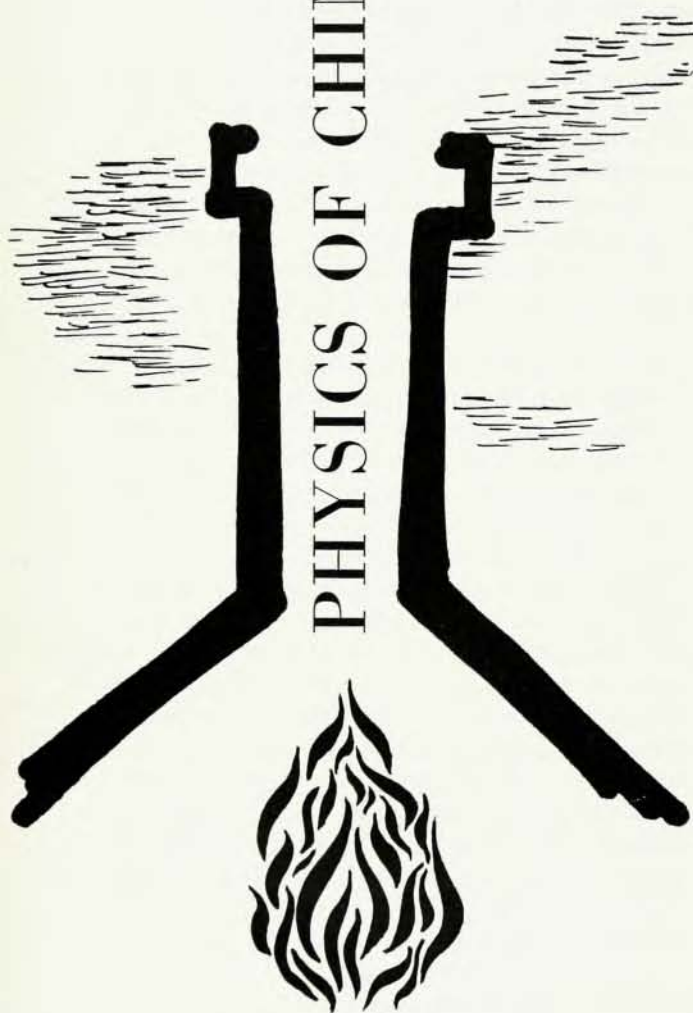


PHYSICS OF CHIMNEYS



Where there's fire there's smoke. How chimneys remove it is told in this article.

by Paul R. Achenbach

Greek and Roman architects used chimneys in kitchens and baths, though they took great care to conceal them from view. Yet it was not until the twelfth century that the practice of allowing the smoke from a fire to pass out through a hole in the roof was changed in northern Europe to the use of a hollow flue leading upward from the fireplace by the wall.

In the fifteenth century chimney, flues were grouped together in a mass of masonry and were richly ornamented with Gothic pinnacles and niches, heraldic designs, and pilasters above the roof. The chimney of the colonial period in North America was either a thick heavy construction at the center of the roof or an important feature of the end gable walls. The history of chimney design has for centuries been one of development through trial and error, although physical principles can be applied, and in recent years have been applied, to great advantage.

Drafts

Before fires were enclosed in metal stoves or brick enclosures, chimneys were merely ducts that removed objectionable gases. With enclosed heating units the chimney also had to furnish a draft to draw enough air into a furnace to burn its fuel. Thus, today, a chimney has two principle functions: it must provide a draft to bring air to the fire and it must carry the products of combustion outside a building where they can be discharged into the atmosphere with little or no inconvenience to the neighborhood.

Chimney draft is usually thought of as the current of air that flows through a furnace and passes up the chimney as flue gases. It is defined more precisely as the difference in pressure between the air outside the chimney and the gases inside the chimney. How this difference in pressure arises and how it governs the flow of air in a chimney may be best explained by considering two similar chimneys connected together, as in the top figure on the opposite page. The weight of the air in the two would be equal, providing both are at the same temperature, and so the pressure at the bottom of one would be equal to the pressure at the bottom of the other.

If the connection between them were blocked,

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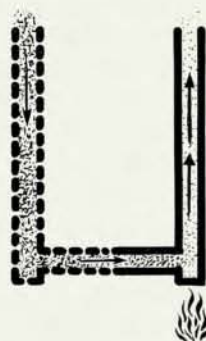
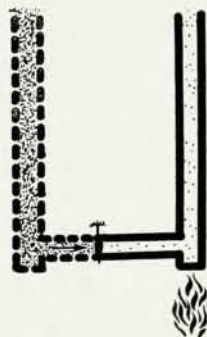
that is, if the right hand chimney were closed off so that it could not draw, and the air in it heated, some air would be driven out the top and the remainder would be less dense; the pressure at the bottom of the right hand chimney would be lower than the pressure at the bottom of the left hand chimney. This difference in pressure is called the theoretical draft, or static draft, since no flow of gases in the right hand chimney is involved in its measure. Pressure differences produced this way are very small and are usually measured with inclined manometers and expressed in fractions of an inch of water difference in head.

If the connection between the two columns were clear, and the right hand chimney permitted to draw, the pressure difference between the two would cause air to flow up the chimney being heated. There would still be a pressure difference between the bottoms of the two chimneys but it would be less than when the connection was blocked, because of the friction between the air and the chimney walls when the air is in motion. This difference in pressure is called the available draft. The available draft of a chimney is the theoretical draft minus the friction losses in the chimney.

The above still holds true if the connection to the right hand chimney is replaced by a smokepipe and the left hand chimney is replaced by a room with cracks and openings around its windows and outside doors.

A gauge, one end connected to the bottom of the chimney and the other end open to the room, would measure the chimney's draft if the resistance to the flow of outside air into the house is negligible. This is usually the case, but some present day construction, with its weatherstripped doors and windows, has been known to restrict the flow of outdoor air into the house sufficiently to require an appreciable fraction of the chimney draft to overcome this friction drop. In such instances a chimney, ordinarily adequate, may not be able to provide the necessary amount of combustion air for the heating plant.

Anything which affected the relative weights of the column of gases in the chimneys and its counterpart column of air would also change the theoretical draft of the chimney. Thus theoretical chimney draft is affected by a chimney's height, the temperature of the air outdoors, the average temperature of the gases in the chimney, the composition



of the chimney gases, the barometric pressure, and the altitude at which the chimney was erected. Of these variables, the first three are of the greatest significance although the theoretical draft of a chimney is decreased about three percent for each thousand feet of elevation above sea level.

The density of flue gases is usually about equal to the density of air at the same temperature since flue gases are often ninety percent or more nitrogen and oxygen, and ten percent or less carbon dioxide. But efficient coal heaters, which produce a relatively high percentage of carbon dioxide when their fires are banked, sometimes produce no draft in a chimney because the greater density of the carbon dioxide more than counteracts the effect of a low flue-gas temperature. Under these conditions, the gases in the chimney are as heavy as the outdoor air and no draft is produced. This, however, is a condition that seldom occurs in practice.

Performance

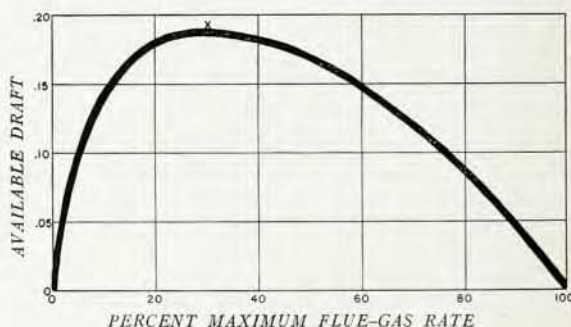
The friction that occurs when flue gases flow through a chimney is a special case of the general theory of the flow of fluids in ducts. Frictional resistance to the flow of air in a duct is approximately proportional to the square of the velocity of the air, the density of the air, and the length of the duct, and is inversely proportional to the diameter of the duct. A chimney is a special type of duct because it is usually vertical, because an appreciable change of temperature of the gases occurs in the chimney, and because the interior surface of the chimney may be quite rough with mortar projecting at the joints of the liner, or with a layer of soot clinging to the inner surface of the lining.

When the friction in a chimney is computed from the theoretical relationship, using the best accepted value for the friction coefficient, the results are usually considerably lower than the experimental values found from the difference between the observed and theoretical drafts. Observed friction is thought to be greater than the computed value because of turbulence and eddy currents adjacent to the chimney lining. Since the flue gases moving near the perimeter of the chimney are cooled in losing heat through the chimney walls, the outer layers of gas are heavier than the gases in the center. So all the way up the chimney the pressure

at the perimeter of the chimney liner is greater than it is at the center, causing transverse motion of the gases with attendant eddy currents and turbulence. These same conditions of unusual turbulence would not exist if the chimney were horizontal, or if the gases were uncooled at the perimeter. This means that a well insulated chimney would have a lower frictional loss and its actual draft approach more closely the value of its theoretical draft.

Since the available draft of a chimney is the theoretical draft less frictional losses, all factors that affect either the friction or the theoretical draft will affect the magnitude of the available draft. A typical performance curve for a chimney is shown in the figure which illustrates the relation between the available draft and the rate of mass flow of the flue gases for one value of inlet flue gas temperature. A family of such curves would show the chimney performance for a number of inlet temperatures.

The point marked X represents the maximum available draft that the chimney will produce. For



low mass flow rates, the flue gases are cooled considerably as they traverse the chimney with the result that both the theoretical draft and the available draft are low. The average temperature of the flue gas increases as the mass flow increases, thus increasing the theoretical draft (and the available draft) for mass flow rates below the value corresponding to point X. At point X, the rate at which the friction increases begins to be greater than the rate at which the theoretical draft increases, so the available draft begins to decrease at this point. To the right of point X the available draft gradually decreases because the friction builds up at an ever increasing rate until finally all of the theoretical draft is required to overcome the frictional resistance. The maximum mass flow rate



is that rate of flow which occurs when both top and bottom of the chimney are wide open and all of the theoretical draft is used to overcome frictional losses in the chimney. This rate is represented as one hundred percent on the horizontal axis of the figure. It is the maximum mass flow of gas that can be attained under natural draft conditions for this flue-gas temperature.

The effectiveness of a chimney has been defined as the ratio of the observed draft or available draft produced by the chimney for a given inlet temperature to the available draft that would be observed if the gases traversed the chimney without cooling and without friction. A curve showing the variation of chimney effectiveness with mass flow of the flue gases is similar in shape to the figure for available draft. The maximum effectiveness occurs for about the same percentage of maximum flow as is represented by point X. House chimneys vary in effectiveness from about fifty-five to ninety percent in normal usage.

A chimney for a given heating system should be designed to operate at its point of maximum effectiveness for its highest desired heat output. Actually chimneys are operated over a considerable range of effectiveness on either side of the maximum value, but are more often oversized than not which means they operate at lesser mass flows than that represented by point X on the performance curve.

A chimney would have an accelerating effect on a solid-fuel heating device if it were operating to the left of point X because each additional increment of mass flow would increase the available draft a small amount and tend to increase mass flow still more. On the other hand, a chimney operating to the right of point X would tend to decelerate the combustion rate because any increase in mass flow of the flue gases would reduce the available draft and tend to reduce the mass flow of combustion air. A process similar to this actually takes place when a given heating plant and chimney combination are allowed to attain their maximum combustion rate undampened.

Pickup

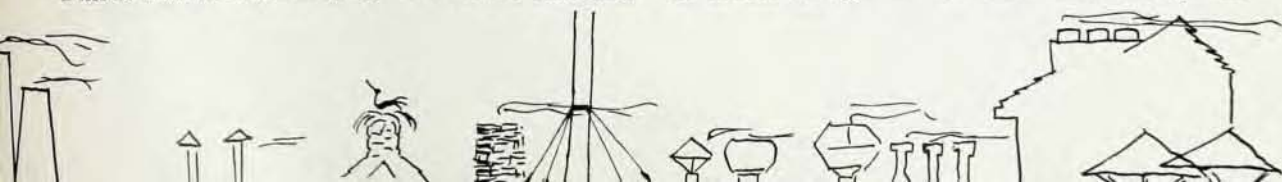
For solid fuel burning devices it is desirable for a chimney to accelerate the combustion rate rapidly from a banked fire condition to full output. This is known as picking up the fire. No standards

have been set up for the time in which a coal fire should be picked up and, indeed, it is difficult to evaluate the pickup time of a given furnace and chimney in an absolute way because of the variability in the composition of solid fuels and the inability to define or reproduce a fuel bed of a given resistance. Pickup is relatively unimportant for liquid and gaseous fuels since the rate of combustion can readily be changed from a low to a high value in a short time. For these fuels the chimney must provide only enough draft to maintain a negative pressure in the combustion chamber to prevent leakage of flue gases into the living space.

A chimney of small mass and of low specific heat will warm up rapidly from a cold start and provide a more rapid draft pickup than one of heavy construction. Although the draft pickup for different chimneys can readily be compared for a given rate of temperature change of the gases at the inlet by using gaseous or liquid fuel, it is difficult if not impossible to interpret these results in terms of the effect on a coal fire which can hardly be duplicated for comparative tests. A number of insulated metal chimneys have been developed in recent years in an effort to lower cost, decrease the mass of the materials used, and effect more rapid draft pickup. These chimneys use enameled metal or stainless steel liners surrounded by one or more inches of incombustible insulation or one or more air spaces. No method has been found as yet for comparing precisely the relative pickup characteristics of these insulated metal chimneys and the more conventional chimney made of brick or other masonry. A well insulated chimney will cool the flue gases less and will, therefore, maintain a higher average flue-gas temperature and produce more draft than an uninsulated chimney.

Height and Area

The cross sectional area of a chimney must be such that it can carry away the flue gases as fast as they are produced without excessive frictional resistance. Tables have been published showing the relationship between chimney area, chimney height, and the heat delivery of the furnace connected to the chimney for gaseous fuel. Similar data are not available for liquid and solid fuels. According to present requirements a gas appliance must be able to induce enough air for combustion through its



combustion chamber without a chimney. Hence, for a gas appliance, the chimney is used only to carry the products of combustion outside the building.

The selection of chimney areas for liquid and solid fuel burning devices is complicated by the variability in efficiency of different models, the possibility that soot on the lining will restrict the chimney's area, and the variation in the combustion air requirements of different solid fuels. Consequently there has been no simple rule developed for selecting chimney areas for liquid and solid fuel heating devices. Many building codes specify minimum chimney areas for various types of heating equipment, but these areas were not determined by any rigorous formula based on physical principles.

The design of large industrial chimneys is usually more straightforward than that of domestic chimneys. The height of industrial chimneys are not limited by architectural considerations and frequently extend one hundred feet above adjacent buildings, but a domestic chimney seldom reaches more than five feet above the roof of the house. A chimney of large diameter has less friction loss for a given gas velocity and is less affected by the layer of soot that may adhere to the chimney walls. The furnaces or boilers served by industrial chimneys probably receive more expert and more frequent attention than domestic heating plants and are, therefore, in better condition to respond to changes in heat demand than domestic heating plants which often receive sporadic attention.

At least two mathematical methods have been proposed for designing large industrial chimneys. One of these expresses the height of the chimney in terms of the required draft, average flue-gas temperature, average outdoor temperature, weight of gases flowing, and the frictional resistance, and expresses the diameter in terms of the weight of gases flowing, flue-gas temperature, and flue-gas velocity. Assuming that a chimney will be least expensive to build when the product of the diameter and height is a minimum, the product of the height and diameter is differentiated and the resulting expression set equal to zero. By assuming an average flue-gas temperature and a coefficient of friction, this equation can be simplified to yield expressions for the most economical height, diameter, and velocity of the flue gases.

For domestic chimneys there are no formulae in

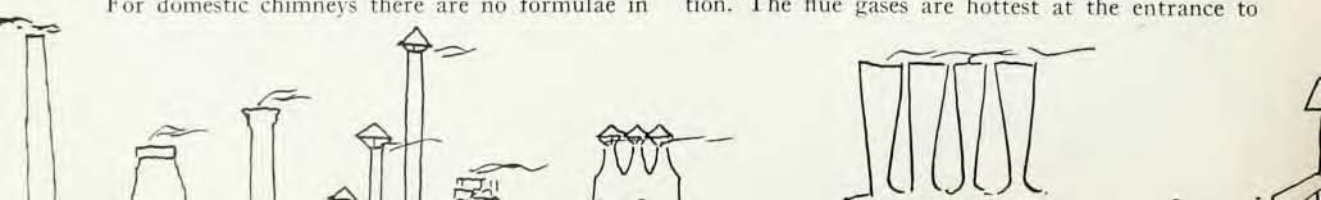
general use for determining the height and area of chimney required for a given application. There are data in handbooks and in the literature showing experimental values of the available draft and average flue-gas temperature of masonry chimneys of several different constructions for a range of inlet flue-gas temperature, a range of mass flow, and for heights from fifteen to thirty-five feet. Chimney areas for domestic application are selected for the most part to meet building code requirements for different classes of heating equipment.

Fire Hazard

Since most heating devices produce flue gases hot enough to start fires in combustible materials a chimney must convey these gases through a structure without endangering it. Most gas heaters are designed to produce flue-gas temperatures below 600° F, and because little or no soot is deposited in gas heaters or their chimneys, a chimney used exclusively for gas devices can safely be built of materials suited for lower temperatures than is possible for oil and coal.

Although an oil burner may not produce flue-gas temperatures in excess of 600° F when properly adjusted, if soot is deposited on the heating surfaces the flue gases will not be cooled as much in the heating plant and may easily reach temperatures above 800° F. In serious cases of chimney sooting a soot fire can occur in the chimney and produce extreme temperatures there for a short time.

Experimental results have shown that chimney constructions, including those built in accordance with building code requirements, may transfer enough heat through their walls to ignite combustible materials in contact with the exterior of the chimney when a coal and wood fire is maintained at its maximum burning rate in the connected heater. Abnormally high temperatures may be produced in the chimney, for instance, if coal heating systems are accidentally left unattended with dampers wide open. Although such extreme temperatures do not occur in every chimney, they are always possible and it is hazardous to place any combustible material in contact with a chimney used with oil or coal heaters. The most dangerous area will often be where the chimney passes through the ceiling construction immediately above the smokepipe connection. The flue gases are hottest at the entrance to



the chimney and there is a natural tendency to place the ceiling construction close to the chimney if the hazards involved are not known.

There is no accepted criterion stating how hot the flue gases may be without producing dangerous temperatures on a chimney's exterior surface, nor is there any criterion for the length of time a chimney may be exposed to these extreme temperatures. A limit of ninety degrees Fahrenheit above room temperature has been established as the maximum permissible temperature on combustible materials adjacent to chimneys for gas appliances, but this requirement is not used for chimneys serving oil and coal heating equipment. In fact, this limitation would so seriously restrict the flue-gas temperature that many chimneys would not produce enough draft to operate oil and coal heating devices.

No Smoking

If a chimney does not project about two feet above the ridge of the house, or if there are taller buildings or trees near at hand, downdrafts may occur when the wind blows across the chimney top in certain directions. In very cold climates the flue gases are sometimes cooled below the dew point and an acid condensate runs down the inside wall surface of the chimney. This happens often in chimneys attached to gas burning devices where flue gases contain more water vapor than flue gases from other fuels. The condensate in flue gases, acid because of the sulfur in the fuel, will attack and dissolve the ordinary lime mortar used for laying brick chimneys. Consequently chimneys for gas burning heaters must either be lined with an acid resisting material or they must be built with acid resisting mortar.

Where there are several heaters in the same house, more than one is sometimes connected to a single chimney. When the two heaters are on different floors this arrangement may work satisfactorily, but it is not recommended because the operation of one heater affects the draft available for the other. Under certain conditions the pickup of one heater may be slow or one may cause the other to smoke. There is always the possibility that a heater will puff and blow soot into the room through some other unused chimney inlet that is covered with a loose-fitting sheet metal plate. It is still common practice to connect the small flue from a gas storage water heater to the chimney serving the stove or central heating system of the house. This arrange-

ment is acceptable in most cases since the water heater flue is small. However, the air that enters the draft diverter of the water heater lowers the flue gas temperature in the chimney and reduces somewhat the draft available for the other heating device. It is better practice to install several liners in one mass of masonry when several heating devices are to be used in the same structure. A wythe of brick should be placed between adjacent liners in such installations to prevent leakage of air or flue gases from one liner to another.

The chimneys for fireplaces require special consideration, because they carry large volumes of gases at relatively low temperature and must have a cross sectional area at least one-tenth the area of the fireplace opening to keep the fireplace from smoking. A fireplace chimney also needs a smoke shelf and a smoke chamber just above and to the rear of the throat. The smoke shelf changes the direction of the downdrafts that are likely to occur in such a large chimney and directs them back into the upward moving stream of warm gases.

Countless millions of chimneys have been built based on experience and on an incomplete knowledge of the physical factors involved in their design. Probably the majority of these have worked satisfactorily but many have been faulty. Chimneys may be eliminated in the future if electric resistance heating, the heat pump, solar heating, or atomic energy become common methods of warming a house, but millions of chimneys will be built in the meantime and further studies should be made of the principles involved in their operation. Further research on chimneys should be conducted especially in the fields of safety for abnormal flue-gas temperatures, the relationship of chimney area to capacity, the demands placed on the chimney when picking up a fire, and the methods for preventing condensation in a chimney or removing the condensate safely after it is formed. If information on these features of chimney performance were available and properly disseminated together with the present knowledge, every new chimney could be a satisfactory chimney.

Black Star

