AMERICAN
JOURNAL
of PHYSICS

VOLUME 49, NO. 6
JUNE 1981

Domestic fire and its improvement: Some qualitative insights

Lawrence Cranberg
Texas Fireframe Co., Austin, Texas 78764
(Received 10 March 1980; accepted 29 August 1980)

Evidences of domestic wood fires have been found in caves occupied by Peking Man, and are estimated to be about half a million years old, so that fire-making with wood must be considered among man's oldest inventions. Perhaps the most remarkable fact about this particular invention, however, is that the technique of making and maintaining a wood fire may have changed very little in the vast stretch of time since Peking Man, in contrast with the striking evolution characterizing all of man's other early inventions, such as tools, clothes, and language.

To be sure, we now have very elegant methods of igniting a fire by the use of matches, fluid lighters, etc., and we have much-improved means of conducting smoke to the outside of our dwellings, but the process called "laying the fire," or arranging the fuel elements of the fire cannot be presumed to have changed materially since earliest times. The configuration of logs to be found in the fireplace of the modern American home is unlikely to differ materially from the arrangement on the hearth of the cave of Peking Man.

What the foregoing suggests is that the physical constraints which must be met to initiate and maintain combustion are severe and do not tolerate much variation. We shall see that this is partly but not entirely true, and that in fact the application of fundamental physical principles suggests improvements on the ages-old methods of laying a fire, with some useful and unexpected consequences.

The essential fact, driven home by universal experience, is that a single log or a pair of logs is insufficient to maintain combustion reliably even if much primer or kindling are laid under or over them. It must have become apparent very early in the history of man's firemaking efforts that there is a "Rule of Three"—that the simplest, most reliable arrangement of logs for maintaining a steady fire is an arrangement of three logs—typically, two resting in general contact, with the third resting on the two below, all with axes generally parallel, as shown in Fig. 1, with kindling in place for starting. The first question to be addressed is what is the controlling physical requirement which is met when one assembles logs as stipulated by the Rule of Three.

The answer is reasonably evident to anyone who has made a fire or who thinks about it. If one disassembles a three-log fire that has been burning for a while, it is clear that the burned surfaces on each log are those which faced each other. Thus the Rule of Three is just the condition that one should create a partially enclosed volume defined by the intersections of the surfaces of the fuel, or what we shall call a combustion volume or combustion space. Within this space are formed the coals which maintain a steady temperature, and when fresh wood is fed into that space, as by the operation of rotating one of the logs ("stirring" the fire), the fresh wood is pyrolized, producing a fresh show of flames, whose body extends outside the cavity through a space between the logs. This gives a visible show of flames

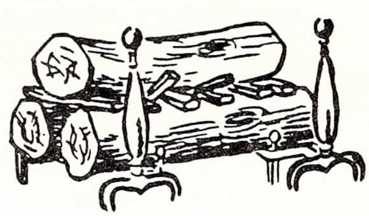

Fig. 1. Log arrangement of conventional fire, illustrating the Rule of Three, with kindling in place for starting.

 0002-9505/81/060596-04$00.50

until the supply of pyrolized material is depleted and another rotation is needed. Typically the flames exhibit an exponential decay in height, diminishing by half in about five minutes. Thus the combustion space acts as a furnace, and the laying of a fire is in effect the construction of a furnace, into which one repeatedly feeds fresh fuel.

What we have just said is all readily observable and has perhaps been intuitively clear for a very long time. But only since the processes of heat transfer have been fully elucidated in the last 150 years or so can it be said that we have an understanding of what is going on in scientific terms, at least at the level of principle. It is significant to observe that thus far no one has calculated in detail how a fire develops, and we shall be concerned here only with a qualitative formulation in terms of the general principles of heat transfer, and the roles played by conduction, convection, and radiation separately and by interaction with each other in the context of the domestic wood fire.

CONDUCTION

The conduction of heat from flame to wood is the usual starting point of the process of igniting wood, and is called "pilot ignition," although convection and radiation ignition are also known, and play a role as we shall see. It is fortunate indeed that wood is a relatively poor thermal conductor, as is air, for if they were not, the heat applied by an open flame would be readily conducted away from the surface into the bulk of the material and into the air, and it would be far more difficult to raise the surface temperature to the ignition point. By the same token, it would be more difficult to maintain the ignition temperature at any particular site and thereby to maintain a self-sustaining combustion process. The presence of appreciable moisture in wood probably affects combustibility at least in part because of the increase it produces in the thermal conductivity of wood.

CONVECTION

Convection is presumably essential as the means of removing the products of combustion and maintaining a steady flow of air to the burning surfaces. The role of convection in transferring heat energy from one surface to another and thereby maintaining combustion conditions is less clear. Much of the convected energy is probably associated with flames, and while these may be rooted in surfaces within the combustion volume, the body of a wood flame typically extends outside that volume. Thus the plumes of the flames, which have been shown by simple calorimetric measurements[1] to transport about two-thirds of the energy of the flames, will typically carry convection energy outside the combustion volume and vent it up the flue. If that energy is not retrieved in some way, it represents a loss of energy whose only benefit is the creation of draft in the flue.

RADIATION

The crucial importance of radiation to the dynamics of the fire-making process, and the fact that our understanding of the properties of radiation is less than 150 years old are perhaps the chief reasons that our understanding of fire making has lagged as much as it has. Thus even the perceptive and highly motivated Count Rumford lacked the scientific tools with which to describe the role of radiation in the fire-making process.

Although our discussion will be limited to qualitative aspects only, it will be evident that such discussion is necessary as a preliminary to more quantitative studies, and in particular, proves useful as a guide to improvements at the practical level.

It is now clear that underlying the Rule of Three is the creation of a combustion volume in which energy exchange by radiation among the facing surfaces can take place freely and with little loss to the outside world. Indeed, this exchange of radiation will impel the surfaces to achieve a uniform temperature, so that the combustion space approximates the blackbody cavity of classical radiation theory.

It is, in fact, quite reasonable to describe the conventional fire as at heart the hohlraum or hole space of classical physics, but one with combustible walls on which there happens to be an ongoing combustion process. And the hohlraum it will be recalled, when provided with a small opening to the outside, becomes the ideal blackbody, which by Kirchhoff's law is the ideal radiator at a given temperature.

Thus the openings which occur fortuitously between the logs of the conventional fire due to their natural roughness become the working equivalents of the small hole which converts the classical hohlraum into the ideal blackbody. And now it becomes clear that the useful output of the conventional domestic fire in the fireplace, which is the radiation which emerges into the room, originates in the haphazard irregularities of the logs, rather than any conscious intent on the part of the fire maker.

What has been said thus far refers to that early stage of the fire before the logs disintegrate into coals. In the later stage, when coals form and accumulate on the hearth, the situation becomes considerably more complex as the radiation from the coals interacts with that from the logs. Without continuing into discussion of that later stage, however, it is already evident where improvements may be sought – namely, in the adjustment of the openings of the hohlraum and in the control of its proportions, rather than in leaving them to chance.

EXPERIMENTAL STUDIES

After a few preliminary studies indicated that the approach we have just described offered promise of interesting results, a simple steel support[2] was constructed which made it possible to arrange logs to enclose a cavity of adjustable proportions and adjustable opening. It is shown in Fig. 2. Logs are supported at a lower level, and one or more logs may be supported at an upper level whose height can be

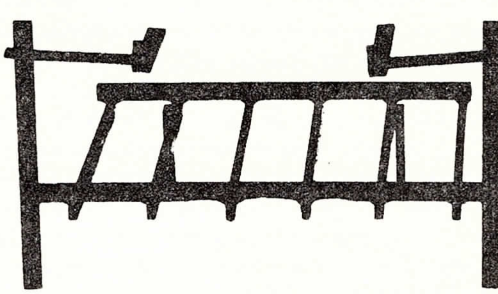

Fig. 2. Log support (Texas Fireframe grate) for experimental study of log arrangements for use in domestic fire making.

adjusted by means of friction-locking arms which slide up and down each of two vertical supports. By this means a cavity with given proportions can be created with logs of widely varying sizes, and conversely, the cavity can be given widely varying proportions with logs of given sizes. At the same time the opening of the cavity to the room can be adjusted. Use of the support is illustrated in Fig. 3.

Systematic investigation with the log support shown in Fig. 2, and with a variety of alternatives, including use of cavities fabricated of shaped wood blocks, quickly narrowed the investigation to study of the log arrangement shown in Fig. 3. In that figure, there is a large back log which provides the back surface of the cavity, several smaller logs which provide the floor, and an upper log or logs which form the roof.

For obvious reasons, the cavity created in accordance with Fig. 3 we call a slot-hohlraum. The properties of such a cavity are reasonably expected to be little different from those of the classical hohlraum, due account being taken of the considerably larger open area, including the entirely open ends. But it turns out that the characteristics of the combustion process which is initiated within such a cavity are so distinctive as to warrant a special name, and we call it the slot fire. The characteristics of the slot fire are as follows.

SLOT FIRE

Investigations with a variety of fuel materials give minor variations in results, but to be specific, we shall discuss observations with seasoned, unsplit oak logs of about 24 in. length, with a slot about 6 in. deep and about 3 in. high.

(1) *Starting.* Typically, three to five sheets of newspaper placed in the cavity and ignited will make the system "go critical" and initiate a steady fire which is confined almost entirely within the cavity, and which rapidly fills the cavity from end to end with flames which are rooted in the lower front logs.

(2) *End-to-end uniformity.* Within a few minutes of starting, it becomes evident that the axial symmetry of the arrangement creates a uniformity of the flames that is partly expected and partly surprising, particularly because it extends to the ends where one might expect less rapid burning than in the middle. Further, the end-to-end uniformity remains steady with time. As the fire progresses, the slot gradually widens as the lower logs are consumed, but the slot retains its essentially rectangular profile with constant proportions along the slot axis.

(3) *Burning of lower front log.* The site of most vigorous combustion appears to be the line of contact between the back log and the smaller log adjacent to it, and in due course these logs are consumed at their points of contact. When contact is broken, the fire cools appreciably, but is restored to full vigor when contact is restored. Thus the maintenance of vigorous combustion requires occasional pushing of the smaller front logs to maintain contact with the back log and with each other, but no rotating of logs is ever needed to maintain vigorous combustion. When the front logs are fully consumed, flaming ceases and the fire is in a banked or smoldering condition. Replacement of the front logs quickly restores flaming, which is evidently initiated by the buildup of radiation within the cavity (radiation ignition).

(4) *Burning of the back log.* The characteristic evolution of the back log is toward providing a wall of coals which faces the cavity and the room, producing probably the largest fraction of the radiant energy which enters the room from the fire. This wall of coals gradually recedes toward the back surface. The crumbling of the back log is the signal for its replacement, which is accomplished by putting the replacement on the upper arms, and letting the new back log fall into its place.

(5) *Burning of the upper log.* The upper log is preferably in close contact with the back log, but there is relatively little combustion at the line of contact. The major combustion process takes place in a fairly uniform manner on the under side of the upper log, which gradually erodes to a flat surface if it was originally cylindrical.

(6) *Radiation pattern.* As must be expected, the radiation pattern from the slot is directed toward the principal opening of the slot, and is therefore in a predominantly horizontal direction. This pattern is clearly indicated by simply passing one's hand across the slot, and measurements by Walker[3] have confirmed it. Walker has also established the interesting fact that the radiant energy from the conventional fire is predominantly upward, a result which has unfavorable implications both for the efficiency and for the safety of the conventional fire. Since upward-directed energy increases the risk of so-called chimney fires, the horizontal beaming of energy from the slot fire has a potential safety benefit.

INTERPRETATION

The combustion process is in fact a complex of physical-chemical processes which extend far beyond the narrow reach of simple physical ideas. To calculate so basic a feature as combustion rate would go far beyond the physics of heat transfer. But it is interesting nonetheless to see how far one can go with those simple physical ideas, and we consider two aspects of the slot fire which are particularly striking: the ease of starting and the end-to-end uniformity.

A. Ease of starting

At first blush, the ease of starting is anomalous. The slot-hohlraum is far more open than the conventional hohlraum, with its almost totally enclosed combustion space, so that radiation can leak much more freely into the room when it is badly needed to sustain the process of ignition. The only resolution of this anomaly which is evi-

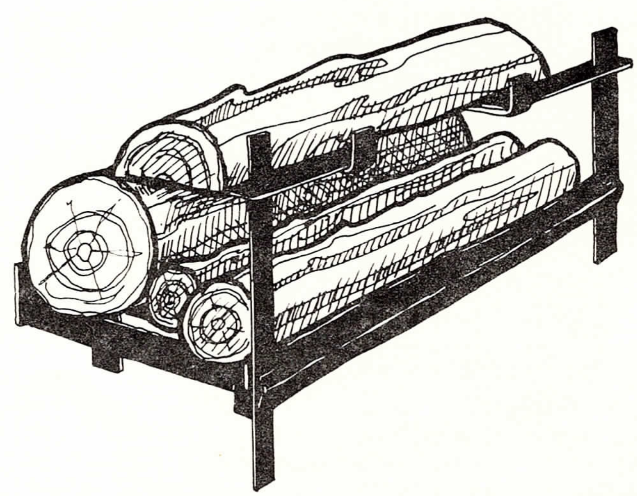

Fig. 3. Slot fire log arrangement.

dent to the author is that a crucial role is played by convection during the starting process. As indicated above[1] studies on simple flames showed that a very large fraction (two-thirds) of the energy produced by a flame is transported vertically in the plume. With the conventional fire, that energy is lost up the flue. But with the slot fire, that energy is intercepted by the upper log and much of it must be transferred to its under surface, where it is fed back into the cavity as radiant energy. Thus one may view the upper log as a convection-to-radiant energy converter, and the same may be said for the slot as a whole.

B. End-to-end stability

If we postulate that the economics—that is, the gain and loss—of radiation holds the key to the combustion rate once the fire is started, then a simple feedback argument can be adduced to interpret the end-to-end stability of the combustion rate. For if the combustion rate were to increase locally, the slot would enlarge at that place, increasing the solid angle through which radiation escapes into the room and decreasing the fraction retained within the cavity, with a corresponding reduction in combustion rate. This negative feedback coupling of geometry to combustion rate is just what is needed to produce the stable result which is observed.

ANALOGY BETWEEN COMBUSTOR AND NUCLEAR REACTOR

It is to be expected that the domestic fire and a nuclear reactor might exhibit significant similarities since both are exothermic chain-reacting systems based on solid fuel. In the fire, the photon plays a role which is analogous to the neutron in being the carrier or trigger of the chain reaction, as well as its byproduct. But the fire is in fact a much more complex system than the nuclear reactor. Despite its newness, a nuclear reactor can be designed from first principles, and such fundamental quantities as dimensions, criticality conditions, and power level can be calculated with a good deal of accuracy. None of these quantities is within the present compass of theory for the solid-fuel fire. It might be hoped, however, that the axial symmetry of the slot fire, which if infinitely extended reduces the complexity of the various processes by one dimension, increases the feasibility of a theoretical approach.

EFFICIENCY OF THE SLOT FIRE AND THE CONVENTIONAL FIRE; THERMAL COMFORT

Much has been said about the inefficiency of the conventional fire as a converter of chemical energy to useful heating energy, and much of what has been said is undoubtedly correct. But there is still a good deal of uncertainty about the magnitude of the observed efficiency, and the same applies, as of this date, to the slot fire. In a recent publication, Trefil[4] has given a figure of 11% for the conventional fire, with an efficiency for the slot fire which is 2.6 times greater. It would be useful to have further measurements by independent observers. In any event, it should be kept in mind that efficiency measurements give only one parameter of the utility of the domestic fire. Thermal comfort, which is the ultimate desideratum, is a direct function of one's proximity to the fire, and of the fraction of one's time spent in proximity to it. Those quantities are determined by a set of considerations even more complex than those which determine combustion rate. Among those considerations are the fascination of the fire itself as a visual spectacle and as a scientific challenge. Both promise to be of enduring value.

[1] L. Cranberg, Bull. Am. Phys. Soc. **25** (1), 23 (1980), paper DF-7.

[2] The device illustrated in Fig. 2 is marketed under the trademark Texas Fireframe Grate. It is covered by applicable U. S. Patent No. 4069808, "Apparatus and Method of Combustion," Jan. 24, 1978, which describes the slot fire and its method of use. See also, L. Cranberg, Bull. Am. Phys. Soc. **20** (19), 1183 (1975), Series II, paper DC-12.

[3] J. Walker, Sci. Am. **239** (2), 143 (1978).

[4] J. Trefil, Pop. Sci. **216** (1), 44 (1980). Trefil's results are for the standard, 25-in. model of the Texas Fireframe Grate. J. Shelton [Wood Burning Quart. 3 (3), 169 (1978)] reported results for the shortest (17-in.) model of the five available models, of 20% and 24% on two trials. Trefil's and Shelton's data are both consistent with an estimated efficiency for an infinitely long slot-hohlraum of about 42%, assuming there was no recovery of end losses in both sets of measurements. With perfect recovery of end losses—for example, with perfect reflectors directing end-loss energy into the room, the estimated realizable efficiency with a finite slot-hohlraum is therefore about 42%.