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FAN OUTLET FLOW RATE

INTRODUCTION

Question: Is the volumetric flow rate at the fan outlet the same as the volumetric flow rate at the fan inlet?

Answer: Sometimes.

This paper provides guidelines for determining when the volumetric flow rate at the fan outlet materially differs from the volumetric flow rate at the fan inlet and the recommended procedures for calculating the volumetric flow rate, density and temperature at the fan outlet, excluding fan shut-off conditions.

In its most authentic form, volumetric flow rate is expressed as the mass flow rate divided by the density of the air,

$$Q = \dot{m} \div \rho \qquad [1]$$

where:

Q = volumetric flow rate (acfm)

$\dot{m}$ = mass flow rate (lbm/min)

ρ = air density (lbm/cu ft)

Note: In this paper, ρ represents the density of air; in practice the density of any gas can be used.

For fans, both the volumetric and mass flow rates are defined by the air density at the fan inlet. The mass flow rate is constant between the fan inlet and outlet1, or $\dot{m}$fan-inlet = $\dot{m}$fan-outlet. This is not the case with the fan volumetric flow rate. The work performed by the fan causes a change in density between the fan inlet and outlet due to the change in absolute pressure and absolute temperature. As the fan compresses the air, there is a temperature rise due to the compression of the air and its increase in internal energy from the inefficiency of the fan. It follows then from Formula 1 above that the volumetric flow rate between the fan inlet and outlet will vary with the change in density, or Qfan-inlet ≠ Qfan-outlet. From this it is understood that the volumetric flow rate at the fan outlet is determined based on the fan mass flow rate and the change in density between the fan inlet and outlet.

GUIDELINES AND RECOMMENDED PROCEDURES

Two (2) approaches can be used to determine the fan outlet volumetric flow rate:

1) If the cumulative change in absolute pressure and absolute temperature between the fan inlet and outlet is less than 5%, correction to the volumetric flow rate, air density, and temperature at the fan outlet is minimal and at the user's discretion. In this case, the fan outlet volumetric flow rate, air density and temperature can be considered the same as that at the fan inlet i.e.,

$\dot{m}$ fan-inlet = $\dot{m}$ fan-outlet

Q fan-inlet = Q fan-outlet

ρ fan-inlet = ρ fan-outlet

T fan-inlet = T fan-outlet

2) If the cumulative change in absolute pressure and absolute temperature between the fan inlet and outlet is 5% or more, correction to the volumetric flow rate, air density and temperature at the fan outlet should be evaluated and corrected at the user's discretion. This can be done using either the *Exact Method* or *Approximate Method*:

a) *Exact Method:* This method requires a fan selection with a known fan total efficiency, inlet temperature, inlet air density, and fan inlet and outlet total pressures. This method calculates the fan outlet volumetric flow rate, air density, and temperature based on the change in absolute pressure across the fan and the polytropic and isentropic exponents. The process is adiabatic (no heat transfer) and polytropic.

b) *Approximate Method:* This method does not require a fan selection or a known fan efficiency but instead uses the air density, temperature, absolute total or static pressure at the fan inlet duct connection and the estimated absolute total or static pressure at the fan outlet duct connection. This method calculates the fan outlet volumetric flow rate and air density from the change in absolute pressure and absolute temperature between the fan inlet and outlet. A commonly accepted temperature rise between the fan inlet and outlet for this method is 0.5 °F per 1.0 ″wg change in absolute pressure[2] when using a fan total efficiency of 74%. This process is also adiabatic (no heat transfer) and polytropic.

The *Approximate Method* will normally be within 1-3% of the *Exact Method*.

Corrections to the fan outlet volumetric flow rate, air density, and temperature using the *Exact Method* or *Approximate Methods* are outlined below.

THE EXACT METHOD

When the fan total efficiency, inlet temperature, air density at the fan inlet, and total pressures at the fan inlet and outlet are known, the highest degree of accuracy is correction to the fan outlet volumetric flow rate using the change in absolute total pressure between the fan inlet and outlet and the polytropic exponent of the thermodynamic process through the fan.

The polytropic exponent is calculated from the fan total or polytropic efficiency and the isentropic exponent (the gas specific heat ratio for an isentropic process). The temperature rise between the fan inlet and outlet is calculated using the absolute temperature at the fan inlet, the fan total pressures, the fan total or polytropic efficiency, and the isentropic exponent.

Fan Outlet Volumetric Flow Rate

The fan outlet volumetric flow rate is calculated using Formula 2[3],

$$Q_2 = Q_1 \left(\frac{P_2}{P_1}\right)^{-\frac{1}{n}} \qquad [2]$$

where:

Q_2	=	Fan outlet volumetric flow rate (acfm)
Q_1	=	Fan inlet volumetric flow rate (acfm)
P_2	=	Total pressure, fan outlet, absolute (in.wg)
P_1	=	Total pressure, fan inlet, absolute (in.wg)
P_a	=	Absolute pressure, 407 ″wg
n	=	Polytropic exponent
η_t	=	Fan total efficiency (when >30%)
γ	=	Isentropic exponent for air, 1.4 (specific heat ratio of an air or gas, C_p/C_v)

Example: The Exact Method

For a given fan selection,

Q_1	=	14,000 acfm
SP_1	=	- 20 ″wg fan inlet static pressure
VP_1	=	+0.43 ″wg fan inlet velocity pressure
P_1	=	387.4 ″wg fan inlet absolute total pressure
T_1	=	380°F, fan inlet temperature
ρ_1	=	0.0414 lbm/cu ft, air density, fan inlet
SP_2	=	+1 ″wg fan outlet static pressure
VP_2	=	+0.97 ″wg fan outlet velocity pressure
P_2	=	409.0 ″wg fan outlet absolute total pressure
ω	=	0.05 lb water/lb dry air, airstream moisture
z	=	1,400 ft asl, elevation
$\dot{m}$	=	579.6 lbm/min, mass flow rate
η_t	=	82.1%, fan total efficiency
γ	=	Isentropic exponent for air, 1.4
n	=	Polytropic exponent

First, the polytropic exponent must be calculated using Formula 3[4],

$$n = \frac{\eta_t \left(\frac{\gamma}{\gamma - 1}\right)}{\eta_t \left(\frac{\gamma}{\gamma - 1}\right) - 1} \qquad [3]$$

$$n = \frac{0.821\left(\frac{1.4}{1.4-1}\right)}{0.821\left(\frac{1.4}{1.4-1}\right) - 1}$$

and so,

$n = 1.534$

Then, the fan outlet volumetric flow rate can be calculated using Formula 2,

$$Q_2 = Q_1 \left(\frac{P_2}{P_1}\right)^{-\frac{1}{n}}$$

$$Q_2 = 14{,}000 \left(\frac{409.0}{387.4}\right)^{-\frac{1}{1.534}}$$

and so,

$Q_2 = 13{,}513$ acfm

Finally, the fan outlet air density, ρ_2, can be calculated using Formula 1,

Since $Q = \dot{m} \div \rho$, then
$\rho = \dot{m} \div Q$, and
$\rho_2 = 579.6 \div 13{,}513$ and
$\rho_2 = 0.0429$ lbm/cu ft

Fan Outlet Temperature

The fan outlet temperature T_2 is calculated using Formula 4 where T is absolute, °R,

$$T_2 = T_1 + \frac{T_1}{\eta_t}\left[\left(\frac{P_2}{P_1}\right)^{\left(\frac{\gamma-1}{\gamma}\right)} - 1\right] \qquad [4]$$

$$T_2 = 840 + \frac{840}{0.821}\left[\left(\frac{409}{387.4}\right)^{\left(\frac{1.4-1}{1.4}\right)} - 1\right]$$

and so,

$T_2 = 856$°R, or 396°F

Summary – The Exact Method

Using the *Exact Method*, the volumetric flow rate, air density, and temperature at the fan inlet and outlet are:

Fan Inlet

Q_1	=	14,000 acfm
ρ_1	=	0.0414 lbm/cu ft
T_1	=	380°F

Fan Outlet

Q_2	=	13,513 acfm
ρ_2	=	0.0429 lbm/cu ft
T_2	=	396°F

THE APPROXIMATE METHOD

The Approximate Method requires knowing the air density, temperature and total or static pressure at the fan inlet duct and the estimated total or static pressure and temperature at the fan outlet duct.

The Approximate Method is a simple and practical approach for the system designer, particularly prior to fan selection. It corrects the fan outlet volumetric flow rate, air density, and temperature by either of the following methods:

a) The fan outlet volumetric flow rate can be calculated by multiplying the fan inlet volumetric flow rate by the ratio of the absolute pressure at the fan inlet to the fan outlet and the ratio of the absolute temperature at the fan outlet to the fan inlet:

$$Q_2 = (Q_1)\,(P_1/P_2)\,(T_2/T_1) \qquad [5]$$

where:

Q_2	=	Fan outlet volumetric flow rate (acfm)
Q_1	=	Fan inlet volumetric flow rate (acfm)
P_2	=	Static or Total pressure, fan outlet, absolute (in.wg)
P_1	=	Static or Total pressure, fan inlet, absolute (in.wg)
T_1	=	Temperature, fan inlet, absolute (°R)
T_2	=	Temperature, fan outlet, absolute (°R)
P_a	=	Absolute pressure, 407 ″wg

b) The fan outlet volumetric flow rate can also be calculated by dividing the mass flow rate by the air density at the fan outlet. The density at the fan outlet is calculated by multiplying the density at the fan inlet by the ratio of the absolute pressure from the fan outlet to the fan inlet and the ratio of the absolute temperature from the fan inlet to the fan outlet:

$$Q_2 = \dot{m} \div [(\rho_1)\,(P_2/P_1)\,(T_1/T_2)] \qquad [6]$$

where:

Q_2	=	Fan outlet volumetric flow rate (acfm)
$\dot{m}$	=	Mass flow rate, fan inlet (lb/min)
ρ_1	=	Air density, fan inlet (lbm/cu ft)
P_2	=	Static or Total pressure, fan outlet, absolute (in. wg)
P_1	=	Static or Total pressure, fan inlet, absolute (in. wg)
T_1	=	Temperature, fan inlet, absolute (°R)
T_2	=	Temperature, fan outlet, absolute (°R)
P_a	=	Absolute pressure, 407 ″wg

Notes: For the *Approximate Method*, a commonly accepted temperature rise between the fan inlet and outlet is 0.5 ºF for each 1.0 ″wg pressure when using a 74% fan total efficiency[2].

Recommended practice is to use absolute total pressure for all calculations. However, if the designer is working on a static pressure basis, then the absolute static pressure values at the fan inlet and outlet duct connections can be used with an acceptable level of deviation.

Example: The Approximate Method

Using the data from the Exact Method and a 26″ diameter duct at the fan inlet and outlet connections, then for Formulas 5 and 6,

Q_1	=	14,000 acfm
SP_1	=	- 20 ″wg static pressure at the fan inlet duct
VP_1	=	+0.50 ″wg velocity pressure at the fan inlet duct
P_1	=	387.5 ″wg absolute total pressure at the fan inlet duct
T_1	=	380°F, temperature at the fan inlet duct
ρ_1	=	0.0414 lbm/cu ft, air density at the fan inlet duct
SP_2	=	+1 ″wg static pressure at the fan outlet duct
VP_2	=	+0.50 ″wg velocity pressure at the fan outlet duct
P_2	=	408.5 ″wg absolute total pressure at the fan outlet duct
T_2	=	390.5°F, temperature at the fan outlet duct
ω	=	0.05 lb water/lb dry air, airstream moisture
z	=	1,400 ft asl, elevation
$\dot{m}$	=	579.6 lbm/min, mass flow rate

Using Formula [5]

$$Q_2 = (Q_1)\,(P_1/P_2)\,(T_2/T_1)$$
$$Q_2 = (14{,}000)\,(387.5/408.5)\,(850.5/840)$$
$$Q_2 = 13{,}446 \text{ acfm}$$

or, if using absolute static pressure instead of absolute total pressure

$$Q_2 = (14{,}000)\,(387/408)\,(850.5/840)$$
$$Q_2 = 13{,}445 \text{ acfm}$$

Using Formula [6]

$$Q_2 = \dot{m} \div [(\rho_1)\,(P_2/P_1)\,(T_1/T_2)]$$
$$Q_2 = 579.6 \div [(0.0414)\,(408.5/387.5)\,(840/850.5)]$$
$$Q_2 = 13{,}446 \text{ acfm}$$

or, if using absolute static pressure instead of absolute total pressure

$$Q_2 = 579.6 \div [(0.0414)\,(408/387)\,(840/850.5)]$$
$$Q_2 = 13{,}445 \text{ acfm}$$

Using Formula [1]

$$\rho_2 = \dot{m} \div Q_2$$
$$\rho_2 = 579.6 \div 13{,}446$$
$$\rho_2 = 0.0431 \text{ lbm/cu ft}$$

Summary – The Approximate Method

Using the *Approximate Method*, the volumetric flow rate, density, and temperature at the fan inlet and outlet are:

Fan Inlet

Q_1	=	14,000 acfm
ρ_1	=	0.0414 lbm/cu ft
T_1	=	380°F

Fan Outlet

Q_2	=	13,446 acfm
ρ_2	=	0.0431 lbm/cu ft
T_2	=	390.5°F

CONCLUSIONS

For the same inlet conditions, comparisons using the *Exact Method* and the *Approximate Method* are:

Fan Inlet

Q_1	=	14,000 acfm
ρ_1	=	0.0414 lbm/cu ft
T_1	=	380°F

The Exact Method

Q_2	=	13,513 acfm
ρ_2	=	0.0429 lbm/cu ft
T_2	=	396°F

The Approximate Method

Q_2	=	13,446 acfm
ρ_2	=	0.0431 lbm/cu ft
T_2	=	390.5°F

While the mass flow rate between the fan inlet and outlet is constant, the volumetric flow rate, density and temperature are not. Corrections are made at the user's discretion.

The *Exact Method* uses known data from a selected fan, absolute total pressures and the polytropic and isentropic exponents to calculate the fan outlet volumetric flow rate, air density and temperature, while the *Approximate Method* uses the air density and temperature at the fan inlet duct, and either the absolute total or static pressure at the fan inlet and outlet duct connections and an estimated fan outlet temperature for the same calculations.

The principal difference between the *Approximate Method* from the *Exact Method* is the effect of the temperature rise due to both the compression of the air and an increase in (fan) internal energy resulting from the inefficiency of the fan during compression. From the comparisons above, while either method is suitable for typical system design calculations, the *Exact Method* is recommended for high capacity, critical process system design.

REFERENCES

[1] Air Movement and Control Association International; Laboratory Methods of Testing Fans for Certified Aerodynamic Performance Rating, AMSI/AMCA Standard 210-16, ASHRAE Standard 51-16, Appendix E.4.2

[2] Howden Buffalo, Inc.; Fan Engineering, An Engineer's Handbook on Fans and Their Applications, 9th Edition, Chapter 2,

[3] Air Movement and Control Association International; Laboratory Methods of Testing Fans for Certified Aerodynamic Performance Rating, AMSI/AMCA Standard 210-16, ASHRAE Standard 51-16, Appendix D, Eq.D.2

[4] Air Movement and Control Association International; Laboratory Methods of Testing Fans for Certified Aerodynamic Performance Rating, AMSI/AMCA Standard 210-16, ASHRAE Standard 51-16, Appendix D, Eq.D.10

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