# Fireplace Operation Depends Upon Good Chimney Design

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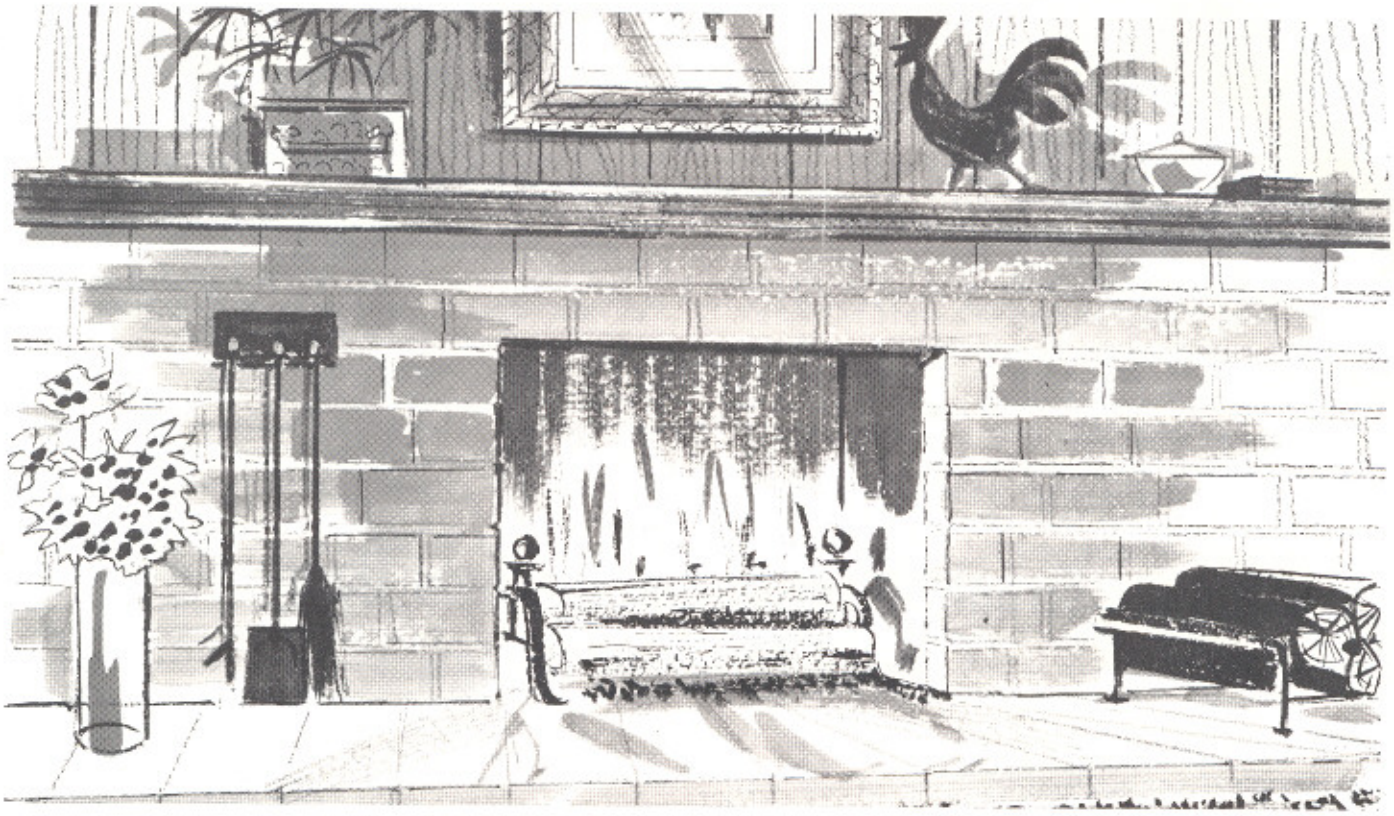

# Fireplace Operation Depends Upon Good Chimney Design

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FIREPLACES, with natural draft chimneys, obey the same gravity fluid flow law as gas vents and thermal flow ventilation systems. Mass flow of hot flue gases up to some limiting value is induced in a vertical pipe as a function of rate of heat release, and is regulated by chimney area, height, and system pressure loss coefficient. A fireplace may be treated analytically as an inlet fitting having a characteristic entrance loss coefficient, and an internal heat source. This same concept applies equally to draft hoods in gas vents, or to ventilation hoods exhausting fumes from some hot process, where a gas combustion reaction or other source delivers hot gases with negligible inlet velocity to a collector hood, and thence to a duct system.

Proper functioning of these various systems requires that all gases generated by combustion or other heat source, be captured and carried out through the gravity chimney or vent system. Control of smoking (or prevention of draft hood spillage) is achieved by producing adequate intake or face velocity across those critical portions of the hood in order to nullify effects of external drafts or internal convection effects.

In a fireplace-chimney system, the equations assume that all potential buoyant energy is converted into flow as controlled by various losses. This system is analogous to a gas venting system having a draft hood, thereby allowing use of similar concepts as a starting point for size or capacity analysis. The amount of available draft ahead of the fireplace opening is insignificant and need not be considered. Since chimney efficiency, by one possible definition, equals available draft divided by theoretical draft, the numerical efficiency value approaches zero. Thus the flow conversion basis is preferable for design over the efficiency approach.

System parameters for prevention of gas spillage from a draft hood or similar collection fitting can be computed with considerable certainty when heat input is constant, or cannot exceed a predictable limiting value. Fireplaces, however, can be fired at extremes ranging from smouldering embers, to flash fires of newspapers or dry kindling. Normal opening width and length allows for greater access of combustion air to the fires than a typical chimney can carry away; thus combustion overloading occasionally leads to some smoking. At low rates of combustion, flow velocities into the fireplace face are less than the velocity of those natural convection currents which are induced at side walls by heat stored in the brick, and carry wisps of smoke away from the main flow path. Smoking tendencies are compounded at low firing rates by indoor-outdoor pressure differentials, due to winds, thermal forces, or fans, since accompanying thermal force of low chimney gas temperature is insufficient to overcome strong wind or fan effects.

From the analysis to follow, note that fireplaces are primarily air collecting hoods, diluting a small amount of combustion products with large amounts of air. Maxi-

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mum mass flow of air into any given fireplace chimney not only is limited, but actually diminishes past a certain maximum. Thus as combustion rate increases, chimney gas temperatures rise to the point where masonry cracks, metals overexpand, warp and oxidize, and steady smoking can occur because heated gases are being evolved beyond the limited capacity of the chimney.

An inoperative fireplace is completely at the mercy of indoor-outdoor pressure differences caused by winds, building stack effects, and from operation of forced air heating systems or mechanical ventilation. Thus, the complaint of smoking during start-up can have complex causes seldom related to the chimney. Increasingly in new homes and especially in high-rise multiple family construction, fireplaces of normal design cannot cope with mechanically induced reverse flow or shortages of combustion air. It is mandatory in such circumstances to treat and design a fireplace as a constantly operating mechanical exhaust system, with induced draft blowers of sufficient capability to overpower other mechanized air consuming systems, and to develop sufficient flow to avoid smoking and excessive flue temperatures.

The gravity flow capacity equation[1] of a fireplace chimney system equates mass flow with the resultant system driving forces and losses.

$$w = A_c \left( \frac{2gL\,H}{k} \right)^{1/2} \left[ \rho_m \; (\rho_o - \rho_m) \right]^{1/2} \qquad (1)$$

where

$w$ = flue gas flow rate, lbs/sec
$A_c$ = chimney flue cross-sectional area, sq ft
$gL$ = gravitational constant, 32.2 ft/sec/sec
$H$ = height of chimney above lintel, ft
$k$ = system equivalent resistance coefficient, dimensionless
$\rho_m$ = flue gas density at mean temperature, lbs/cu ft
$\rho_o$ = air density of ambient temperature, lbs/cu ft

From Eq (1) it is possible to develop a relationship for average frontal velocity, maximum chimney capacity, and variation of gas temperature with input.

The use of resistance coefficients in these compact systems is preferable to the usual method of equivalent lengths. The summation term k in a vertical chimney is the total of the following four individual resistance factors.

1. Acceleration of ambient air to flue gas velocity ($k_a$) a constant value which must always be included in the total. $k_a = 1.0$

2. Inlet loss ($k_i$) coefficient for fireplace configuration including smokeshelf.

| | |
|---|---|
| Cone type fireplaces | $k_i = 0.5$ |
| Masonry (damper throat = 2X flue area) | $k_i = 1.0$ |
| Masonry (damper throat = flue area) | $k_i = 2.5$ |

3. Chimney flue pipe friction ($k_c$) at a typical Reynolds No. 10,000 and roughness of .001, where $R_h$ = hydraulic radius, ft

$$k_c = .0083 \frac{H}{R_h}$$

4. Termination coefficient ($k_t$)

| | |
|---|---|
| For open top, pipe or tile, same size as chimney | $k_t = 0$ |
| Disk or cone cap at D/2 above outlet | $k_t = .5$ |
| Manufactured caps | $k_t = 0$ to 4.0 |

For a 12-ft high open top chimney, 12 in. in diameter on a typical fireplace, the system resistance,

| | |
|---|---|
| $k_a =$ | 1.0 |
| $k_i =$ | 2.5 |
| $k_c = .0083 \frac{12}{.25}$ | 0.4 |
| $k_t =$ | 0.0 |
| $k =$ | 3.9 summation |

Observe that in a short chimney, the wall friction coefficient, $k_c$, is only 0.4 and has a minor effect on system flow. Greater or lesser chimney roughness, or a change from low to high heat loss materials will have little bearing on fireplace effectiveness in short chimneys. In some situations, it may be necessary for completeness to include a k term for air supply resistance.

To determine frontal velocity $V_F$ of ambient air, the term w will be replaced using the substitution:

$$w = \rho_o A_F V_F \qquad (2)$$

where

$A_F$ = fireplace frontal opening area, sq ft
$V_F$ = fireplace mean frontal velocity, ft/sec

accordingly, then mean frontal velocity $V_F$ becomes:

$$V_F = \frac{A_c}{A_F} \left( \frac{2gL\,H}{k} \right)^{1/2} \left[ \frac{\rho_m}{\rho_o} \frac{(\rho_o - \rho_m)}{\rho_o} \right]^{1/2} \qquad (3)$$

For present purposes, the molecular weight or specific gravity of dilute chimney gases is practically the same as that of air, and both can be expressed with adequate accuracy in terms of absolute gas temperature by the same relationship:

$$\rho_o = 1.325 \frac{B_o}{T_o} \qquad (4)$$

$$\rho_m = 1.325 \frac{B_o}{T_m} \qquad (5)$$

where

$B_o$ = existing barometric pressure, in. of mercury
$T_o$ = ambient temperature, F absolute
$T_m$ = mean chimney gas temperature, F absolute

The substitution of the density-temperature relationships, Eqs (4) and (5), into Eq (3) permits further simplification leading to the general frontal velocity expression:

$$V_F = \frac{A_c}{A_F} \left( \frac{2gL\,H}{k} \right)^{1/2} \frac{[T_o\,(T_m - T_o)]^{1/2}}{T_m} \qquad (6)$$

Here, frontal velocity is a function of the product of three terms.

a. The dimensionless area ratio $\frac{A_c}{A_F}$

b. The height-resistance term: $\left[ \frac{2gL\,H}{k} \right]^{1/2}$

c. The dimensionless temperature effects:

$$\frac{[T_o\,(T_m - T_o)]^{1/2}}{T_m}$$

For the 12-ft high chimney previously referred to, assume ambient temperature (for calculation purposes) is 70 F, or $T_o = 530$ F indoors and outdoors, with no air supply resistance. Eq (6) expresses variation in $V_F$ with gas temperature as shown in Fig. 1. Assume also $A_c/A_F = 0.10$, so that frontal opening is ten times chimney area.

Regardless of system resistance coefficient, mean flow velocity into a fireplace frontal opening is practically constant from 300 deg F gas temperature rise up to any higher temperature. Local velocities vary within the opening, depending upon its design, since initially the path of air is horizontal along the hearth, into the fire, then upward clinging to the back wall, as in Fig. 2. A tendency exists for a recirculating eddy to form just inside the upper front half of the opening, induced by the high velocity of flow along the back which transfers momentum to a slow moving mixture of air and smoke. Restrictions or poor construction in the throat area between lintel and damper also increase the tendency to eddy. Since the eddy moves smoke away from the zone of maximum velocity, its tendency to escape must be counteracted by some minimum air movement inward over the entire front of the fireplace, but particularly under the lintel.

Construction of a fireplace, its internal configuration, damper location, height and location of lintel, slope of back and sides, etc. all have some bearing on minimum frontal velocity to achieve freedom from smoking with ordinary fires. It seems desirable to maintain a smooth gradual tapering transition between hearth or flame region up into the damper location. A sudden transition induces velocity components which tend to increase eddying unless such transition is located well above the lintel. With a shallow chamber between lintel and damper zone there is insufficient volume for convection currents, and some gases may be diverted horizontally before being captured by the main flow. Masons following the dimensional parameters recommended in Architectural Graphic Standards,[2] or in damper literature can avoid these design flaws. In the case of pre-fabricated units, many of which tend to be unconventional, careful testing is essential to assure safe smoke-free performance at minimum chimney height.

From observation, a minimum mean frontal inlet velocity of 0.8 ft/sec seems to control smoking adequately in a well constructed conventional masonry fireplace. As noted in Fig. 1, this velocity can be achieved even in low chimneys by system resistance of 2.9 or less, in conjunction with rates of combustion producing gas temperatures above a certain miminum level.

Fig. 1 is particularly significant in establishing why increases in gas temeprature above 300 F have no perceptible effect on fireplace smoking, since mass flow and face velocity actually decrease above temperature rises of 500 F. For practical purposes, then, chimney gas temperature has little influence on fireplace performance, providing temperature is at least 300 F above ambient. Fireplace performance analysis thus can be continued assuming a constant temperature term corresponding to 500 deg F rise above ambient:

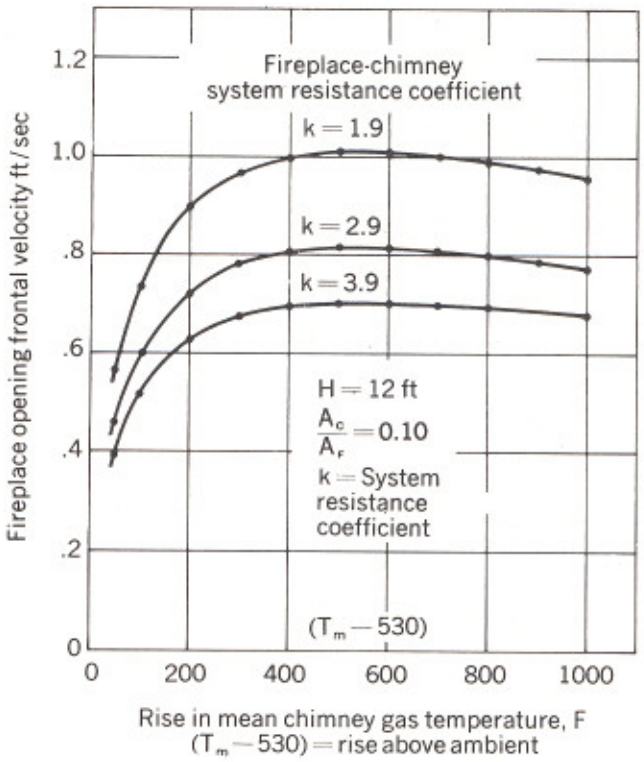


*Fig. 1 Effect of chimney gas temperature on fireplace frontal opening velocity*

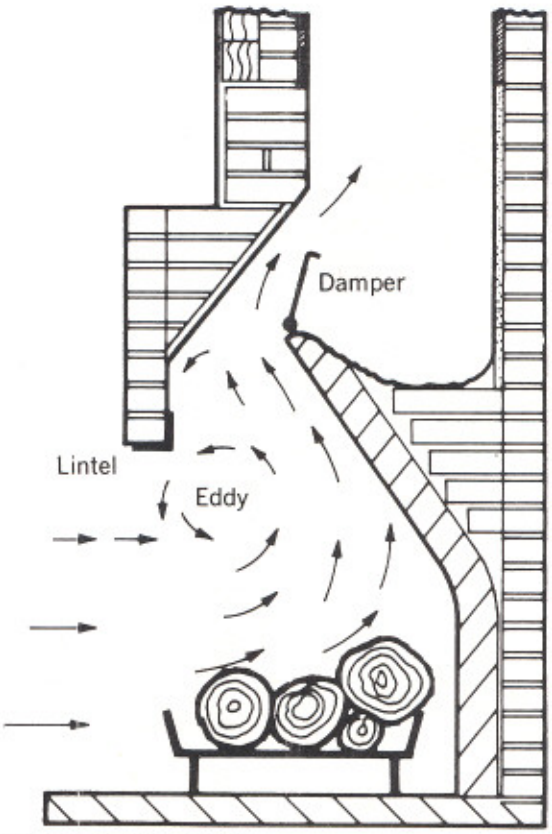


*Fig. 2 Eddy formation*

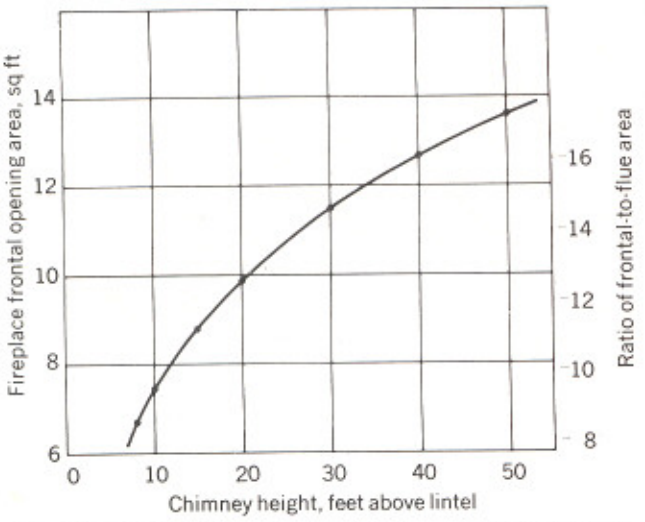


*Fig. 3 Permissible fireplace frontal opening area for design conditions: 0.8 ft/sec mean frontal velocity with a 12-in. inside diameter round flue*

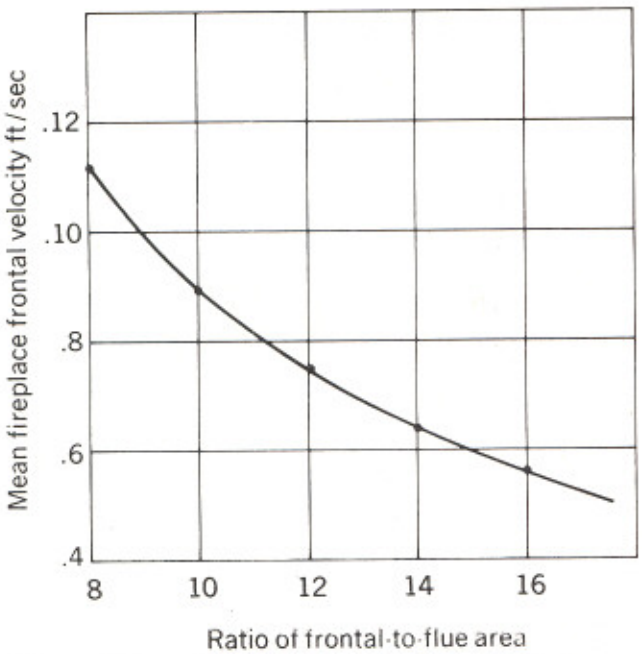


*Fig. 4 Effect of area ratio on frontal velocity for constant chimney height of 15 ft with a 12-in. inside diameter round flue*

$$\frac{[T_o\,(T_m - T_o)]^{1/2}}{T_m} = 0.5 \quad @ \quad T_m = 1030\ F, \quad T_o = 530\ F$$

Assuming further the usual 70 F ambient ($T_o$ = 530 F absolute), and factoring out 2gL, Eq (6) becomes roughly:

$$V_F = 4.0\,\frac{A_c}{A_F}\left(\frac{H}{k}\right)^{1/2} \tag{7}$$

This expression states that relative fireplace performance is purely a matter of geometry. It permits evaluation of the opening size to maintain minimum frontal velocity as a function of height, while permitting quick analysis of effect of frontal area on velocity.

Fig. 3 shows that 0.8 ft/sec face velocity requires a relatively small area ratio at 8 ft of height, while the fireplace can be twice as large with a 40-ft high chimney. To compute this curve, system resistance is assumed as:

$$k = 2.5 + .033\ H/D$$
$$D = 1.0\ \text{ft diameter}$$

This expression of resistance assumes fully open free area of the damper throat to be twice chimney flue area.

A corollary application of Eq (7) assumes constant chimney size and height, and explores variation in frontal velocity with area ratio. Fig. 4 shows that a 12-in. diameter 15-ft high chimney cannot produce adequate velocities for frontal area ratios greater than 11. These curves point out the possibility of further simplification to yield a fireplace-chimney design equation for a constant face velocity of 0.8 ft/sec.

$$A_F = 5.0\ A_c\ \left(\frac{H}{k}\right)^{1/2} \tag{8}$$

This permits determination of permissible frontal area $A_F$ as a function of chimney area, height, and system resistance. It can also be used to determine $A_c$ if $A_F$ is known. However, in this latter case Eqs (9) and (10) are preferable, since chimney size appears twice in the right hand side:

For circular flues

$$A_F = 3.93\ D_c^2\ \left(\frac{H}{2.5 + .033\ H/D_c}\right)^{1/2} \tag{9}$$

For other shapes

$$A_F = 5A_c\left(\frac{H}{2.5 + .0083\ H/R_h}\right)^{1/2} \tag{10}$$

where

$D_c$ = chimney diameter, ft

Face velocity is 0.8 ft/sec at maximum mass flow

Damper opening free area is twice chimney flue area

These relationships clearly reveal the origin of rules of thumb specifying opening area as 8, 10, or 12 times chimney area. Some design guides go beyond and classify chimneys by height groups so that short ones serve smaller fireplace openings. Use of a mean face velocity of 0.8 ft/sec yields ratios and heights which fall well

within the limits of such rules, as well as providing a unifying concept for computing design charts.

The foregoing relationships are descriptive primarily of masonry single face fireplaces of conventional construction, but are applicable to other types with considerable validity providing that face or opening area is properly treated. Corner or double face designs, and many free standing types such as "Franklin Stoves" embody conventional smokeshelf construction with similar resistance coefficients.

The preceding equations can be applied to illustrate the effect of excessive firing rates on chimney gas temperature. Masonry fireplaces are highly inefficient as heating devices and observation shows that over a wide range of controlled inputs obtained using a drilled port non-aerated gas burner, 75 to 80% of the gross heating value goes up the chimney. With constant flue loss of 30%, 70% of the heat loss is sensible heat contributing to rise in flue gas temperature. This heat input-temperature relationship may be developed by expressing the system flow relationship in terms of heat input:

$$w = \frac{q}{c_p\,(T_m - T_o)} \qquad (11)$$

where

$q$ = heat content of chimney gases, Btu/sec
$c_p$ = specific heat of chimney gases (assumed to be approximately 0.25 Btu/lb, F)

Equating Eqs (11) and (1), and eliminating w:

$$\frac{q}{c_p\,(T_m - T_o)} = A_c \left(\frac{2gL\,H}{k}\right)^{1/2} \left[\rho_m\,(\rho_o - \rho_m)\right]^{1/2} \qquad (12)$$

Substituting Eqs (4) and (5) for density and solving for q

$$q = \frac{1.325\,B_o\,A_c\,c_p}{(T_o)^{.5}} \left(\frac{2gL\,H}{k}\right)^{1/2} \frac{(T_m - T_o)^{1.5}}{T_m} \qquad (13)$$

For any given system, all terms except $(T_m - T_o)^{1.5}/T_m$ may be considered constant; therefore gas temperature rise for a fireplace can be obtained as a concise function of heat input:

$$q = \overline{C}\,\frac{(T_m - T_o)^{1.5}}{T_m} \qquad (14)$$

where

$\overline{C}$ is a constant

The flow-temperature function of a carefully controlled experimental fireplace [Eqs (13) or (14)] which indicates the constancy of $\overline{C}$, is plotted in Fig. 5 as chimney gas temperature vs heat content. Data taken on a fireplace chimney combination in this manner may readily be evaluated to determine system resistance coefficient k.

Eq (9) is readily applied to computation of a fireplace and chimney sizing grid chart, Fig. 6, for the specific conditions of circular flues at 0.8 ft/sec frontal velocity. The chart solves readily for maximum frontal opening for a given chimney as well as for chimney size and height with a predetermined opening. For other face

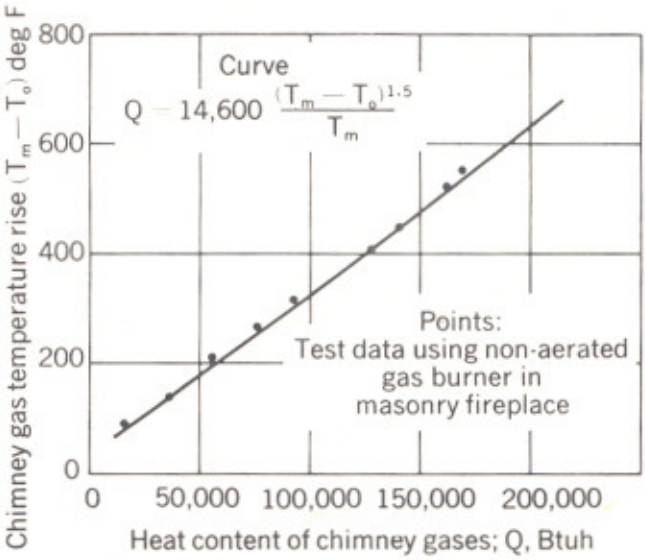


*Fig. 5 Variation of chimney gas temperature with heat content of flue products*

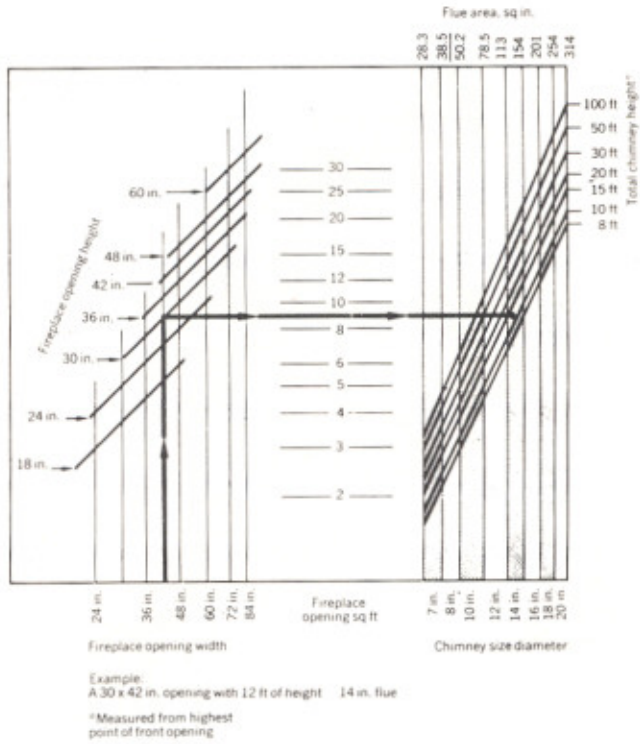


*Fig. 6 Fireplace sizing chart for circular chimneys; mean face velocity = 0.8 ft/sec*

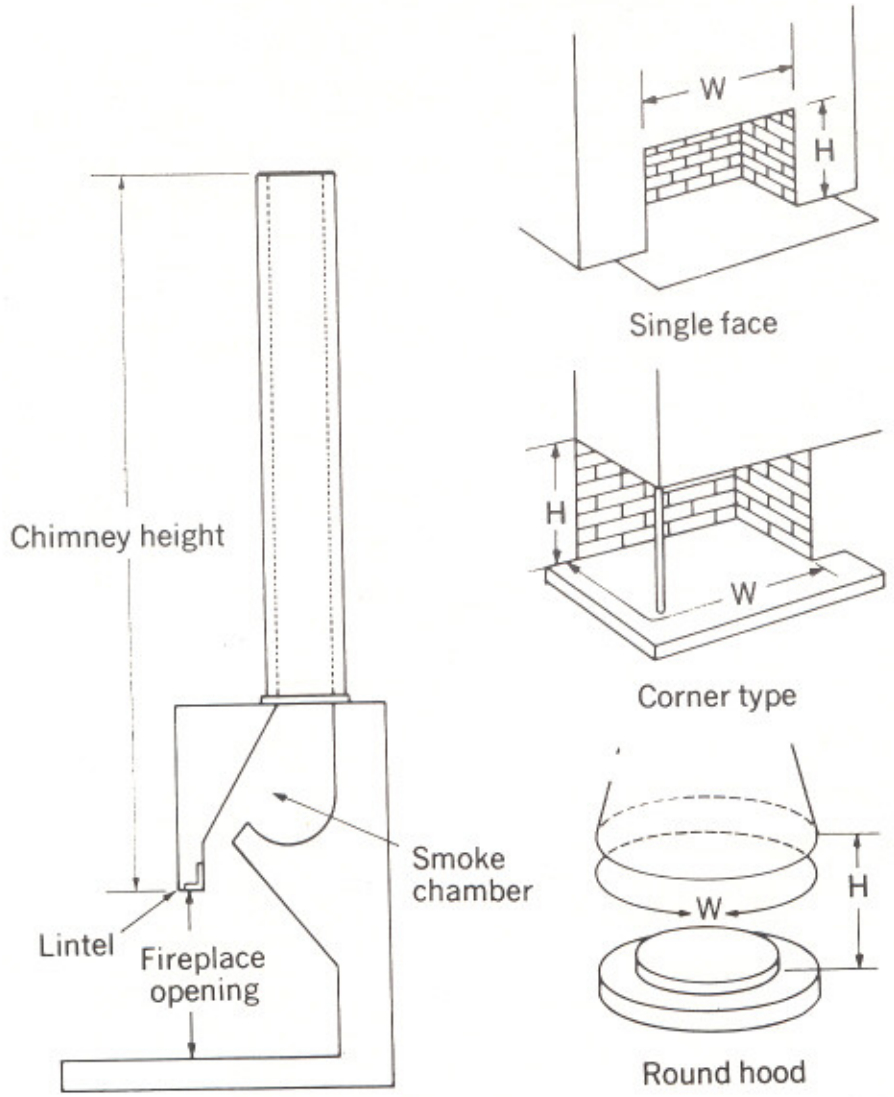


*Fig. 7 Estimation of fireplace frontal area*

velocities, $A_{F2}$ is found by multiplying frontal area (center scale) by velocity ratio $0.8/V_{F2}$.

While derived specifically for circular flues, it applies with negligible sacrifice in performance to such sections as squared or rounded ovals, because flue area is a much more important factor than friction resulting from changes in hydraulic radius. For example, in a 20-ft high chimney, assuming a square flue section equal in area to an 8-in. circle, frontal area is reduced from 4.16 sq ft with the round, to 4.09 with the square, or about 2%, a difference which will hardly be observable. For certain typical constructions, Fig. 7 suggests methods of estimating frontal area.

Flue or chimney material is of little relevance to fireplace-chimney operation. Materials to which these equations and charts apply include the very hazardous uninsulated single wall metal, through conventional masonry, as well as the various constructions of lightweight, insulated, factory-built low heat appliance chimneys. (Safety standards classify fireplaces as "low heat appliances.") Because most fireplace chimneys are short and vertical, neither heat loss, nor wall roughness has any important effect on flow. The governing factors in chimney selection for fireplaces are mainly safety, installation, convenience, and esthetics.

The relationships developed here apply to steady-state conditions which are obtained only after warm-up. Ignition of a rapidly flammable charge in a cold system creates pulses of expanding hot gas which frequently escape from the fireplace. In a typical chimney, priming time or ability to accelerate from no flow to full upward velocity, is of the order of 5 to 10 sec. Thus initial or intermittent smoking due to momentarily excessive combustion rates occurs because of system inability to increase velocity in pace with the surges in the combustion process.

In the conventional fireplace, the greater the frontal velocity, the more freedom from smoking. The damper free area, together with its resultant resistance coefficient, are thus major factors in obtaining good masonry fireplace performance, especially with short chimneys. Certain laboratory fireplace studies indicate

that the damper free area need not exceed twice the required flue area, because little further resistance reduction occurs past this limit.

If the damper selected has a free area equal to or less than required area, it will be definitely restrictive, in spite of complete adequacy of other factors. Sales and dimensional literature distributed by damper manufacturers seldom includes damper free area or opening dimensions, and the dimensions may vary further after installation due to interferences with lintels and other parts. In any case it seems expedient to select dampers of adequate free area for best results.

Partially closing a damper during a vigorous fire will illustrate this point; what is not so obvious is that greater damper openings may be needed in some cases to obtain control of smoke by achieving adequate frontal velocities.

Many free-standing fireplaces are built without the usual smokeshelf-throat damper configuration. The same parameters and relationships apply to these as to masonry; however, in many designs it is difficult to assign a true frontal area for velocity analysis. Where such free-standing units include back outlets, or require a horizontal run to reach the chimney, compensation is necessary for the resistance or pressure losses entailed by turns. As a rough approximation the system resistance coefficient k should be increased about 1.5 for two 90-deg elbows, or a back outlet with lateral run into a tee.

The losses caused by lateral connectors and tees generally result in a one size increase being sufficient, such as 7 to 8, or 9 to 10, etc. Collar sizes generally determine correct chimney size, and instructions are furnished to cover special situations. More sophisticated designs of prefabricated fireplace units are provided with matching correctly sized chimneys, the combination being intended for installation within conventional residences of wood frame construction.

The equations and design charts presented here assume no wind or air supply difficulties. Lack of replacement air, competing ventilation exhaust fans, negative interior pressures due to winds, are all obvious causes of smoking, or poor fireplace priming. Even when fully primed and hot, the thermal forces in a fireplace chimney can be overpowered by a combination of adverse influences. In modern high-rise residential apartment construction, where an effort has been made to provide all amenities, fireplaces may have to cope simultaneously with all of these troubles. Continuous induced draft for the chimney alleviates most of these problems by maintaining a chimney prime at all times. An inducer for this purpose should be capable of producing 0.8 to 1.0 ft/sec fireplace face velocity of ambient air in any individual flue. Where multiple flues are installed within a chase, a single larger inducer serving the chase can be simultaneously sized for the combined fireplace frontal area. Even where flues are of different heights and sizes, a draft inducer selection, assuming all flues to be some compromise median height and size, produces far greater user satisfaction than reliance on gravity alone.

In single family dwellings fireplace problems are caused by reduced interior pressures due to wind effects more frequently than by poor chimney terminal location or characteristics. Efforts to cure smoking, slow priming, or blow-back of ashes, most frequently involve one of the myriad forms of stationary or rotating caps, cowls or chimney pots. This questionable expedient has contradictory effects. Usually, the added still air resistance of a cap reduces fireplace frontal velocity which limits combustion rate, and thus may tend to increase smoking. On the other hand, a cap, by reducing air dilution of smaller fires, raises chimney temperature, improves stability of flame, thus tends to mitigate wind impulses during operation which cause momentary flow reduction. The usual fireplace damper can also be used to restrict flow, and thus raise temperature.

Remedies for fireplace malfunctions may be analyzed using Eq (7). For example, it is apparent that any change of parameters on the right hand side which might decrease $V_F$, can increase smoking tendencies. If frontal area A increases, or if k increases, there will be a corresponding decrease in $V_F$. Similarly if $A_c$ chimney area or H chimney height are reduced, then $V_F$ will decrease. Further, because frontal velocity varies as the square root of the term H/k, it is more effective to reduce frontal area, thereby increasing $A_c/A_F$, than to increase H or reduce k.

Logical expedients for increasing $V_F$ frontal velocity and thus improving fireplace performance of fireplaces and chimneys, include the following:

(a) Increase chimney height (using the same flue area) and extend the last tile 6 in. upward, or more.

(b) Decrease frontal opening by lowering the lintel, or raising the hearth. (Glass doors may help by increasing $V_F$.)

(c) Increase free area through damper. (Check that it opens fully without interferences.)

Over the years, tradition, common sense, and practical experience have blended to provide fireplace builders with empirical rules for sound designs. Such factors as width, height, lintel and damper location, and many others, could be studied in depth using modern techniques of flow tracing, but would probably lead to very little improvement over what is presently known. Combustion of usual fireplace fuels is a highly random process, amenable only with great difficulty to modern research techniques. Elimination of these random factors by theoretical and experimental means is a useful tool for understanding fireplaces, but does not invalidate the teachings of the past.

It has been shown here, however, that a rational mathematical approach, founded on simple fluid flow laws, does exist to provide a general framework for understanding fireplace functioning. Although fireplaces are seldom the main heating unit for modern residences, they will continue their useful and esthetic functions for many years to come. The application of the modicum of science to this ancient art is an initial effort to dispel some remaining mysteries, and may lead to better fireplace understanding in the future.

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