Impact of Chimney-top Appurtenances on Flue Gas Flow

Final Report

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FOREWORD

The results of this study show that there exists information and data related to flow resistance and impedance of gas flue in the literature. The data are also primarily available for chimney top appurtenances such as chimney caps, exhaust termination, and venting systems. While there are gaps in information on the topics related to chimney top dampers and decorative shrouds. The sources of such information are standards and codes, as well as reports of research studies and data from manufactures. This report provides a summary of published research results and data related to flow resistance of chimney-top appurtenance and identifies existing gaps. Specifically, a summary of findings related to flue gas through venting system in solid fuel burning appliances is provided. These publications include those reporting testing (including product testing of chimney-top devices) and modeling of the entire venting system of the chimney.

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The content, opinions and conclusions contained in this report are solely those of the authors.

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Keywords: appurtenances, chimney-top, draft, flue, gas flow, testing

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Impact of Chimney-top Appurtenances on Flue Gas Flow

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Executive Summary

Design of a chimney structure requires knowledge of specific characteristics and parameters that affect the system performance. The parameter of flow resistance coefficient is especially important since it is a major determinant of the chimney's resistance to flow. In order to ensure that a chimney has proper draft, the flow resistance of the entire system should be less than induced draft. As such, the flow resistance coefficient is an important design parameter. While numerous existing papers and experimental data highlight most portions of a typical chimney assembly, such as elbows and bends, fewer research studies have focused on the flow resistance coefficient of chimney top appurtenances, such as rain caps, exhaust terminations, chimney-top dampers, and decorative shrouds for solid fuel burning appliances. The results of this study show that there exists information and data related to flow resistance and impedance of gas flue in the literature. The data are also primarily available for chimney top appurtenances such as chimney caps, exhaust termination, and venting systems. While there are gaps in information on the topics related to chimney top dampers and decorative shrouds. The sources of such information are standards and codes, as well as reports of research studies and data from manufactures. This report provides a summary of published research results and data related to flow resistance of chimney-top appurtenance and identifies existing gaps. Specifically, a summary of findings related to flue gas through venting system in solid fuel burning appliances is provided. These publications include those reporting testing (including product testing of chimney-top devices) and modeling of the entire venting system of the chimney.

1. Introduction

The main function of a chimney structure is "draft" through which, flue gases and smoke are removed from the building. Several parameters influence draft including the chimney height and the temperature differences between the outside air and combusted gases inside the flue. Flow resistance decreases the induced draft. Moreover, additional turns and sharper parts in a chimney also influence the process and often maximize the flow resistance and minimize the draft in the system. Furthermore, rain caps and other terminals increase flow resistance depending on the terminals' materials, geometries, and size. Proper design of a venting system requires information and specific data that address flue gas flow through the venting system, especially in solid fuel appliances. Such information and pertinent data can be obtained from published materials describing modeling and reported testing of the entire venting system (including test results published by manufacturers on their products).

This report summarizes findings of a comprehensive search of available published papers on chimney-top device flow resistance including reported testing and modeling, fire accident investigations, and other related studies. The gap in the needed knowledge is determined in an effort to provide insight into what is needed for development of guidance for installing rain caps and other chimney-top devices with technical substantiation.

2. Background Review

Description of typical chimneys

Modern chimneys are categorized into three types including:

I. Masonry chimneys: These chimneys are built using masonry materials such as clay, brick, ceramic [1], and concrete. Masonry chimneys are constructed using bricks or concrete blocks. Some are also equipped with a stainless steel lining that is considered helpful in enhancing safety [2].

II. Metal chimneys: These chimneys are made up of stainless steel or copper. For the metal and masonry chimneys, the use of a cap is necessary to avoid water and moisture penetration that may result in damage to the chimney and a potential failure in a short time. Metal chimneys are often used in wood stoves and prefabricated fireplaces, venting out harmful gases.

III. Factory-built chimneys: These chimneys are pre-fabricated and are often made of stainless steel. For insulation, their outside is coated with galvanized steel or covered with stainless steel to prevent the exterior surface from reaching high temperatures. Most factory-built chimneys include caps [3].

Description of a typical chimney-top appurtenance and their performance

A chimney-top appurtenance may consist of: Chimney Cap, Spark Arrestor Screen, Chimney Crown, Chimney Fans, Exhaust Termination, Damper, Chase Cover, Flue Liner, Decorative Shrouds, Adjustable Roof Flashing, and Chimney Extension. The following explains those components in more detail.

Chimney Cap: The role of a chimney cap termination is to reduce the damage caused by water penetration. Some caps have screens which help keep animals away from the chimney. Screens also prevent spark and cinder from leaving the chimney and rain, snow, and leaves from entering the chimney. The most common materials for caps are stainless steel, copper, and galvanized steel. Masonry chimney caps are also available and are made of such materials as brick, concrete, or stone [4]. Appendix A presents the basic features of different types of chimney caps.

Spark Arrestor Screen: The screen prevents burning sparks from escaping from the source of combustible materials. A chimney must have a spark screen if the source of spark is a fireplace or solid-fuel appliance [5] (Figure 1).

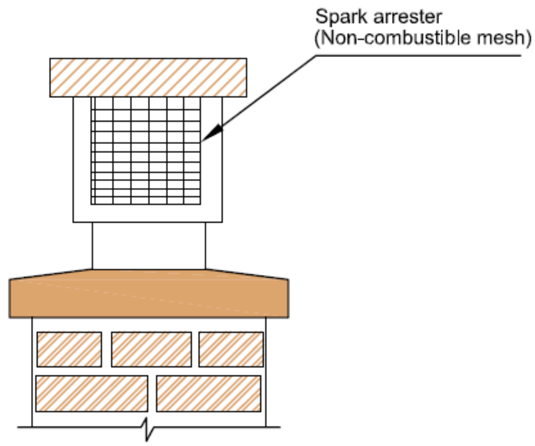

Figure 1: Spark arrestor (5/8 inch standard mesh suggested by California code) and Rain cap [Adopted from Ref. 6]

Chimney Crown: A Chimney crown is a cast-in-place concrete or mortar piece atop the chimney and prevents water from infiltrating into the stack by sealing off the distance between the outer wall and flue liner. It is also helpful to avoid frost damage to the flue or to the chimney. Chimney crowns must have 3 in/ft slope away from the flue [6]. The Brick Institute of America recommends that the chimney crown made of pre-cast or cast-in-place concrete must have a minimum of 2 inch thickness with an extension of 2 1/2-inch outside the face of the masonry (Figure 2) [7].

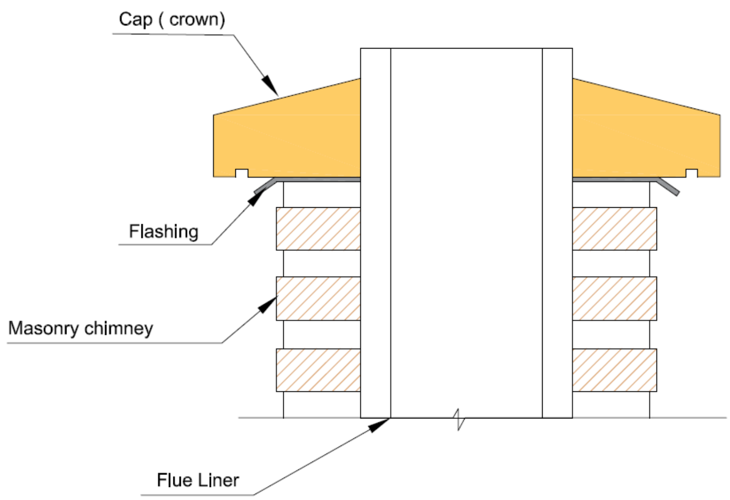

Figure 2: Details of chimney- top device [Adopted from Ref. 7]

Chimney Fans: Chimney fans are used when the system is improperly designed or a drafting condition exists that cannot be fixed. Chimney fans are useful for short chimneys and chimneys facing wind. A fan can be installed on the top of the chimney. In those cases, fans prevent smoke from backing up if operated and sized properly.

Exhaust Termination: Exhaust termination includes different parts including storm collar, flue, and cap. They are used to transfer combusted air outside. It is important to consider minimum clearance distance between exhausted termination and other features. A typical termination cap is shown in Figure 3.

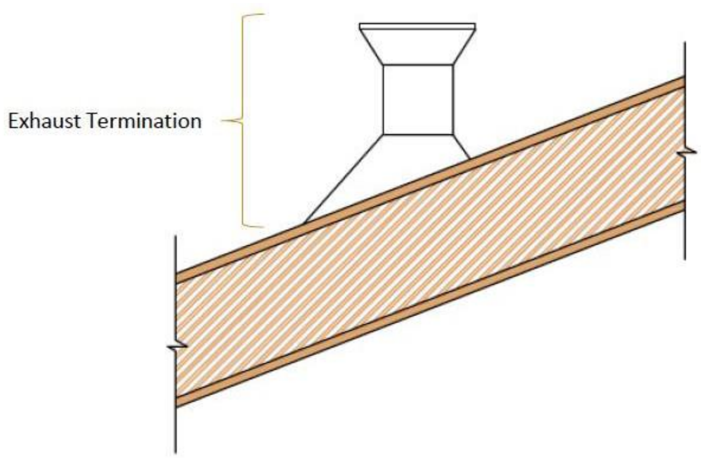

Figure 3: Typical exhaust termination [adopted from Ref. 38]

Damper: A damper is used when the air flow is not complete. It is designed to prevent the cold and hot air from going down and up the flue, respectively (Figure 4). Chimney top damper must be properly sized to prevent a restriction in the airflow.

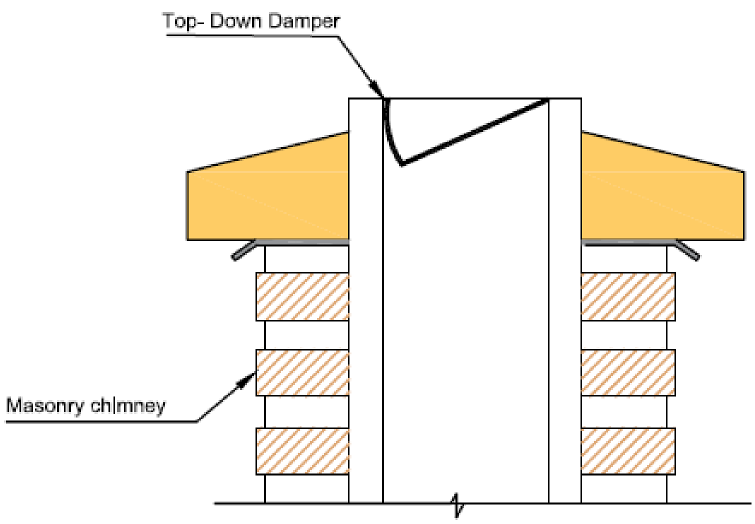

Figure 4: Chimney- top fireplace flue damper [Adopted from Ref. 39]

Chase Cover: A chase cover is used to cover the top of chimney. The galvanized chase cover has a significantly shorter life-span when it is used near a coastal area or area exposed to high temperature or acids.

Flue Liner: A flue liner is used to transfer the combusted air throughout the building chimney. To resolve the chimney's draft issue, the height can be increased (Figure 2). In fact, a flue liner is used to transmit all byproducts of combustion and any additional entrainment to the exterior of the building.

Decorative Shrouds: Decorative shrouds are often used for aesthetics. They can also function as a chimney cap equipped with bird guards (Figure 5). NFPA requires that shrouds be listed to work with the specific appliance being vented.

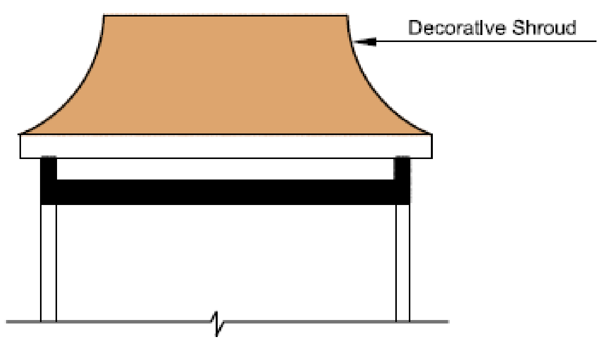

Figure 5: Chimney decorative shroud [Adopted from Ref. 6]

Adjustable Roof Flashing: Adjustable roof flashing is used to smooth out roof roughness and/or discontinuities. The flashing prevents water infiltration into the building at points of discontinuities (Figure 6).

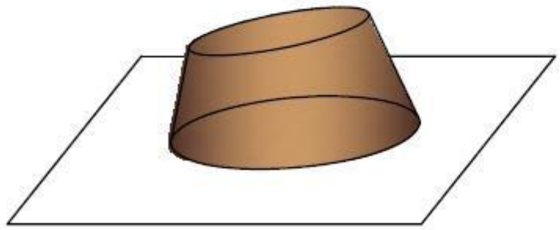

Figure 6: The roof flashing useful for angled surface [Adopted from Ref. 40]

Chimney Extension: Short chimneys are not safe. They present an increased level of risk of fire due to potential sparks and heat built-up. They can also have draft issues that interfere with proper chimney function. A solution to these issues is to install chimney extensions while it will have problem on solid-fuel burning appliances. An extension must be properly designed to allow a leak-free operation [6] (Figure 7).

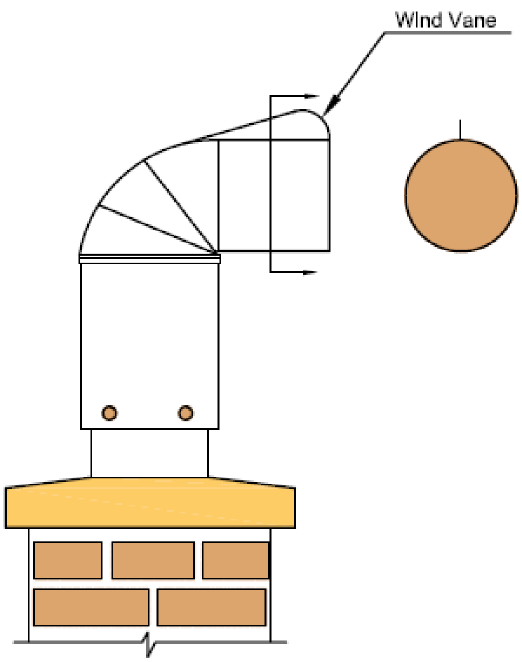

Figure 7: Chimney extension for improving draft issue in chimney structure
[Adopted from Ref. 6]

Factors and parameters affecting chimney performance in solid- fuel burning appliances
The common parameters affecting chimney performance are draft and flow. Draft causes the combusted gases to go out of the chimney; and the air flowing into the appliance. The Pressure Meter: "inches of water column" is used to measure the draft. As an example, in residential oil furnaces with pressure atomizing burners, the outlet draft range is [-0.04,-0.06] of water column.

A zero value for the pressure means that the gas cannot flow out of the chimney. This can be a potential problem since it is an indication of the gas not rising through the chimney. This can be caused by blockage of flue, improper chimney height, temperature difference, air inversion, improper size and configuration of stovepipe, mechanical pressurization, and intrusion of air into the flue [14].

Temperature difference, between the outside air and the average temperature of flue gas and height of the chimney are two significant parameters affecting the draft. Draft improves significantly as temperature difference increases. The parameters affecting the temperature difference are: outdoor temperature, heat induced by fire, and the chimney's ability to hold the heat. Figure 8 shows the effects of some of those parameters on the chimney's draft. The temperature difference can also affect the pressure, which causes natural draft. As such, the chimney will achieve a minimum heat loss leading to an enhanced performance [3].

Proper chimney height also improves the draft. A variety of parameters such as type of appliance, need for draft, types of roof construction, and building height are effective in determining the proper height. In certain solid fuel boilers, the chimney height should be more than 50 to 70 feet total in order to make a proper draft. This height is essential to overcome any adverse effect because of the change in the flow resistance coefficient [5].

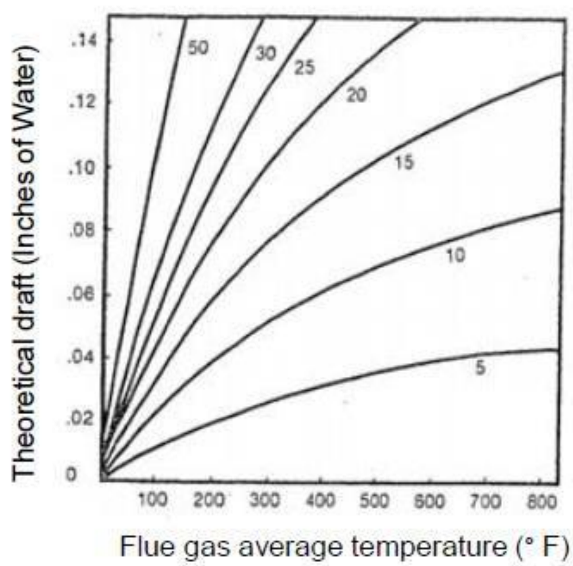

Figure 8: Static Draft as a function of chimney's height and temperature of flue gas
[Adopted from Ref. 12]

System flow resistance to the stream of exhausted gas is a main design parameter for chimneys. Sharper turns, bends, and elbows in the chimney have higher friction between the gases and the chimney, and therefore, possess a greater flow resistance coefficient. Use of a vent connector is a solution that avoids sharp turns for decreasing the resistance coefficient. Conventional open masonry fireplace dampers have the highest flow resistance and cause draft to be less than the flow resistance [3].

Two airflow environments occur around chimney caps. First, the internal airflow gas in a fireplace system rises out of the flue with the minimum flow resistance. Second, the external flow (wind) creates a low air pressure around the chimney cap causing additional draft [13]. To have a system with a proper draft, the flow resistance must be less than the draft itself. Resistance in a chimney system increases because of: 1) key dampers and elbow, 2) creosote deposits, 3) improper size of the chimney, and 4) baffles in the stove system [3].

Several other parameters affect the flue gas flow including vent size, direction of the wind, pressure condition, building segment higher than the chimney top, and altitude. The chimney's cross-sectional area must provide the proper size, i.e., it must not be excessively large. This is because the gas flows are slower in a wider area and it loses the heat more than a narrower flue. [14].

The measure of the volume of gases which pass through the venting system is known as "flow" and is defined as the maximum gas flow (lb/hr) under the typical temperature situation [16]. The flow of gas depends on four parameters: 1) the temperature difference between outdoor air and flue gas flow, 2) chimney height, 3) chimney diameter, and 4) the flow resistance coefficient of the system. Eq. 1 shows the flue gas flow in a chimney system [16].

$$M = \left(\frac{A}{K}\right) \times \sqrt{2ghd_f(d_a - d_f)} \quad (1)$$

where, A is the flue cross-sectional area, h is the chimney height, g is the gravitational acceleration, k is the flow resistance coefficient and, d_f and d_a are the density of flue gas flow and the density of outdoor air, respectively.

Standards pertinent to fuel gas flow in chimney appurtenance (for solid-fuel burning appliances)

Numerous standards, guides, and codes mention the effects of different parameters on flue gas flow in chimney systems. These include:

1) NFPA211, "Standard for Chimneys, Fireplaces, Vents, and Solid Fuel-Burning Appliances" - 2003 [15]
2) Guidance and supplementary information on the UK implementation of European standards for chimneys and flues (Draft 03-08) [16]
3) EN 16475-7 (Edition 2012-10-01) Chimney – Accessories, Part6: Rain Cap-Requirements and methods [17]
4) BS EN 16475-2 Chimneys-Accessories Part 2: Chimney fans - Requirements and test methods
5) BS EN 13216-1:2004: Chimneys. Test methods for system chimneys - General test methods International Mechanical Code, 2006 [18]
6) UL 103: Standard for Factory-Built Chimneys for Residential Type and Building Heating Appliances
7) UL 1777 (ISBN 1-55989-760-0), Chimney liners [19]

The National Fire Protection Association Standard #211 states that "Chimneys and vents shall terminate above the roof level in accordance with the requirements of this standard" (Figure 9).

Chimneys must be extended three feet higher than the highest point of the roof, and at least two feet higher than any portion of all structures within 10 feet [15].

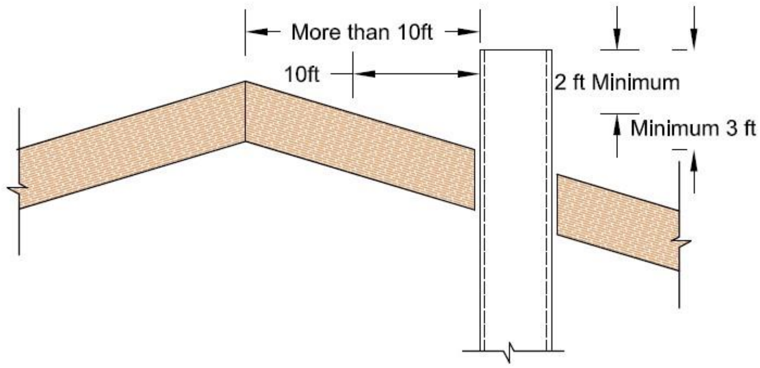

Figure 9: The minimum height of the chimney [Adopted from Ref. 15]

1. The guidance and supplementary information on the UK implementation of European standards for chimneys and flues (Draft 03-08) indicates [16]: "*Chimneys are classified in accordance with the following performance characteristics: Temperature, Pressure, Condensate resistance, Corrosion resistance, Sootfire resistance and distance to combustibles. In addition, the chimney manufacturer must give information on the following characteristics: thermal resistance, flow resistance, and freeze-thaw resistance (where applicable).*" Also: "*The chimney designation scheme used as a basis for developing the harmonized products standards (e.g. BS EN 1457, BS EN 1857) is detailed in EN 1443: 2003: Chimneys, General requirements."* Moreover: "*The execution standard for metal chimneys, BS EN12391-1, includes physical checks to confirm the functional ability of chimneys. Three tests are detailed in the informative annex of the document and covers: Flue flow test, Smoke test, Pressure test*."

2. UL 1777 provides information about chimney caps as [19]:
"*7.1 A Cap shall be provided to resist the entrance of debris and rain into the flue gas conveying conduit of the chimney liner, and into any space where exposed thermal insulation is located.*
7.2 A Cap shall be constructed so that leaves and debris fallen or blown onto it are not retained so as to obstruct flue gas or cooling- air passages. A cap shall be constructed to resist the accumulation of soot that obstructs the flue-gas or cooling-air passages.
7.3 A cap shall be removable and replaceable by the use of simple hand tools (screwdriver, wrench, or pliers) to allow for chimney cleaning in accordance with the installation and maintenance instruction without bending or deforming the chimney liner, or parts thereof."

Also, the code definition is: "*UL 1777 Standard contains basic requirements for products covered by Underwriters Laboratories Inc. (UL) under its Follow-Up Service for this category. These requirements are based upon sound engineering principles, research, records of tests and field experience, and an appreciation of the problems of manufacture, installation, and use derived from consultation with and information obtained from manufacturers, users,* *inspection authorities, and others having specialize experience. They are subject to revision as further experience and investigation may show is necessary or desirable*" [19].

3. Ohio Administrative Code states [20]:
"*1805.3.1 Size of chimney flue for solid-fuel appliance: Except where otherwise specified in the manufacturer's installation instructions, the cross-sectional area of a flue connected to a solid- fuel-burning appliance shall be not less than the area of the flue collar or connector, and not larger than three times the area of the flue collar.*
1804.2.2 Decorative shrouds shall not be installed at the termination of gas vents except where such shrouds are listed for use with the specific gas venting system and are installed in accordance with manufacturer's installation instructions."

4. International Code Council (2009) indicates [35]:
"*G2427.10.6 (503.10.6) Flow resistance. A vent connector shall be installed so as to avoid turns or other construction features that create excessive resistance to flow of vent gases.*
G2427.10.13 (503.10.13) Fireplaces. A vent connector shall not be connected to a chimney flue serving a fireplace unless the fireplace flue opening is permanently sealed."

5. Virginia Mechanical Code (2006) –Chapter 8- Chimney and vent indicates [36]:
"*801.16.1 Residential and low-heat appliances (general)*
Flue lining systems for use with residential-type and low-heat appliances shall be limited to the following: 1. Clay flue lining complying with the requirements of ASTM C 315 or equivalent. Clay flue lining shall be installed in accordance with the International Building Code, 2. Listed chimney lining systems complying with UL 1777, 3. Other approved materials that will resist, without cracking, softening or corrosion, flue gases and condensate at temperatures up to 1,800°F (982°C)."

6. UL 103 states [37]:
"*1.1 These requirements cover factory-built chimneys intended for venting gas, liquid, and solid- fuel fired residential-type appliances and building heating appliances in which the maximum continuous flue-gas outlet temperatures do not exceed 1000°F (538°C). Factory-built chimneys are intended for installation in accordance with the Standard for Chimneys, Fireplaces, Vents, and Solid-Fuel Burning Appliances, NFPA 211, and in accordance with codes such as the International Mechanical Code, the International Residential Code, and the Uniform Mechanical Code. They are intended for installation inside or outside of buildings or both, in a manner that provides a vertical (30 degree maximum offset) conduit or passageway to transport flue gases to the outside*."

3. Flow Resistance of Chimney Devices (for solid fuel burning appliances)

Flow resistance of different chimney devices

Flow resistance is defined as the friction between moving flue gases and the surrounding environment. Flow resistance is one of the main design features for a venting system. Chimney appurtenances (e.g., straight walls, bends, turns, and top devices) have flow resistance. The most common reasons for the creation of flow resistance in the chimney include elbow, key dampers in flue pipe, baffles in stoves, and creosote. Moreover, undersized chimneys lead to excessive flow resistance [3]. The calculation of flow resistance for chimney sections including fittings and termination components, according to EN 13384-1, are shown in Table 1 [21].

Table1: Flow resistance of all parts of chimney [21]

Component	Z (Zeta- Value) Single resistance	
Pipe tee 87°	1.14	
Pipe tee 45°	0.35	
Pipe bend 87°	0.40	
Pipe bend45°	0.28	
Pipe bend 30°	0.20	
Pipe bend 15°	0.10	
Terminals: (Only for Operation in Negative Pressure)		
Rain Cap	1.0	
Fin Cap type	≤Ø=140 mm	0.1
	≥Ø=150 mm	0.2
Wind Deflector	≤Ø=140 mm	0.1
	≥Ø=150 mm	0.2

There are prefabricated piping systems which can be used for all types of building heating equipment. The respective measured flow resistance for this model is summarized in Table 2 [22].

Table 2: Flow resistance of top devices [22]

Component	Features	Flow Resistance Factors
Insulated Exit Cone	316 Stainless Steel	K = 1.25
Stack Cap& the rain collection ring	Provides partial protection with low flow resistance 304 and 316 Stainless Steel	K = 0.5

For products used with different types of fuel such as LP gas, fuel oils, wood, and coal, the flow resistance coefficient for the top device of a chimney is summarized in Table 3 [8].

Table 3: Flow resistance top device [8]

Component	Features	Flow resistance factor
Velocity Cone	It increases velocity of exiting flue gases. It includes: velocity cone, vee band and rain skirt.	K = 1.25
Double Cone Rain Cap (DCR)	The DCR is for vertical terminations. The Double Cone Rain Cap comes with or without a screen. Part includes: double cone rain cap, vee band and rain skirt.	K = .50

Specific issues of the chimney-top devices as pertain to impedance of gas flue
Issues related to the draft problem include:

- If the chimney is too small, the flue gas velocity reaches the point that flow resistance is more than draft. Rectangular shaped ducts are especially susceptible to this problem. In this situation, the chimney cannot handle the gases generated by a fireplace.
- Height is a factor for a proper draft. A chimney shorter than the building's height has draft issues.
- Some tall chimneys also experience draft problems. The increase of draft is not monotonic with increase of chimney's height.
- Large chimneys are used to increase the capacity of the flue. However, this causes the flow resistance to decrease. In situations with no wind (or when only horizontal wind is present), and less flow resistance is desired, use of a flat disk or cone cap offers an ideal solution. This type of design will result in about 0.5 flow resistance.
- Other issues, such as installing chimneys in an improper location or chimneys without insulation, also cause draft problems.
- A building with substantial draft problems will overcome the flue gas flow in the system and cause a "reverse back flow." Down draft is also another common problem in chimney structures.
- An exposed chimney does not work properly compared to a chimney which is protected with a surrounding wall [23].
- Unsuitable Chimney Pot; Chimney pots which are not tapered and with square base have less flow resistance and thus offer a better option for open fire places [23].

4. Flue Gas Flow Through Venting Systems

Issues related to flue gas flow

- One problem that affects a chimney's performance is wind induced downdrafts causing flow directions backward into the chimney. Increasing the height of the chimney will be helpful to extend the chimney into a higher level of turbulence zone. Use of improper cap can also be the economical solution for the downdraft problems which are caused because of improper wind direction [14].
- Open fireplaces need chimneys with more capacity to draw excess air. Larger chimneys cause decreasing gas temperature and, consequently, require less draft. In fact, improper draft is one of the common problems in open fireplace systems.
- A wind direction which results in a downdraft causes the flow to go back to the chimney. When analyzed properly, the airflow on top of the building can be effective in designing the best location for the chimney and decreasing the problems related to back draft (Figure 10 and 11) [5].

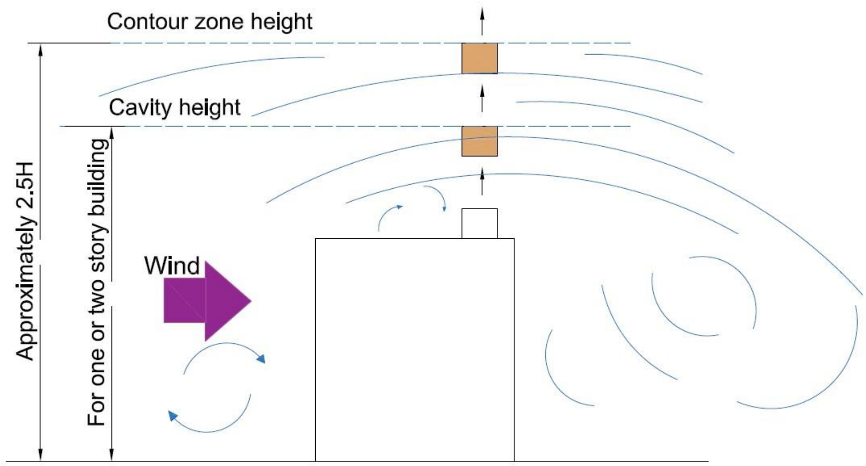

Figure 10: Airflow diagram used to find the best chimney location (width and height of building are the same) [Adopted from Ref. 5]

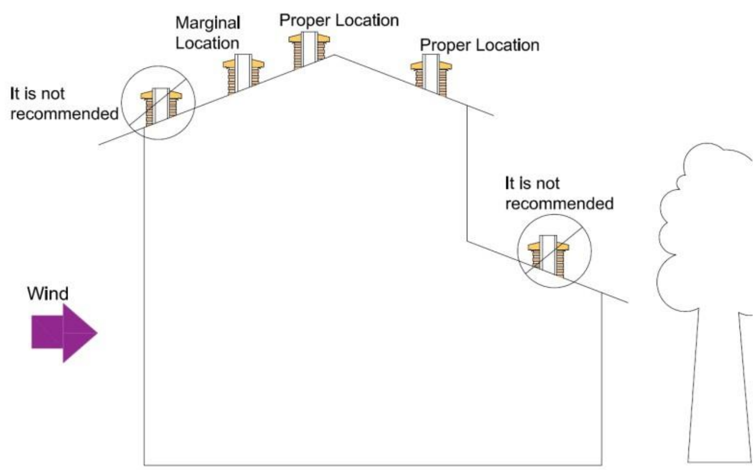

Figure 11: Proper location for a chimney [Adopted from Ref. 41]

- Inadequate temperature difference also causes draft problems. Air leaks in a chimney can also cause flow related problems in the system [33].
- Dynamic Wind Loading happens when the wind blows on one side of the house causing a positive pressure, while there is negative pressure on the other side of the house. Figure 12 illustrates issues related to wind pressure and a possible solution to alleviate the problem [25].

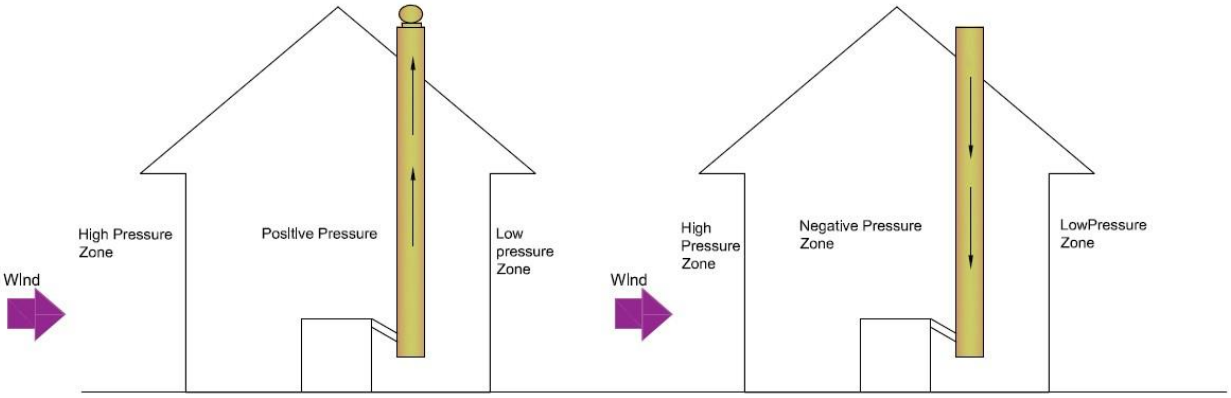

Figure 12: The problem due to because of wind direction [adopted from Ref. 25]

Other potential cases that may result in draft problems in vent systems are:

- Existence of fans in the house.
- House situated atop mountains. In this situation, air actually blows down the chimney. Improper height of the chimney causes odor or soot issues in the system. An unsafe appliance can also cause a draft problem. In these situations, the use of a draft inducer may solve the problem [6].
- Chimneys which are too close to each other may also cause problems because of an inadequate clearance between them (Figure13). Negative pressure within the dwelling may also draw smoke down into the living space when the upper chimney in Figure 19 is not in operation.

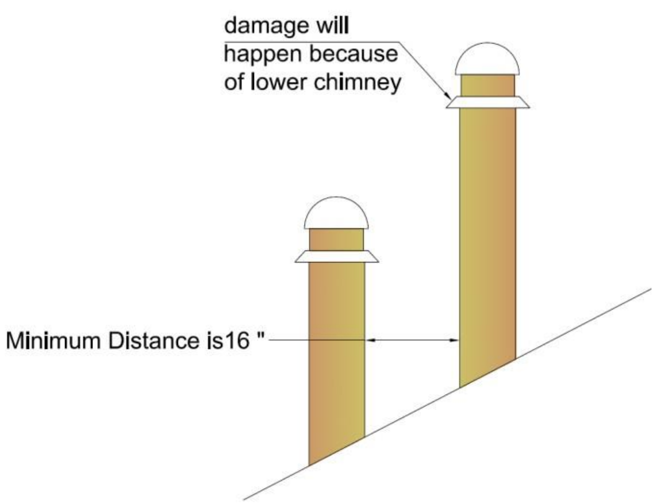

Figure 13: Minimum requirement for chimney distance [Adopted from Ref. 6]

Testing and modeling pertinent to venting system

Fireplaces using natural draft follow the gravity fluid flow law [24]. There are two methods to calculate flow losses caused by friction: (1) the equivalent length method and (2) the loss coefficient method (velocity head) [26]. To find flow losses because of velocity and resistance, the Bernoulli equation is used.

It is shown that pressure losses are directly proportional to the square root of velocity and also resistance factor (Eq. 2) [26]:

$$\Delta p = \frac{k \rho_m V^2}{5.2(2g)} \tag{2}$$

where, k is the dimensionless resistance coefficient of piping and fittings, V is system gas velocity at mean conditions (fps), g is gravitational constant (ft/s^2), and ρ_m is flue gas density (lb/ft^3).

Chimney gas velocity is effective on piping friction factor, K_L, and roughness correction factor [26]. Analytical software can be used for oil-fired heating appliances. The software is used to have a cost effective integration of the vent system and heating appliance. This program is used in steady state cases and avoids complexity related to condensation, heat loss, and corrosion [27]. The software application manual is useful in finding the flow resistance factor for venting systems [24]. Three parameters affecting the mass flow of hot flue gases are: (1) heat release around the chimney area, (2) height, and (3) flow resistance [24]. Using a fan is suggested to reduce draft problems, especially in an unclean environment. The other advantage of using a fan is that it can be installed in different types of chimneys such as brick or steel chimneys. It is designed to resist high temperature and follows the UL Standard 378 for draft equipment. While using a fan will be a restriction to the flow, its flow resistance measure is about 0.5 and is comparable to a 45° elbow [24]. The total static pressure loss or flow resistance in a vent system is obtained from [24]:

$$P_s = 0.015 \times d_m \times V_{pipe}^2 \times \sum k \tag{3}$$

$$P_s = 0.015 \times d_m \times \left(\frac{Q_t}{A_{pipe}}\right)^2 \times \sum k \tag{4}$$

d_m = gas density, lb/ft3
V_{pipe} = system gas velocity (flue gas volume/flue area) at mean condition, ft/s
A_{pipe} = Area of flue, in^2
$\sum$k = sum of all resistance factors

Several factors cause resistance in a chimney system (serving solid-fuel burning appliance). Among these include the flue of the system and its component and the transition from firebox to flue. Any part of a chimney system has its own flow resistance coefficient. The resistance from the negative building pressure and other external building pressure need to be added to the resistance coefficient, which can be determined using a pressure gauge in a fireplace chimney prior to starting the fire [24]. In a flue pipe, the higher the roughness of the pipe (which is considered as a Reynolds number or k-value), the more flow resistance as:

$$k_I = \frac{F \times L}{d_I} \tag{5}$$

where, F is the friction factor (Figure 14), L is the length of the pipe (feet), and d_I is the diameter of flue in inches.

Some examples of friction factors for different types of pipes are: (1) for pressure tight stacks, friction factor= 0.22, (2) for Gas Vent (B- Vent), 0.25, (3) for Single wall steel pipe, 0.32, (4) for poured liners, 0.34, (5) for clay tile liners, 0.38, and (6) for corrugated liners, 0.5 [24]. In situations in which the size of the chimney is unknown, flow resistance coefficient for the entire system is assumed 0.5. In order to simplify the equation, the value of 0.4 is defined for all sizes of vent or chimneys in all velocity and temperature cases. This offers a higher safety factor (more conservative) design.

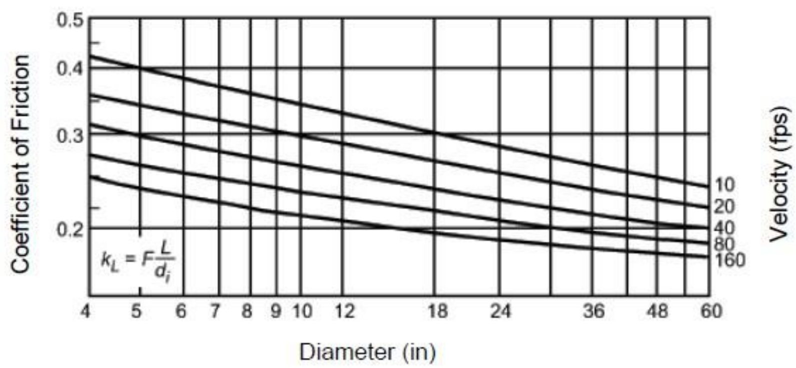

Figure 14: Friction factor F versus velocity and diameter for commercial iron and steel pipe at a flue gas temperature of 300°F [Adopted from Ref. 26]

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) has defined a range of k-values for different appurtenance of chimney systems (Table 4).

Table 4: Resistance Loss Coefficients [26]

Component	Suggest Design Value, Dimensionless	Estimated Variations and Notes
Inlet acceleration (k1)		
Gas vent with draft hood	1.5	1.0 to 3.0
Barometric regulator	0.5	0.0 to 0.5
Direct connection	0.0	Also dependent on blocking damper position
Round elbow (k2)		
elbow 90°	0.75	0.5 to 1.5
elbow 45°	0.3	-
K3		
Tee or 90° connector	1.25	1.0 to 4.0
Y connector	0.75	0.5 to 1.5
Cap, top (k4)		
Open straight	0.0	-
Low-resistance (UL)	0.5	0.0 to 1.5
Other	-	1.5 to 4.5
Spark screen	0.5	-
Converging exit cone	$\left(\frac{d_{i1}}{d_{i2}}\right)^4 - 1$	System designed using d_{i1}
Tapered reducer (d_{i1} to d_{i2})	$1 - \left(\frac{d_{i1}}{d_{i2}}\right)^4$	System designed using d_{i2}
Increaser	-	Chapter 2, 2005 ASHRAE Handbook
Piping (kL)	$0.4 \times L$ (ft)/d_i (in)	Numerical coefficient, [0.2,0.5]

As shown in Table 4, ASHRAE uses the velocity head method to determine resistance losses in order to find a flow resistance coefficient for every component of the chimney, such as fittings, piping, configuration, or interconnection factors [26].

Flow resistance of fittings such as a tee (where flue gases enter the side and make a 90° turn) is assumed to be constant and equal to k=1.25. This is independent of parameters such as size, velocity, orientation. On the other hand, flow resistance of a tee (where gases pass through it such as in a manifold) is zero. It is independent of the area and flow which goes from the side branch. Total resistance of a chimney with fittings is constant whereas the resistance of a pipe is a function of the centerline length divided by diameter (Table 5).

Table 5: Resistant coefficient in fire place appliance [26]

Component	value
Ambient air to flue gas velocity change rate (ka)	1
Inlet loss coefficient (Ki) for fireplace configuration	
Cone-type fireplaces	0.5
Masonry (damper throat = 2x flue area)	1
Masonry (damper throat = flue area)	2.5
Chimney flue type friction (kc) – at Re = 10000 & Roughness = 0.001	Kc = 0.008 H/r_h
Termination Coefficient Kt	
Open top pie (similar to chimney size)	0
Disk or Cone Cap	0.5
Manufactured Cap	0 to 4

Corrugated 90° elbow flow resistance has a higher value. However, it is generally lowered by long-radius turns (in Table 4, they are d_{i1} and d_{i2} as the inlet and outlet, respectively). Finally, flow resistance of a system can be measured by adding fixed fitting loss coefficients and the amount of piping resistance loss. Fixed fitting loss coefficient can be measured by considering inlet acceleration coefficient, elbows loss coefficient, tees loss coefficient, and cap, top, or exit cone loss coefficient.

As indicated in ASHRAE, "*For a system connected directly to the outlet of a boiler or other appliance where the capacity is stated as full-rated heat input against a positive static pressure at the chimney connection, minimum system resistance is zero, and no value is added for existing velocity head in the system. In most cases, kL = 0.3 L/di gives reasonable design results for chimney sizes 18 in. and larger because systems of this size usually operate at flue gas velocities greater than 10 fps*." [26].

Since Table 4 is for commercial iron and steel pipes, values listed need corrections (by increasing 20%) due to the surface roughness at the temperature above 1000 °F. ASHRAE further indicates: "*For most chimney designs, a friction factor F of 0.4 gives a conservative solution for diameter or input for all sizes, types, and operating conditions of prefabricated and metal chimneys; alternately, F = 0.3 is reasonable if the diameter is 18 in. or more. Because neither input nor diameter is particularly sensitive to the total friction factor, the overall value of k requires little correction*" [26].

Masonry chimneys with clay flue tile and possible mortar protrusions have rough surfaces and their cross-sectional areas may be less than the expected size. Therefore, to measure kL, smooth faces are assumed and the coefficients related to the shape factor and friction loss are then added to the calculated coefficient for the smooth face condition. In reality, this approach is approximate and the capacity of metal and prefabricated chimneys is higher than in site- constructed masonry chimneys [26]. Flue gas flow rate of a fireplace considering gravity-flow capacity equation is defined as:

$$W = A_c \left(\frac{2gH}{k}\right)^{1/2} [\rho_m(\rho_0 - \rho_m)]^{1/2} \quad (6)$$

where, *Ac* is the chimney flue cross sectional area (ft), *H* is the height of chimney above lintel (ft), and *k* is the entire system's coefficient of equivalent resistance (Table 5), and, ρ_m and ρ_0 are flue gas density at mean temperature and air density of ambient temperate, respectively [26] [34].

Another study was done by Paavilainen in 2012 to determine the characteristics of flue gas flow of boilers in residential chimneys [28]. The pitot-static probe is used to calibrate and develop the velocity pressure for non-steady state situation in residential chimneys. The fuel for combustion selected in the investigation was wood. The results show that the single point dynamic velocity pressure measurement has a significant error, and as such, it needs to be calibrated. The significant velocity profile shows the change "*in the normal combustion power modulation range of a residential boiler*" [28]. The paper also reports that it is difficult to predict the velocity profile at low flow rates, and avoid obtaining a skewed velocity profile. The probe size is also a significant factor because of blockage and wall proximity effects [28].

In another study, Peacock investigated gas flow in modern heating appliances and reports on wood heating safety specific to solid fuel appliances [47].

To control many modifications in the building code regarding masonry fireplaces in residential masonry construction, a series of tests was performed by Peacock [29]. These tests were intended to provide new ideas to improve the safety of masonry chimneys and fireplaces. Moreover, there is a test conducted to evaluate the performance of FlueCube cowl device at Advanced Stoves Laboratory at Colorado State University's Engines and Energy Conversion Laboratory. The lab test included a laminar flow hood and outdoor winter conditions [30].

Testing and modeling pertinent to chimney top-device

As indicated earlier, top-devices in chimneys are considered to be different types of caps, chimney-top dampers, and decorative shrouds. All types of chimney caps have flow resistance factors. In general, chimney caps listed by the Underwriters laboratories (UL) have a flow resistance factor of about 0.5 [24]. It has been reported in a laboratory test conducted to investigate the effects of various caps such as turbine cap, draft inducer, dryer vent, as well as open pipe with sub-slab depressurization system on the system's flow resistance [31].

This study shows that the type of rain cap has an effect in increasing the amount of back pressure. According to this study, the turbine cap increases the amount of back pressure more than others. In the wind speeds greater than 12 Km/H, the use of caps will be more effective [31]. A comprehensive research was performed by Koski-Harja in 1994. Wind tunnel testing of chimney caps was conducted to compare the performance of different types of chimney caps. Using tests conducted, the value of chimney cap resistance and inlet section resistance were obtained experimentally. In order to measure the flow resistance, a Pitot-static tube was inserted near the location where the test was performed. [32].

5. Need for additional information (gap in literature)

Table 6 summarizes areas where information and data are available in regard to flow resistance
and impedance of gas flue as related to specific chimney components. Areas where additional studies will be needed are identified as "gaps" in information and/or data and summarized in Table 6.

6. Summary and Conclusions

The following summarizes major work and conclusions of this study:

(1) Review of published reports on chimney structures, including reports on modeling, testing, and fire investigations, indicate that available information and/or data related to flow resistance and impedance of gas flue are primarily available for such chimney components as chimney caps, exhaust termination, and venting systems.

(2) The sources of such information are guides, standards and codes, as well as reports of research studies and data from manufacturers.

(3) There are partial gaps in information on the topics of chimney top dampers and decorative shrouds (Table 6).

Table 6: Available Information and Gap in the knowledge regarding flow resistance and impedance of gas flue

	Component	Available Information (such as Codes and Standards)	Published paper based on testing and modeling	Available Information from Manufacturers
Flow Resistance and Impedance of gas flue	Chimney Cap	There are codes such as ASHRAE which mention the characteristic of the cap [Refs 17, 26]	Research conducted by Koski-Harja and laboratory test performed by M. Clarkin et al are the example of published papers in this regard [Refs 31, 32]	Flow resistance of commercial products such as “Stack Cap”, “Double Cone Rain Cap” is defined by some companies [Refs. 8, 21, 22, 24].
	Exhaust Termination	ASHRAE indicates the specification of “Spark screen”, “Converging exit cone” [Ref. 26]		Flow resistance of commercial products such as “Exit Cone” and “velocity cone” are performed by some companies such as AMPCO [Refs. 8, 22, 24].
	Chimney-top damper	Gap in Information and/or Data		
	Decorative Shrouds	Gap in Information and/or Data		
	Complete venting system	There are codes and Standards such as ASHRAE and UL 1777 [Refs 15,18,19,20,26]	Knowledge related to flow resistance of complete venting system such as inlet and round elbow is available [Refs 3, 8, 12, 21, 22, 28, 30]	

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Appendix A

Table A1: Draft and flow resistance of chimney-top devices

	Types	Details & Basic Feature	Draft and flow resistance characteristics and issues
Chimney Caps	Standard Chimney Cap • Single Flue Chimney Caps • Multi-Flue Chimney Caps	• It can be fitted to different flue with different shapes such as square, round, rectangular, or oval flue tiles. • Multi- Flue cap allows the cap to fit over the entire chimney.	• Increases draft by increasing height of the chimney • Some caps have more restriction than others. • Caps with mesh screens will be plugged by creosote causes flow resistance.
	Draft increasing Chimney Cap [42] • Wind Resistance • Wind Directional Cap	• Vacuum cap is uses in flat roofs. • To install this type of Chimney Cap in masonry chimneys, the adaptor is used. • They can create a venturi and can cause flue gases to flow up and out of the chimney.	• A draft increasing chimney cap may clog up with smoke and other deposits from the fireplace. • Wind directional caps may create low air pressure • It also prevents downdraft in a high wind environment.
	Draft Master cap	• Uses wind to increase performance of the chimney flue. • Decrease resistance by providing laminar air flow instead of turbulent air flow.	• It prevent downdraft • Air inside of the flue has higher static pressure while it has lower speed.
	Integral Damper Mechanisms Top Sealing fireplace Dampers	• In old fireplaces without damper mechanism, the integral damper causes a better draft • The top sealing chimney fireplace dampers reduce heat and cool loss and also, help to reduce downdrafts, odors, toxins, pollutants, and noise.	• Reduce the airflow with the help of tight sealing

Table A1: Draft and flow resistance of chimney-top devices (Continued)

	Types	Details & Basic Feature	Draft and flow resistance characteristics and issues
Chimney Caps	Turbine Ventilator	• Australian Standard is used to test performance and flow rate capacities.	• Turbine Causes centrifugal force so it creates partial vacuum in the system.
	Chimney Fan	• Causes a negative pressure in the chimney system.	• Installing chimney fan restricts the flow • Fan must be tested for K- Value and this value may be limited to 0.5 which is similar to 45° elbow
	Reverse Cone-Rain Cap[45]	• It provides a solution for condensation problems with the use of Hollow wool formulation [43]	• Use of 360° pattern reduces flow resistance of the cap.
	Z-Vent Single Wall low resistance rain cap [44] Stack Cap	• It is useful to prevent debris or rain into vent system. • The effectiveness of this cap also depends on the wind velocity, size of debris and rate of gas flow	• Flow resistance of this system is low • It is not recommended to use with turbine exhaust
	Weather Shield Caps	• It is recommended for house near the ocean • It improves chimney performance by preventing debris, leaves, snow and rain	• None was found
	Masonry Chimney Caps	• It can hide most "Exhaust" chimney fans for aesthetics. • It is made of Clay, masonry block, cinderblock, Brick, stone chimney	• The vents at the base of the chimney pots assist with the draft.
	Decorative Shroud	• Optimum height is required to have a proper draft.	• Decorative shrouds must not be used at the factory-built fireplace chimney expect it is mentioned for using in those system.