Quenching of Flames and Flashback on Shutoff with Gas Appliance Burners

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The occurrence of flashback, when the supply of fuel gas to certain "critical" appliance burners is quickly shut off, is considered from the viewpoint of theoretical treatments of flame quenching. This phenomenon may present a restriction, in gas utility practice, on the proportion of a fast-burning gas which may be mixed with a slow-burning base fuel gas such as natural gas to supply peak loads. Experimental work indicates that the occurrence of flashback on shutoff conforms with the theory of flame quenching. Its incidence can be predicted for a given appliance burner and fuel supply from data readily determined in the laboratory. Measures available to remedy field conditions may then be appraised with confidence.

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One of the most annoying varieties of consumer's service complaint encountered by gas utility companies, when it is necessary to supplement a slow-burning base supply fuel gas by mixing with it a substantial proportion of a fast-burning gas, is the occurrence of flashback when the supply of gas to the burner is quickly shut off. This flashback is often accompanied by a loud explosive noise, usually referred to as "noise of extinction." The loudness of the noise depends largely on the volume of explosive air-fuel mixture enclosed by the burner head, although it is influenced also by the composition of the air-fuel mixture and the nature of the fuel gas. The noise can be loud enough to be frightening to a consumer when it occurs in a large househeating burner, or in a water heater burner. Fortunately, however, there is little related hazard, since it occurs when the burner is shut off.

The probability of encountering this type of unsatisfactory performance, when the supplementary gas is included in the fuel distributed to consumers, has in the past been tested empirically and qualitatively. Certain burners, known through experience to be "critically" responsive may be used as test burners. They are adjusted in the customary manner when supplied with the base gas. Then, when supplied with the substitute or supplementary gas mixture, it is observed whether or not flashback on shutoff occurs. No other tests have been devised by which this behavior can be appraised quantitatively, to evaluate the effect of gas composition on its occurrence, to determine whether or not any burner will exhibit it, or what adjustment can be made to alleviate the trouble. It is fortunate that the design and normal adjustment of most contemporary gas appliance burners allow them to operate satisfactorily beyond the range of this type of flashback. However, there are enough "critical" burners in current use that the phenomenon can present an undesirable limitation to the proportion of the supplementary gas which may be distributed during peak-load periods.

In this report the results of theoretical considerations and of some experiments are presented, which it is believed clarify our understanding of this phenomenon. A quantitative method for measuring the tendency of a fuel to flash back on shutoff is proposed, which, when combined with port dimensions of any appliance burner, will indicate the air-entraining adjustment which will prevent flashback and noise of extinction.

Theoretical Background

Flashback on quickly shutting off the fuel supply to a burner occurs because the velocity of the combustible mixture through the ports is suddenly brought to zero. The composition of the air-fuel mixture in the burner head will be determined by the air-shutter adjustment and the gas density just prior to shutoff. It should be noted that if the burner cock of the ordinary atmospheric burner is shut off slowly the proportion of air entrained decreases gradually as the fuel flow decreases. The situation differs importantly, however, with a quick shutoff, in that the air entrained and remaining in the burner head is the maximum value permitted by the air shutter adjustment. This should be kept in mind, since it differentiates as well between the behavior of certain appliance burners which are controlled by the throttling and by snap-acting thermostats, respectively.

Consider a bunsen flame stabilized above a cylindrical burner port. Quickly but smoothly stop the flow of combustible fuel-air mixture through the port, as by turning off the burner cock. The flame will be quickly reduced in size until it becomes nearly flat across the port. It will then either flash back through the port, or will be quietly extinguished, depending on the composition of the fuel and fuel-air mixture and on the diameter of the port. If the diameter exceeds a certain critical size the flame will penetrate the port; if it is less than the critical size the flame will be quenched.

These observations are in accord with modern theories of flame stabilization.(5) For example, according to a thermal theory, heat from the combustion zone or flame front flows to the colder burner port wall cooling the flame in the region near the port rim to such an extent that the burning velocity is reduced and at some point in that region becomes equal to the local flow velocity. This stabilizes the flame at the port. There is then near the rim a region in which temperature gradient exists, wherein the flame is quenched, referred to as the "quenching zone." Its effective width is denoted as the "quenching distance." If the size of the flame is reduced, its area becoming smaller, a critical area may be reached, depending on the stream or port diameter, at which the heat released in the combustion zone is equal to that which flows to the walls and there is no excess available for self-propagation. If, on the other hand, the port diameter is large enough, so that when the flame is at minimum size there is sufficient energy released in excess of that flowing to the walls, the flame surface will penetrate past the rim and continue to burn within the cylindrical port, i.e., will flash back through the port.

Because of the similarity of heat conduction and active particle diffusion equations, it is possible to derive equivalent conclusions by considering the quenching action as the destruction of flame propagating chain carriers by the burner port wall. It seems likely that in reality a combination of both processes may be occurring.

Expressions for the magnitude of the quenching distance and of the critical tube diameter have been deduced theoretically. One equation for the quenching distance is given by Friedman(3) as

$$x = \frac{k}{sc}\left(\frac{1}{f} \cdot \frac{T_f - T_i}{T_i - T_o}\right)^{1/2}$$

Unfortunately, the simplifying assumptions introduced, and uncertainties in properties of gases at higher temperatures permit only approximate values of x to be calculated. Many comparisons with experiment, however, appear to provide sufficient basis for the belief that the formulation of the quenching phenomena is basically correct.

It is the purpose here to indicate the practical utility of quenching data, and in particular of measurements of the critical port diameter and its variation with air-fuel mixture composition for different fuels. It will be shown that flashback and noise of extinction will occur when the proportions of air and fuel in the combustible mixture are such that the flame is not quenched at the port rim. This will occur most readily with fast-burning gases.

Experimental Work

The apparatus consisted essentially of a glass manifold to which were connected seven glass burner tubes, 6 to 8 inches long, having nominal inside diameters 2, 3, 5, 8, 10, 12 and 15 mm. At the inlet end of each burner tube a 2 mm bore glass stopcock was inserted. A premixed fuel-air mixture was supplied to the manifold.

The composition of air-fuel mixtures was determined which would just fail to flash back through the tubes of different diameters, that is, which would just be quenched by the respective tubes. Several different fuels were used, supplied in compressed gas cylinders. These are listed with their properties in Table I. Fuel and air were separately metered by differential flowmeters, and mixed at a T-connection immediately before entering the burner manifold. Proportions of fuel and air, in addition to the total flow rate, were adjusted and controlled with needle valves at the flowmeter inlets. A head of water in a suitable bottle connected to the manifold outlet determined the mixture pressure at the burner inlets, since an excess of the mixture was always allowed to escape the overflow bottle.

TABLE I

Fuel Gases

	Specific Gravity, (Air = 1.0)	Heating Value, Btu/SCF	% Gas in Stoichiometric Mixture
Methane‡	0.554	1013*	9.5*
Ethane‡	1.049	1792*	5.65*
Propane‡	1.531	2590*	4.08+
Ethylene (anesthetic grade - 99+%)	0.974	1614*	6.55*
Propylene‡	1.45	2336*	4.46*
Natural Gas	0.594	1046+	9.24+
Synthetic Mixture (H_2, 24.4%; CH_4, 45.1%; C_2H_4, 30.3%; CO_2, 0.2%)	0.564	1026+	9.79+

* From "Gaseous Fuels," American Gas Association, New York (1948) p. 118.
\+ Calculated from analysis.
‡ Technical grade - purity 95% or better.

A combustible mixture of approximately the desired proportions was admitted to the burner manifold by adjusting the fuel and air flow rate appropriately. One of the burner stopcocks was then opened slightly and the mixture was ignited at the burner port with a small pilot flame. When a small stable flame was established, the burner cock was quickly closed. The flame was then either extinguished at the burner rim or it flashed back down the tube. By successive adjustments of either fuel or air rate that mixture composition was found for which the flame would just fail to flash down the tube on shutting off the flow. The experiment was repeated for each size tube in turn, with mixtures on both the lean and rich side of stoichiometric. It was often not possible to establish a stable flame when the mixture was on the fuel-lean side. In these cases, a small pilot flame was maintained as the ignition source near the emerging jet just above the port.

Subsequently, tests were made with several appliance burners, using the synthesized three-component mixture,* in order to determine whether their performance agreed with that expected from consideration of the quenching curves. Pertinent dimensions of the appliance burners may be seen in Table II.

* The three-component mixture was prepared to simulate closely the burning characteristics of a manufactured oil gas. Extended experience has shown that the "synthetic" mixture reproduces the behavior of oil gas adequately for these tests.

TABLE II

Appliance Burners Tested

Burner	Type	Ports	Port Dimensions	Remarks
A	Range top	Cylindrical	2.8 mm diameter	Ports arranged in two circles.
B	Range top	Cylindrical	2.95 mm diameter	Star-shaped arrangement
C	Range top, removable head	Rectangular	6.35 x 2.38 mm	Designed for natural gas
D	Range top, removable head	Square	2.57 x 2.57 mm	Designed for manufactured gas
E	Water heater	Cylindrical	2.7 mm diameter	Two rows of ports
F	Hotel range	Cylindrical	1/4"	Two concentric circles designed for manufactured gas
G	Hotel range	Cylindrical	5/16"	Burner F after enlarging ports

In all cases the composition of the limiting mixture which was quenched by the respective burners was determined for air-fuel mixtures richer in fuel than stoichiometric. For three of the burners determinations were made with lean mixtures also. Only the former are of practical interest.

Data were obtained for all the fuels listed in Table I with the glass burners. They are presented graphically in Figures 1-3, in which the proportions of air and fuel, represented by the value of F, in mixtures quenched by tubes of different diameters are plotted. F is the ratio of the percentage of gas in the combustible mixture to the percentage in a stoichiometric mixture of the fuel and air. The region on the concave side of the respective curves represents flashback conditions, while the region on the convex side represents quenching.

The data observed with the several appliance burners are plotted in Figure 4. The solid curve represents the data obtained with the group of seven glass burner tubes. The individual points plotted represent the performance of the appliance burners indicated by the respective labels. Data obtained with the removable head type range-top burners, having rectangular or square ports, are plotted at positions representing equivalent cylindrical ports as discussed in the following section.

Discussion of Results

Some of the curves plotted in Figures 1-3 may be compared with published data.(4) The purpose of using some of the fuels was to establish thus the validity of the experimental results obtained with the glass tube apparatus. For example, the quenching curves for methane and propane shown in Figures 1 and 2 are in agreement with published experimental results within limits believed to be consistent with the purity of the compressed gases used.

It will be observed that all curves resemble inverted burning velocity curves, the minimum of the quenching curves occurring approximately at the air-fuel ratio at which the maximum burning velocity occurs. Moreover, the fuels can be arranged progressively, with respect to the minimum port diameter, in the same order as if arranged according to their maximum burning velocities. The "faster burning" gases require the smaller minimum size port to quench the flame. The olefines are "faster burning," and their quenching curves fall below the curve for the corresponding paraff hydrocarbon.

The utility of the results of this investigation may be examined first by comparing the observed performance of several appliance burners with the data obtained in the laboratory quenching tests. For brevity, this will be limited to performance with the simulated oil gas mixture.

Most range top burners have cylindrical ports, and practical port diameters recommended by the American Gas Association (1) minimize unsatisfactory performance because of flashback on extinction. There are, however, some burners, of the removable head type, for example, and some commercial equipment which because of large port size are classified as "critical burners" in this respect. That is, they are critically responsive to the proportion of oil gas which may be mixed with natural gas.

When tested with the simulated oil gas mixture, it was found that quenching occurred with the three drilled port domestic range top burners in conformity with results predicted from the curve as indicated in Figure 4. Performance points representing the observations are plotted on the graph. For example, it was found with the star-shaped burner that flames were extinguished quietly without flashback for all simulated oil gas-air mixtures with F values greater than 1.4. The fact that the port diameters of these three burners are sufficiently small, to quench flames of all mixtures except those near stoichiometric proportions explains why the burners are not "critical," since the normal operation is with air-fuel mixtures far to the right of the curve, at, say $F = 1.6 - 1.8$.

The small differences between the curve and the performance points for the respective appliance burners may be attributed to uncertainties in the actual port diameters (since measured diameters would tend to be too small), or to inadvertent heating of the burner during an experiment. Either reason would account for divergence from the curve in the direction indicated.

The removable-head burner results require further analysis, since the ports are rectangular, and in addition the port axes are inclined at an angle of about 45° to the vertical. Berlad and Potter(2) have derived relationships theoretically on the basis of a diffusion mechanism for the combustion wave for the difference in quenching effect for ports having different shapes. They give the following expression for the relation between rectangular dimensions and the diameter of a circular port which gives equivalent quenching effect:

$$\frac{d_c}{d_r} = \frac{32}{12}^{1/2}\left[1 - 0.300\left(\frac{d_r}{b_r}\right) - 0.047\left(\frac{d_r}{b_r}\right)^2 \right]$$

According to this equation, the ports of the burner designed for natural gas, being 0.635 x 0.238, would be equivalent in quenching effect to a circular port 0.342 cm in diameter. Similarly, the ports of the manufactured gas head are square, 0.257 on a side, and would be equivalent to circular ports 0.275 cm in diameter. Points are plotted on Figure 4 representing quenching by these two burner heads at the equivalent circular port diameters. They are displaced somewhat in the fuel-rich directior and it is suspected that the displacement may be caused in part by the angle of the ports. The basis for this conclusion is that the apparent burning velocity of a fuel-air mixture, as determined by the rate of flame travel in a mixture enclosed in a vertical tube, depends on whether the propagation is upward or downward, due to buoyancy effects. It is again different in horizontal tubes. Since quenching and burning velocity are directly related, one would expect to detect buoyancy effects in quenching experiments. The direction of the expected change corresponds with the observed. Practically, then, the angle of the ports in these burners permits the flashback to occur over a greater range of mixture compositions on the gas-rich side. In other words, these burners are somewhat more sensitive to this type of faulty operation.

A ring-type hotel range burner was available for test. This is considered a "critical" burner with regard to noise of extinction. The example tested was originally designed for use with manufactured gas, having 1/4" diameter ports. A diameter thought to be more suitable when the burner is supplied with natural gas is 5/16". In the tests with the simulated oil gas mixture in this laboratory determinations were made first with the 1/4" diameter ports. The limiting mixtures which were quenched are plotted in Figure 4. Following these tests the ports were drilled to 5/16" diameter and additional quenching tests made. It is observed from the plotted data that the increase in port size increased the rich quenching limit from F = 1.5 to F = 1.75. That is, the small ports would quench the flame of a much leaner mixture (air-gas ratio = 5.8) compared with the larger ports (air-gas ratio only 4.8). Thus, by enlarging the ports the burner became more "critical" with regard to flashback and noise of extinction, since it is necessary to operate it at lower aerations. In good practice this burner is adjusted to entrain primary air in the ratio of about 5.6 to gas when supplied with natural gas having a specific gravity of 0.6. As seen in Figure 5 the performance point corresponding to this adjustment already falls within the flashback region of the simulated oil gas curve. If manufactured oil gas having a specific gravity greater than 0.6 were supplied to the burner, the primary air-gas mixture would become even leaner, in effect moving the performance point further to the left.

Further utility of laboratory quenching data in lieu of direct tests on appliance burners may be illustrated by the following example. Certain other appliance burners which often show this type of critical performance in practice include two models of drilled port househeating conversion burners. It has not been possible to determine quenching limits with this equipment, but predictions of interest from laboratory quenching data may be made of their behavior.

The performance points farthest to the right indicated for the conversion burners in Figure 5 represent their respective port diameters and approximate normal primary air adjustment with natural gas. If manufactured oil gas is supplied in place of the natural gas its greater specific gravity will result in a higher primary air-gas ratio. This corresponds to moving each performance point to the left (toward leaner mixtures) by an amount corresponding to the square root of the ratio of the specific gravities of oil gas and natural gas. If the specific gravity of the oil gas were 0.8 the change in aeration would be toward the leaner mixtures indicated for the respective burners on the graph. These points lie within the flashback region for the simulated oil gas. Since flashback and noise of extinction were observed in experiments with an actual manufactured oil gas, its quenching curve cannot be substantially nearer to stoichiometric proportions than that for the simulated oil gas used in these experiments. If the quenching curve for the oil gas were available the aeration adjustment of these burners on natural gas could be determined which would avoid this faulty performance when manufactured oil gas is substituted. A smaller primary air-gas ratio would be required.

It should be noted that the quenching data make no reference to the occurrence of yellow flames. The appearance of yellow tips or the occurrence of traces of carbon monoxide in combustion products at lower aerations would mark other limits of practical adjustment in that direction. It is clearly possible that there may be no air shutter adjustment compatible with the avoidance of all these faults. A clear-cut limitation of the utility or "interchangeability" of the oil gas would in that case be imposed by such appliance burners. The present approach to flashback and noise of extinction, however, permits a quantitative evaluation of this difficulty and of required remedies not provided in any earlier studies on the subject.

Summary

1. An experimental study has been made of the quenching of flames by burner ports of different diameters. The observed data are plotted as curves showing the relation between port diameter and the composition of the combustible fuel-air mixtures just failing to flash back through the ports. Five simple hydrocarbon gases were studied, in addition to natural gas and a synthetic mixture of hydrogen, methane, and ethylene simulating the combustion properties of manufactured oil gas.

2. Quenching was also studied with certain appliance burners. It was found that quenching occurred with these burners when they were supplied with combustible mixtures of air and simulated oil gas having compositions predicted from the curve obtained with glass laboratory test burners.

3. The performance of some of these burners when supplied with manufactured oil gas has been regarded as "critical" in limiting the proportion of oil gas in mixtures with natural gas which may be distributed during periods of peak demand. The reasons for this "critical" behavior are examined in the light of the quenching theory. As a result, appropriate air-shutter adjustments are suggested by the data which will alleviate this difficulty. (The occurrence of yellow-tipped flames will represent a limitation of air-shutter adjustment at lower aerations).

4. Thus, the phenomena of flashback on shutoff and noise of extinction, encountered in the practical operation of some gas appliances, are clarified with the aid of fundamental flame stability theory.

It is a pleasure to acknowledge the assistance of Mr. Edward Early in carrying out many of the measurements reported here.

Nomenclature

x = quenching distance

k = thermal conductivity

s = burning velocity

c = heat capacity per unit volume

f = a dimensionless geometric factor

T_f = flame temperature

T_i = ignition temperature (also sometimes referred to in these relations as quenching temperature)

T_o = unburned gas temperature

F = fraction of stoichiometric gas in combustible mixture

$$\left(= \frac{\text{percent gas in mixture}}{\text{percent gas in a stoichiometric mixture}} \right)$$

d_c = diameter of circular port

d_r = width of rectangular port

b_r = length of rectangular port

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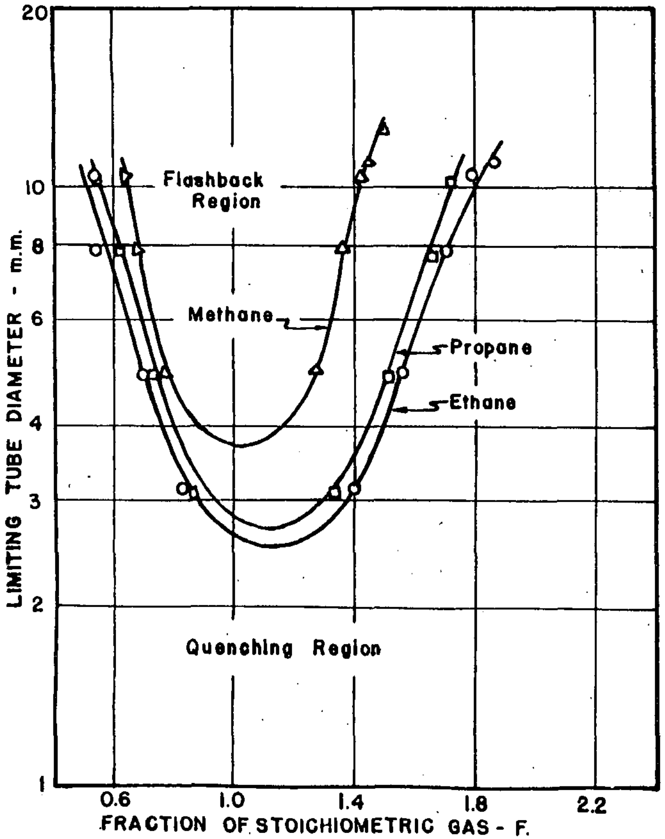

Figure 1. Quenching Diameter; Paraffins

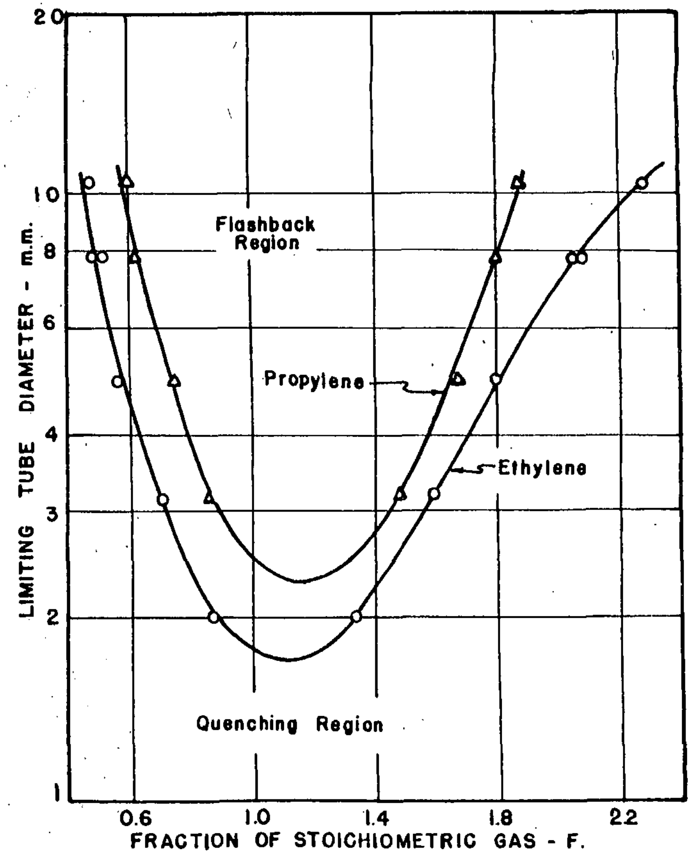

Figure 2. Quenching Diameter; Olefins

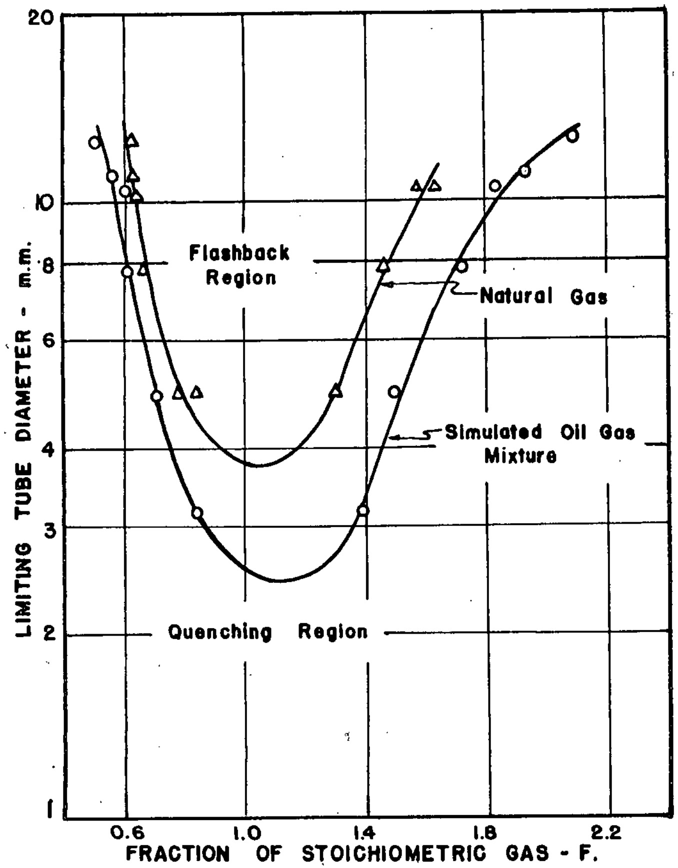

Figure 3. Quenching Diameter; Natural Gas and Simulated Oil Gas Mixture.

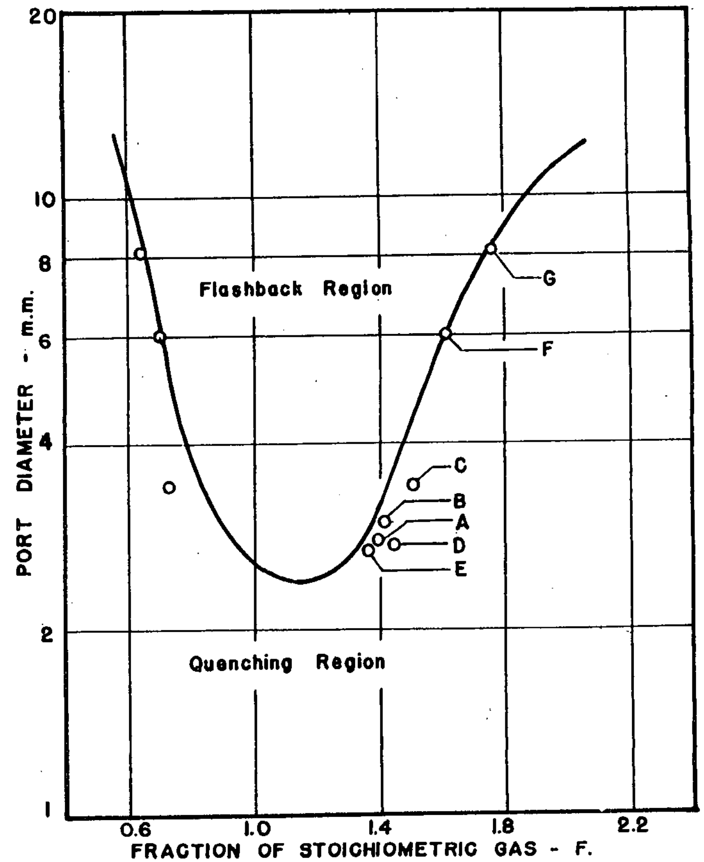

Figure 4. Quenching with Gas Appliance Burners; Simulated Oil Gas Mixture

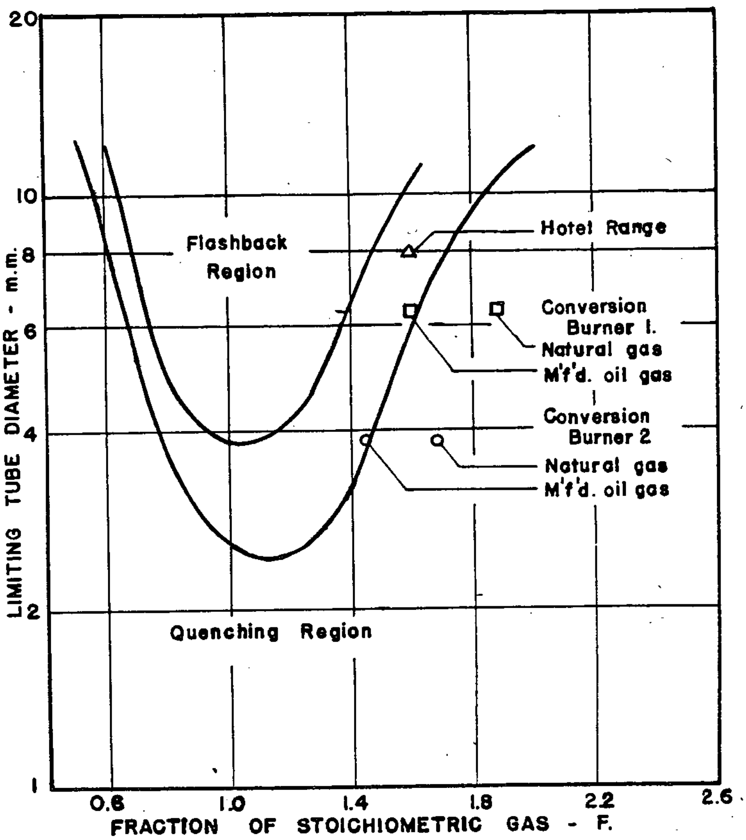

Figure 5. Quenching with Gas Appliance Burners; Natural Gas and Simulated Oil Gas Mixture.