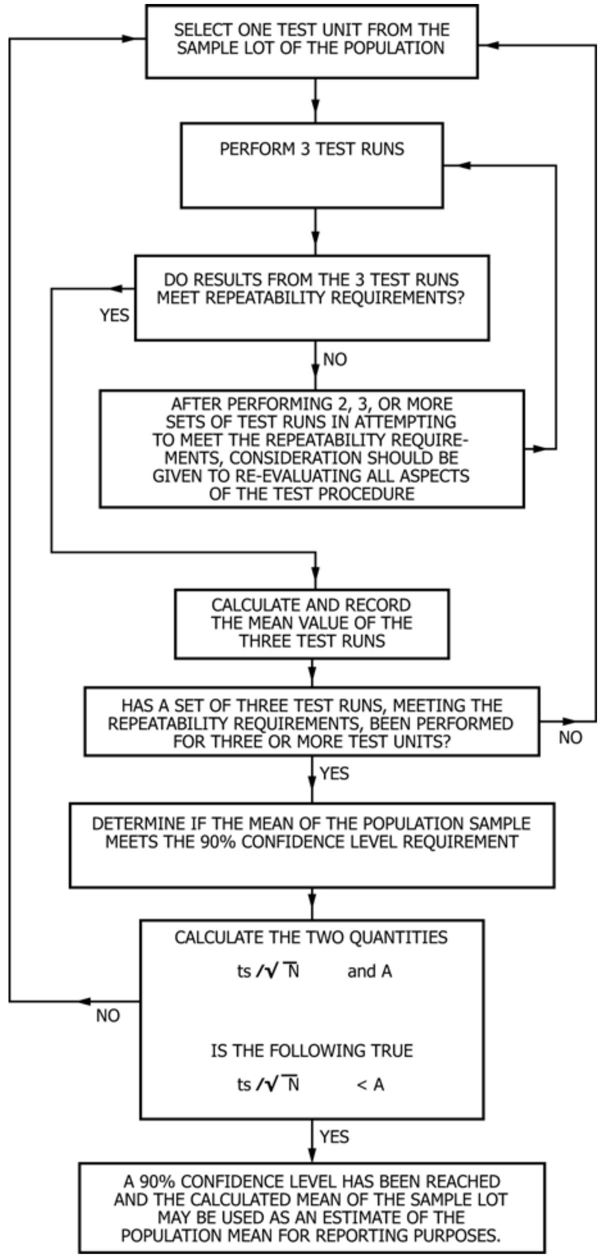


FIG. A2.1 Testing Procedure Flowchart

This value is greater than the repeatability limit required in Section 11. The results shall be discarded and three additional test runs performed.

A2.3.4 Test run scores for Test Unit No. 1:

Test Run No. 4 = 146.7
Test Run No. 5 = 146.0
Test Run No. 6 = 146.0

A2.3.5 Maximum spread = 146.7 – 146.0 = 0.7

$$\%\ \text{difference} = \text{maximum spread/maximum score} = \frac{0.7}{146.7} = 0.48\,\% \qquad (A2.7)$$

This value is less than the repeatability limit requirement of 11.1.

A2.3.6 Unit No. 1 score = (146.7 + 146.0 + 146.0)/3 = 146.2.

NOTE A2.2—If it is necessary to continue repeated test run sets (7, 8, 9 – 10, 11, 12, etc.) because the spread of data within a data set is not less than the repeatability limit requirement stated in Section 11, there may be a problem with the test equipment, the execution of the test procedure, or any of the other factors involved in the test procedure. Consideration should be given to reevaluating all aspects of the test procedure for the cause(s).

A2.3.7 A minimum of two additional test units must be tested, each meeting the repeatability limit requirement. For this procedural example, assume those units met the repeatability requirement and the individual unit scores are:

Score of Test Unit No. 1 = 146.2
Score of Test Unit No. 2 = 144.4
Score of Test Unit No. 3 = 153.4

A2.3.8 $\bar{x}$ = ⅓ (146.2 + 144.4 + 153.4) = 148.0

A2.3.9

$$s = \sqrt{\frac{3[(146.2)^2+(144.4)^2+(153.4)^2]-[146.2+144.4+153.4]^2}{3(3-1)}} \quad (A2.8)$$

where:

s = 4.76.

A2.3.10 A = 0.05 (148.0) = 7.40.

A2.3.11 Df, n – 1 = 3 – 1 = 2

$t_{0.95}$ statistic = 2.920.

A2.3.12 $ts/\sqrt{n} = 2.920\ (4.76)/\sqrt{3} = 8.03$.

A2.3.13 8.03 > 7.40. The requirement that $ts/\sqrt{n} < A$ has not been met because s is large; therefore, an additional test unit from the population shall be tested.

A2.3.14 Score of test unit No. 4 = 148.2.

A2.3.15 $\bar{x}$ = ¼ (146.2 + 144.4 + 153.4 + 148.2) = 148.0.

A2.3.16

$$s = \sqrt{\frac{4[(146.2)^2+(144.4)^2+(153.4)^2+(148.2)^2]-[146.2+144.4+153.4+148.2]^2}{4(4-1)}} \quad (A2.9)$$

$$s = 3.89$$

A2.3.17 A = 0.05 (148.1) = 7.4.

A2.3.18 Df, n – 1 = 4 – 1 = 3

$t_{0.95}$ statistic = 2.353.

A2.3.19 $ts/\sqrt{n} = 2.353\ (3.89)/\sqrt{4} = 4.58$.

A2.3.20 4.58 < 7.4 (meets requirements).

A2.3.21 Thus, the value of $\bar{x}$, 148.0, represents the air power score for the vacuum cleaner model tested and may be used as the best estimate of the air power rating for the population mean.

APPENDIXES

(Nonmandatory Information)

X1. DERIVATION OF DENSITY RATIO FORMULA

X1.1 Symbols

D_r = density ratio, which is the air density at time of test divided by the standard density, dimensionless.
R = gas constant = 1545/MW, ft/°R.
MW_a = molecular weight of dry air = 28.9644.
MW_v = molecular weight of water vapor = 18.016 or 0.622 MW_a.
V = specific volume of fluid = 1/[ρ], lb/ft^3.
ρ_{std} = standard air density = 0.075 lb/ft^3.
ρ_{test} = density of moisture-laden air, lb/ft^3.
ρ_a = density of dry air portion of moisture-laden air, lb/ft^3.
ρ_v = density of water vapor portion of moisture laden air, lb/ft^3.
ρ_m = density of mercury at 32°F = 848.713 lb/ft^3.
P = absolute pressure of gas, lb/ft^2.
b = absolute pressure of gas, inch of mercury.
B_t = test station pressure at time of test, inch of mercury.
T = absolute temperature, °R.
T_d = dry-bulb temperature, °F.
T_w = wet-bulb temperature, °F.
svp = saturated vapor pressure at wet-bulb temperature, inch of mercury.
e = partial vapor pressure at test condition, inch of mercury.

X1.2 Derivation

X1.2.1 See AMCA Standard 210–85.

$$PV = RT \text{ and } V = 1/\rho, \text{ therefore} \quad (X1.1)$$

$$P/\rho = RT \text{ or } \rho = P/RT$$

X1.2.2 Conversion of P to b:

$$P = \rho_m(b/12) = (848.713/12)b = 70.7261b \quad (X1.2)$$

X1.2.3 ρ_a Calculation:

$$R = \frac{1545}{MW_a} = \frac{1545}{28.9644} \quad (X1.3)$$

$$\rho_a = \frac{P}{RT} = \frac{70.7261b}{53.34(T_d + 459.7)}$$

$$b\ (\text{dry air portion}) = (B_t - e)$$

$$\rho_a = \frac{70.7261}{53.34} \times \frac{B_t - e}{(T_d + 459.7)}$$

X1.2.4 ρ_v calculation:

$$R = \frac{1545}{MW_v} = \frac{1545}{0.622(MW_a)} = \frac{53.34}{0.622} \quad (X1.4)$$

where:

b (water vapor portion) = e

$$\rho_v = \frac{70.7261}{53.34} \times \frac{0.622e}{(T_d + 459.7)} \quad (X1.5)$$

X1.2.5 ρ_{test} calculation:

$$\rho_{test} = \rho_a + \rho_v \quad (X1.6)$$

$$= \frac{70.7261}{53.34} \times \left(\frac{(B_t - e) + 0.622e}{T_d + 459.7} \right)$$

$$= \frac{1.32595\,(B_t - 0.378e)}{T_d + 459.7}$$

X1.2.6

$$D_r = \frac{\rho_{test}}{\rho_{std}} = \frac{\rho_{test}}{0.075} \quad (X1.7)$$

$$= \frac{17.68\,(B_t - 0.378\,e)}{T_d + 459.7}$$

X1.2.7

$$e = svp - \frac{B_t\,(T_d - T_w)}{2700}$$

.

X1.2.8 $svp = 2.959910\text{-}^4 T_w^2 - 1.5927 \cdot 10\text{-}^2 T_w + 4.102\,(10^{-1})$.

X1.2.9 Combining the equations in X1.2.5, X1.2.6, and X1.2.7:

$$D_r = [17.68\,B_t - 0.001978\,T_w^2 + 0.1064\,T_w \quad (X1.8)$$

$$+ 0.0024575\,B_t\,(T_d - T_w) - 2.741]/(T_d + 459.7)$$

X1.3 Error Analysis for Usable Range of svp Equation

X1.3.1 See error analysis for usable range in AMCA Standard 210–85.

X1.3.2 *Computation Methods for svp Comparison*—The svp equation is taken from AMCA Standard 210–85 and used in X1.2 versus svp value tabulations in Ref (**2**).

X1.3.3 *Analysis:*

X1.3.3.1 *Probability of Error in svp*—The plot of data shows very little error at 80°F (26.7°C) and below but increasingly larger error as T_w increases above 80°F.

X1.3.4 *Effect of svp Error on Calculation of E (X1.2.6)*—The worst error is when $T_d = T_w$ (that is, 100 % relative humidity). At that point the *"e"* error = *svp error*. Error in *"e"* reduces with decreasing humidity.

X1.3.5 *Effect of Error in svp on Calculation of D_r (X1.2.5):*

X1.3.5.1 The $B - 0.378e$ factor greatly reduces any error in *"e"* (or *svp*) since B is far greater in magnitude than $0.378e$.

X1.3.5.2 The worst-error case is with lowest *"B"* and highest *"e"*.

X1.3.6 *Conclusion:*

X1.3.6.1 The worst-error condition is with low barometric condition, high wet-bulb temperature, and 100 % relative humidity.

X1.3.6.2 If the D_r equation is restricted to minimum value of B = 27.00 in. of mercury absolute and maximum value of T_w = 100°F (37.8°C) then at the worst-case condition of 100 % relative humidity the D_r error = +0, –0.23 %.

X2. DERIVATION OF AIR FLOW FORMULA FROM ASME STANDARDS

X2.1 From Ref (**3**):

$$Q_1 = 0.099702 \frac{(CYd^2F_a)}{\left(\sqrt{1-\beta^4}\right)} \sqrt{\frac{h_s}{\rho_{std}}} \quad (X2.1)$$

Q_1 = flow rate at standard, air density and temperature, ft^3/s,
C = coefficient of discharge, dimensionless,
Y = expansion factor, dimensionless,
F_a = thermal expansion factor, dimensionless,
β = d/D, dimensionless,
d = orifice diameter, in.,
D = diameter of pipe upstream, in.,
h_s = differential pressure at standard conditions in. H_2O, and
ρ_{std} = air density at standard conditions, 0.075 lb/ft^3.

X2.1.1 This equation determines the rate of gas flow in a pipe system, and measured with a venturi tube, a flow nozzle, or an orifice plate measuring device mounted in the pipe.

X2.1.2 The equation from Ref (**3**), uses the symbol ρ, instead of ρ_{std} for the air density at standard conditions, q_1 instead of Q_1 for flow rate at standard air density and temperature, and h_s instead of h_w for differential pressure at standard conditions. The symbols ρ_1, q_1, and h_w were changed to ρ_{std}, Q_1 and h_s, respectively, as a matter of consistency within this standard and clarity ($\rho_1 = \rho_{std}$, $h_s = h_w$, $Q_1 = q_1$).

X2.2 Converting to ft^3/min flow rate, substituting 0.075 for the value of ρ_{std} substituting K for $CF_a/\sqrt{1-B^4}$ and simplifying:

$$Q = 21.844KYd^2\sqrt{h_s} \quad (X2.2)$$

where:

Q = flow rate at standard, air density and temperature, cfm,
K = orifice flow coefficient, dimensionless,
d = orifice diameter, in., and
h_s = differential pressure at standard conditions, water, in.

X2.3 The ASTM plenum chamber, as specified in Specification F431, is not a measuring device that uses a pipe. The flow from ambient into the sharp edged orifice plate is unrestricted and a plenum chamber is placed immediately, downstream of the orifice plate.

X2.3.1 Thus, the orifice flow coefficient, K, and the expansion factor, of X2.2, are different for the plenum chamber specified in Specification F431.

X2.3.2 For the plenum chamber specified in Specification F431, the combination of the orifice flow coefficient, K, and the expansion factor, Y, were empirically determined as a singular, orifice flow coefficient K_1.

X2.3.3 The value of K_1 will vary for each of the orifice plates identified in Section 9.

X2.4 Replacing K and Y in the equation of X2.2 with K_1 results in:

$$Q = 21.844\, K_1 d^2\sqrt{h_s} \quad (X2.3)$$

where:

Q = flow rate at standard, air density and temperature, cfm,
K_1 = orifice flow coefficient for the Specification F431 plenum chamber, dimensionless,
d = orifice diameter, in., and
h_s = differential pressure at standard conditions, water, in.

X2.4.1 This equation determines the rate of gas flow, in ft^3/min, through a thin-plate square-edged orifice, mounted in accordance with Specification F431.

X3. DERIVATION OF AIR POWER EQUATION

X3.1 Power is defined as the rate of doing work in a given period of time and can be expressed by the following general equation:

$$P = Fv \quad (X3.1)$$

where:

P = power,
F = force, and
v = velocity.

X3.2 Air power as defined in 3.1.1, is the net time rate of work performed by an air stream while expending energy to produce air flow by a vacuum cleaner under specified air resistance conditions, expressed in watts; therefore air power is:

$$AP = 745.7/33000\, Fv \quad (X3.2)$$

where:

AP = air power, W,
F = force generated by the air stream passing through the orifice, lb,
v = velocity, ft/min.

X3.2.1 The constant 745.7/33 000 is used to maintain the correct set of units:

$$1\text{ W} = \frac{33\,000}{745.7}\frac{\text{ft·lb}}{\text{min}} \quad (X3.3)$$

X3.3 For an air stream passing through a given orifice size:

X3.3.1 The force is given by the following equation:

$$F = \frac{1}{12}\, p\, h_s A \quad (X3.4)$$

where:

F = force generated by air stream passing through the orifice, lb,
p = density of water at (68°F), 62.3205 lb/ft^3,
h_s = differential pressure at standard conditions, water, in., and
A = cross sectional area of the orifice, ft^2.

X3.3.1.1 The constant 1⁄12 is used to maintain the correct set of units:

$$F\,(\text{lbs}) = \frac{1}{12}\frac{(\text{ft})}{(\text{in.})}\, p\, \frac{(\text{lb})}{(\text{ft}^3)}\, h_s\,(\text{in.})\; A\,(\text{ft}^2) \quad (X3.5)$$

X3.3.2 The velocity is given by the following equation:

$$V = Q/A \quad (X3.6)$$

where:

V = velocity of air stream passing through the orifice, ft/min,
Q = flow rate at standard, air density and temperature, cfm, and
A = cross sectional area of the orifice, ft^2.

X3.4 Substituting equations from X3.3.1 and X3.3.2 into the equation in X3.2, p = 62.3205 lb/ft^3, and simplifying as follows:

$$AP = 0.117354\, h_s Q \quad (X3.7)$$

where:

AP = air power, W,
h_s = differential pressure at standard conditions, inch of water, and
Q = flow rate at standard air density and temperature, cfm.

X3.4.1 This equation is used to calculate the air power in 9.3.

X4. STANDARD CONDITIONS

Dry-bulb temperature, T_b = 68°F.

Atmospheric pressure = 14.69595 psi.

Relative humidity (approximate) = 30 %.

Density of mercury at 32°F (Note X4.1), (ρ_{H_a}) = 848.71312 lb/ft^3.

Density of water at 68°F, (ρ_{water}) = 62.3205 lb/ft^3.

Density of air at 68°F, 30 % relative humidity, ρ_0 = 0.075 lb/ft^3.

Barometer reading, $B_0 = \rho_0/\rho H_g/(12)^3$ = 14.69595 (1728)/ 848.71312 = 29.9213 in. Hg at 32°F (Note X4.1).

Water column height = $\rho_0/\rho_{water}/(12)^3$ = 14.69595 (1728)/ 62.3205 = 407.4829 in. H_2O at 68°F.

To convert inches of mercury at 32°F to lbf/in.^{2}, multiply by 14.69595/29.921 = 0.491153 (use 0.4912).

To convert inches of water at 68°F to lbf/in.^{2}, multiply by 14.69595/407.4839 = 0.03606511 (use 0.03607).

NOTE X4.1—Mercury barometers are to be corrected to 32°F. See Kent's Mechanical Engineers Handbook.

All constants are from AMCA Standard 210–85 and Refs (**3**) and (**4**).

X5. MINIMUM AND MAXIMUM *h* VALUES BY ORIFICE SIZE

Orifice Diameter, in. (mm)	Manometer Reading, *h*, in. H_2O	
	min	max
0.250 (6.3)	0.1	109
0.375 (9.5)	0.1	100
0.500 (12.7)	0.1	91
0.625 (15.8)	0.1	81
0.750 (19)	0.1	72
0.875 (22.2)	0.1	63
1.000 (25.4)	0.1	55
1.250 (31.7)	0.1	40
1.500 (38.1)	0.1	26
2.000 (50.8)	0.1	11

X6. ALTERNATE EQUATIONS FOR FINDING ORIFICE FLOW COEFFICIENT

NOTE X6.1—These equations are the results of substituting the *r* equation into the Table 1 K_1 equations.

Orifice Diameter, in. (mm)	Flow Coefficient
0.250 (6.3)	$K_1 = \frac{0.020109h + 0.018665B_t}{0.03607h + 0.022988B_t}$
0.375 (9.5)	$K_1 = \frac{0.020029h + 0.009873B_t}{0.03607h + 0.012918B_t}$
0.500 (12.7)	$K_1 = \frac{0.0205382h + 0.004519B_t}{0.03607h + 0.00678B_t}$
0.625 (15.8)	$K_1 = \frac{0.020531h + 0.003684B_t}{0.03607h + 0.005108B_t}$
0.750 (19)	$K_1 = \frac{0.020614h + 0.004519B_t}{0.03607h + 0.006778B_t}$
0.875 (22.2)	$K_1 = \frac{0.020704h + 0.004961B_t}{0.03607h + 0.0077609B_t}$
1.000 (25.4)	$K_1 = \frac{0.020513h + 0.004813B_t}{0.03607h + 0.00717152B_t}$
1.125 (28.6)	$K_1 = \frac{0.020470h + 0.007073B_t}{0.03607h + 0.011052B_t}$

Orifice Diameter, in. (mm)	Flow Coefficient
1.250 (31.7)	$K_1 = \frac{0.020621h + 0.0004764B_t}{0.03607h + 0.007466B_t}$
1.375 (34.9)	$K_1 = \frac{0.020488h + 0.007172B_t}{0.03607h + 0.011543B_t}$
1.500 (38.1)	$K_1 = \frac{0.020628h + 0.004961B_t}{0.03607h + 0.008104B_t}$
1.750 (44.5)	$K_1 = \frac{0.020542h + 0.007073B_t}{0.03607h + 0.011543B_t}$
2.000 (50.8)	$K_1 = \frac{0.020765h + 0.004715B_t}{0.03607h + 0.0077118B_t}$
2.250 (57.2)	$K_1 = \frac{0.020592h + 0.008301B_t}{0.03607h + 0.013704B_t}$
2.500 (63.5)	$K_1 = \frac{0.020416h + 0.011907B_t}{0.03607h + 0.019648B_t}$

X7. EXAMPLE OF CALCULATING AIR POWER AT TWO DIFFERENT TEST LOCATIONS

TABLE X7.1

Orifice Diameter (in.)	Input Power, P_s (watts)	Suction, h_s (in. H_2O)	Airflow, Q (cfm)	Air Power, AP (air watts)
2.500	768	1.70	107.2	21.4
2.000	766	3.80	101.9	45.5
1.750	761	6.00	97.7	68.8
1.500	757	9.40	88.7	97.9
1.375	750	11.70	83.6	114.8
1.250	742	14.30	76.4	128.3
1.125	731	17.70	68.7	142.8
1.000	716	21.50	60.1	151.7
0.875	693	25.70	49.8	150.3
0.750	666	30.40	39.7	141.7
0.625	637	35.20	29.6	122.3
0.500	603	40.20	20.1	94.9
0.375	566	44.50	12.2	63.7
0.250	538	47.00	5.9	32.6
0.000	519	49.30	0.0	0.0

X7.1 This example shows the calculations of air density for two different test locations at two different elevations and the results of the maximum air power calculations.

X7.2 This example attempts to show the importance of using the test station pressure or absolute barometric pressure in the calculations of the air density instead of the equivalent mean sea level value of the absolute barometric pressure.

X7.2.1 Air density or the weight of the air per unit volume at a particular test location is influenced by the local weather conditions, the test locations height above sea level, the heating, cooling and ventilation system of the test facility, etc.

X7.2.1.1 In general, air density decreases as the elevation increases. The amount of the atmosphere above the test location decreases as elevation increases; thus, the weight of the air above the test location decreases resulting in a lower air density.

X7.2.1.2 Air density is affected by the amount of moisture within the air. Water vapor adds weight to the air.

X7.3 For this example, a vacuum cleaner having the following characteristics at standard air density conditions as described in 3.1.12 will be used in Table X7.1.

X7.3.1 The calculated maximum air power for this unit is 152 air watts.

X7.3.2 It will be assumed that this cleaner performs perfectly each time it is used, that is, no motor performance variations, the hose is laid out the exact same way for each test etc.

X7.4 Test Location 1: Low Elevation

X7.4.1 In Harrisburg, PA, an independent test laboratory located 355 ft above sea level measured the maximum air power of the vacuum cleaner described in X7.3 in accordance with Specification F558. At the test location and test time, the laboratory measured the test station pressure, B_t, the wet bulb temperature, T_w, and the dry bulb temperature, T_d. Their values were recorded as follows:

B_t = 29.10 in Hg
T_w = 61.0 °F
T_d = 70.0 °F

X7.4.1.1 The test station pressure, B_t, or absolute barometric pressure was measured with a mercury barometer. The actual reading of the barometer was adjusted for latitude and temperature according to the mercury barometers instruction manual.

X7.4.1.2 The test laboratory also recorded the equivalent mean sea level barometric pressure value. This value was obtained from their local airport. It was 29.50 in Hg and represented what the barometric pressure would be at 0-ft elevation not at the test laboratories elevation of 355 ft.

X7.5 The air density ratio, D_r, was computed using the values in X7.4 because these were the ambient conditions at the test location at the time of the test. D_r was calculated as follows:

$$D_r = \frac{17.68\,(29.10) - 0.001978\,(61.0)^2 + 0.1064\,(61.0) + 0.0024575\,(29.10)(70.0 - 61.0) - 2.741}{(70.0 + 459.7)}$$

$$D_r = 0.9657$$

X7.6 Using the value for D_r, the suction correction factor C_s, and the input power correction factor, C_p, were calculated as shown below:

$C_s = 1 + 0.667\,(1 - D_r)$ $\qquad C_p = 1 + 0.5\,(1 - D_r)$
$C_s = 1 + 0.667\,(1 - 0.9657)$ $\qquad C_p = 1 + 0.5\,(1 - 0.9657)$
$C_s = 1.0229$ $\qquad C_p = 1.0172$

X7.7 These correction factors were then used to compute the corrected suction, h_s, and the corrected input power P_s. In addition, the airflow and air watt values were calculated for each orifice plate. The results are shown in Table X7.2.

X7.7.1 The following calculations show an example of how the corrected suction, h_s, correct input power, P_s, airflow, Q, and the air power, AP, were computed for each orifice. In the calculations below, the 0.750-in. diameter orifice data was used.

X7.7.1.1 The corrected suction is calculated as follows:

$h_s = C_s h$
$h_s = (1.0229)(29.72)$
$h_s = 30.4003$

X7.7.1.2 The corrected input power was calculated as follows:

$P_s = C_p P$
$P_s = (1.0172)(655)$
$P_s = 666$

X7.7.1.3 The airflow for the 0.750-in. diameter orifice was calculated as follows:

$$Q = 21.844\,D^2\;K_1\sqrt{h_s} \qquad \text{(X7.1)}$$

$$K_1\;(\text{for } 0.750 - \text{in. orifice}) = \frac{0.5715r - 0.5807}{r - 1.0138}$$

$$r = \frac{B_t(0.4912) - h(0.03607)}{B_t(0.4912)}$$

TABLE X7.2

Orifice Diameter (in.)	Measured Data		Corrected Data (Data at Standard Conditions)			
	Input Power (watts)	Suction (in. H_2O)	Input Power, P_s (watts)	Suction, h_s (in. H_2O)	Airflow, Q (cfm)	Air Power, AP (air watts)
2.500	755	1.66	768	1.6980	107.1341	21.3483
2.000	753	3.71	766	3.7949	101.8055	45.3390
1.750	748	5.87	761	6.0044	97.7049	68.8465
1.500	744	9.19	757	9.4004	88.6998	97.8511
1.375	737	11.44	750	11.7019	83.6217	114.8346
1.250	729	13.98	742	14.3000	76.3714	128.1638
1.125	719	17.3	731	17.6960	68.8672	143.0164
1.000	704	21.02	716	21.5012	59.8448	151.0033
0.875	681	25.12	693	25.6950	49.7649	150.0619
0.750	655	29.72	666	30.4003	39.7197	141.7041
0.625	626	34.41	637	35.1977	29.6375	122.4203
0.500	593	39.3	603	40.1996	20.1266	94.9488
0.375	556	43.5	566	44.4958	12.2060	63.7367
0.250	529	45.95	538	47.0019	5.9030	32.5601
0.000	510	48.2	519	49.3034	0.0000	0.0000

where:

D = 0.750,
B_t = 29.10,
h = 29.95, and
h_s = 30.40

Solving for r:

$$r = \frac{29.10\,(0.4912) - 29.95\,(0.03607)}{29.10\,(0.4912)} = 0.9244 \qquad (X7.2)$$

Solving for K_1:

$$K_1 = \frac{0.5715\,(0.9244) - 0.5807}{(0.9244) - 1.0138} = 0.5862 \qquad (X7.3)$$

Solving for Q:

$$Q = 21.844\,(0.750)^2(0.5862)\sqrt{30.40} = 39.7197 \qquad (X7.4)$$

X7.7.1.4 For the air power the calculations are as follows:

$AP = 0.117354\ Qh_s$
$AP = 0.117354\ (39.7197)(30.4003)$
$AP = 141.7041$

X7.7.2 The calculations shown in X7.7.2 were made for each of the various orifice plates sizes used in the test.

X7.7.3 The maximum air power is calculated in accordance with the procedure outlined in Appendix X1 and found to be 152 air watts. This is in agreement with the vacuum cleaners characteristics described in X7.3.

X7.8 Had the independent laboratory incorrectly computed the maximum air power using the equivalent mean sea level value of barometric pressure (rather than absolute), the incorrectly calculated maximum air power would have been 150 air watts (based on incorrect air density ratio D_r = 0.9790; using B_t = 29.50, T_w = 61.0°F, and T_d = 71.0°F).

X7.8.1 Although the data was incorrect, the laboratory observed in their case that it does not make much difference in the results. This was due to the small difference between the test station pressure and the equivalent mean sea level value (the small difference was a result of the test laboratory only being 355 ft above mean sea level).

X7.8.2 It is also worth noting that had the test laboratory actually tested the vacuum cleaner under the 29.50 in Hg barometric pressure, the measured suction and input power values would have been slightly different for the vacuum cleaner.

X7.9 Test Location 2: High Elevation

X7.9.1 In El Paso, TX, an independent test laboratory located 3700 ft above sea level measured the maximum air power of the vacuum cleaner described in X7.3 in accordance with Specification F558.

X7.10 At the test location and test time, the laboratory measured the test station pressure, B_t, the wet bulb temperature, T_w, and the dry bulb temperature, T_d. Their values were recorded as follows:

B_t = 24.86 in Hg
T_w = 64.0°F
T_d = 80.0°F

X7.10.1 The test station pressure, B_t, or absolute barometric pressure was measured with an aneroid barometer. The actual reading of this particular aneroid barometer gave the absolute barometric pressure value and did not need any adjustments. It was noted in the instruction manual that this barometer had temperature compensation built into it.

X7.11 The test laboratory also recorded the equivalent mean sea level barometric pressure value. This value was obtained from a digital weather station within their laboratory that had been originally set up to report the mean sea level equivalent barometric pressure to coincide with local weather reports. The value was 28.64 in Hg and represented what the barometric pressure would be at 0-ft elevation not at the test laboratories elevation of 3700 ft.

TABLE X7.3

Orifice Diameter (in.)	Measured Data		Corrected Data (Data at Standard Conditions)			
	Input Power (watts)	Suction (in. H_2O)	Input Power, P_s (watts)	Suction, h_s (in. H_2O)	Airflow, Q (cfm)	Air Power, AP (air watts)
2.500	701	1.51	768	1.7026	107.2412	21.4281
2.000	699	3.37	766	3.7999	101.7847	45.3897
1.750	695	5.32	761	5.9987	97.5589	68.6790
1.500	691	8.34	757	9.4040	88.6285	97.8104
1.375	685	10.38	751	11.7043	83.5185	114.7164
1.250	677	12.68	742	14.2977	76.2585	127.9537
1.125	667	15.70	731	17.7030	68.7675	142.8659
1.000	654	19.07	717	21.5030	59.7434	150.7599
0.875	633	22.79	694	25.6976	49.7152	149.9267
0.750	608	26.96	666	30.3996	39.6695	141.5213
0.625	581	31.22	637	35.2031	29.5966	122.2699
0.500	550	35.65	603	40.1982	20.1050	94.8440
0.375	517	39.47	566	44.5056	12.1678	63.5515
0.250	491	41.68	538	46.9975	5.8739	32.3964
0.000	474	43.72	519	49.2978	0.0000	0.0000

X7.12 The air density ratio, D_r, was computed using the values in X7.10 as follows:

$$D_r = \frac{17.68(24.86) - 0.001978(64.0)^2 + 0.1064(64.0) + 0.0024575(24.86)(80.0 - 64.0) - 2.741}{(80.0 + 459.7)}$$

$$D_r = 0.8087$$

X7.13 Repeating the same calculation in X7.6 and X7.7 using the density ratio D_r from X7.12, the results are given in Table X7.3.

X7.13.1 The air power was calculated to be 152 air watts.

X7.14 Had the independent laboratory incorrectly computed the maximum air power using the equivalent mean sea level value of barometric pressure (rather than absolute), the incorrectly calculated maximum air power would have been 136 air watts (based on incorrect air density ratio $D_r = 0.9328$; using $B_t = 28.64$, $T_w = 64.0°F$, and $T_d = 80.0°F$).

X7.14.1 Seeing the difference, the independent test laboratory realized it was very important to use the correct test station barometric pressure to ensure that the data they would distribute would correlate with other test laboratories at different elevations operating under a different air density.

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