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INTERACTION OF TWO PARALLEL LINE FIRES

by

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ABSTRACT

An experimental investigation is made of the interaction of two parallel simulatedly infinitely long, thin line fires. Over the range of the experiment, the smaller of the two flames has been found to lean toward the larger flame at a relatively small angle from the horizontal, whereas the larger flame has been found to lean toward the smaller flame at an angle the magnitude of which depends very sensitively on the strengths of the two flames and the distance between them. It is hoped that such an investigation will contribute to the understanding of some of the mechanisms by which a free burning fire spreads.

INTRODUCTION

The control of forest fires has become a problem of increasing concern in recent years and many efforts have been directed towards the understanding of the various mechanisms by which a free burning fire spreads through the forest. One such important mechanism is the feedback of heat and matter which likewise moves a fire front through a premixed gas mixture or along a wall board. Normally, the unignited trees and brush in the immediate neighborhood of the fire are heated largely by radiation from the flame and embers in the fire and the flames above the trees. In the absence of a significant prevailing wind the unignited trees will be cooled somewhat by the air entrained by the fire. The net heating causes first drying and then pyrolysis af the fuel to support the combustion in the flame.

In the presence of a prevailing wind, the tilting of the flames has been generally observed. This change in the orientation of the flame front increases the rate of heating of the unburned fuel layer and thus the rate of spread of the flame front. Countryman (1964) [1] experimentally studied full-scale large fires under prevailing wind. He found that the initiation of burning of the fuel in the region in front of the flame front was caused by a combination of radiant heating of the fuel by the heat flames and showers of small firebrands falling on heated fuels. However, this region was much narrower on the windward side than on the downwind side. Laboratory experiments on the rate of spread of fire through a long fuel bed in a controlled prevailing wind in a wind tunnel have been carried on by Fons (1946) [2], Anderson and Rothermel (1965) [3], and Byram et al. (1966) [4]. It is generally established that the rate of spread of the flame front into the unburned region will be independent of the speed of the prevailing wind if the unburned region is in the upwind direction, but will increase with the increase of the speed of the prevailing wind if the unburned region is in the downwind direction. Byram et al. (1966) [4] also investigated the rate of fire spread up a sloping surface and found the flame displaced upslope along the surface and tilted toward the surface in the same manner as the flames for a wind-driven fire on the horizontal. However, the important difference is that the component of buoyancy force along the sloping surface increases with increasing fire intensity, whereas the inertial forces in a wind stream remain constant for a given wind speed. A slope-driven fire in heavy fuel can therefore build up very rapidly to a high rate of spread.

When two free burning fires are reasonably close to each other, their flames will be tilted toward each other due to the pressure field induced by the natural convection flows in much the same way as a slope-driven fire toward the sloping surface. Thomas, Baldwin, and Heselden (1965) [5] experimentally investigated the merging of the established flames above two rectangular fuel beds separated from each other by a distance smaller than their respective representative sizes. Their interest was more on the height of the resulting flame than the interaction between the two contributing flames. Lee and Ling (1967) [6] studied the velocity and temperature fields of the natural convection plume above a thin circular ring fire. They also reported that the flame established at the ring burner in all cases encountered in that investigation was found to be fairly uniform in height along the peripherical length of the burner and leaned toward the burner axis at such a small angle relative to the horizontal plane of the platform that it almost seemed to lie on the platform. It follows naturally that the study of the interaction of two parallel thin, infinitely long, line fires of equal or unequal strengths will prove useful in trying to understand the essential features of the interaction between fires of more general nature. Such a set-up is so variable that it contains most of the more important parameters of the phenomenon, yet so simple that the results obtained therein may be hopefully more easily reported in a universal form. These results can be used to estimate the interaction of the central portions of two reasonably long and approximately parallel line fires.

EXPERIMENTAL APPARATUS

The experimental apparatus consists primarily of two items, the line channel burners and the experimental cage.

(A) The line channel burners.

The two identical line channel burners, as shown in the sketch of Figure 1, are of 1/32-in. galvanized steel plate construction 6 feet long, 7 inches high and with a width tapered from 1 inch at the bottom to about 1-1/4 inches at the top. The top edges of the burners are reinforced with straight 3/4"x3/4"x1/8" steel angles. The parallel faces of the steel angles form an opening of 3/4 of an inch wide at the top of the channel burner. One layer of 200 mesh and four layers of 100 mesh stainless steel screens are stretched across the channel width at a level immediately below the steel angles both to help smooth up the flow of the gaseous fuel to the burner top and to form a flame holder for the burner. Five layers of No. 48 steel screens are stretched across the channel width near the bottom of the channel and the space between the screen layers near the top and those near the bottom of the burner is loosely filled with steel wool to further help smooth up the flow of the gaseous fuel. Thirty-two evenly spaced inlets at the bottom of the burner supply gaseous fuel to the burner from two identical fuel distribution tanks through pieces of flexible plastic tubes of equal length. Propane gas is supplied to the fuel distribution tanks from a pressurized fuel tank through a series of fine pressure regulators and carefully metered passages. A piece of straight 1/2 inch copper tubing is soldered onto the outside on both sides of the burner at a level of about one inch from the burner top to form a cooling jacket for the burner. To prevent the burner from being overheated, cooling water is run through the cooling jacket through a carefully metered passage. A thermometer is placed at the inlet and the outlet of the cooling jacket of each of the two burners to help measure the heat flux from the flame to the cooling water at each burner.

(B) The experimental cage.

The experimental cage is a rectangular steel frame structure 6 feet long, 6 feet wide and 12 feet tall, located in the central portion of a large laboratory room. The two parallel line channel burners are placed horizontally across the width of the cage on a pair of parallel steel beams close to and alongside the sides of the cage. A removable set of rectangular asbestos plates are placed on the sides of the burners and set flush with the top of the burners, now at a height of about two and a half feet from the floor, to form a horizontal platform across the total cross section of the case. Joints around the edges of the asbestos plates are temporarily sealed with strips of asbestos tape to prevent air leakage from below to the test section of the cage above the platform. Four different sets of rectangular asbestos plates are used, each making the distance between the center lines of the two burners 0.5, 1.0, 1.5 and 2.0 feet respectively. The test section of the cage is separated from the surroundings by two parallel vertical walls, one along each side and extending from the level of the platform to the total height of the cage, to provide a two-dimensional passage for the flow therein. The wall on the back side is made of asbestos plates. The wall on the front or observation side is made of two joined sections, the lower section a piece of 1-1/2 feet tall heat-resistant glass of 1/4 inch thickness and the upper section asbestos plates. The joints on both walls are sealed with strips of asbestos tape to prevent air leakage from the sides. The heat-resistant glass section of the wall on the front side is used as the observation window where the shapes of the flames from the two burners are observed and measurements of the orientations of the average axes of flames at the two burners are made. On top of the cage, a tapered metal hood is located to take away the excessive hot gases through a minimum-draft exhaust duct extending to the outside of the laboratory. The two remaining vertical open ends of the cage are covered with a layer of No. 48 aluminum window screen to reduce the undesirable disturbances to the flow in the test section of the cage from the surrounding air. Movable vertical walls are used during experiments to extend the side walls to provide additional two-dimensional passages for the flow of air approaching the open ends of the test section of the cage from the surroundings. A general view of the experimental cage is shown in Figure 2.

EXPERIMENTAL PROCEDURE AND RESULTS

Throughout any one run of the experiment, disturbances in the ambient room air were maintained at a minimum and the constancy of the temperature of the ambient room air was checked continuously. Essentially a steady state situation is achieved before readings were taken of the mass flow rates of fuel to each of the two parallel line burners, the inlet and outlet temperatures and mass flow rates of water of the cooling water jackets and the orientations of the average axes of the flames at the two burners.

To begin with, a relatively small flame was established at the left burner and a matching flame at the right burner. The orientations of the average axes of the two flames were measured from the glass observation windows on the front side of the experimental cage. Then, while the mass flow rate of fuel to the left burner was maintained constant, the mass flow rate of fuel to the right burner was increased in steps and similar measurements of the orientations of the flames were made at each step. Next, the mass flow rate of fuel to the left burner was in steps raised to and maintained at two different values and at each step the previously described procedure was repeated. Furthermore, four series of experiments were conducted, one for each of four selected values of the distance between the centers of the two burners,

Two useful observations were made:

1. In all cases, it was found that the two flames leaned toward each other. It was also found that both flames were reasonably straight so that their orientations could be identified by the angles made with the horizontal plane by their respective average axes. The smaller flame always leaned at a small angle from the horizontal plane while the larger flame leaned at an angle that was extremely sensitive to the ratio of the mass flow rates of fuel to the two burners and to the distance between the two burners.

2. In all cases, it was found that the heat flux going into the cooling water, computed from the mass flow rate and the temperature rise of cooling water, was always so small compared with the total heat flux released from the flame, computed from the mass flow rate of fuel and its heat of combustion in air, as to be negligible.

Let q_L and q_R be the heat flux per unit length of burner released from the left and the right flame respectively, ϕ_L and ϕ_R the angle made with the horizontal plane by the average axis of the left and right flame respectively, and y_o half the distance between the center lines of the two burners as shown in the definition sketch of Figure 3. The selected set of values of q_L for all four series of experiments were 1.44, 2.20 and 2.64 Btu/sec-ft. The four series of experiments correspond to a value of y_o of 0.5, 1.0, 1.5 and 2.0 ft respectively, and the results of measured ϕ_L and ϕ_R are shown in Figures 4 through 7.

ANALYSIS OF RESULTS

Let us direct our attention to the inclination of a test flame caused by the presence of an auxiliary flame placed at a distance of $2y_o$ away. The test flame in the present case can be either the left or the right flame. Then the other flame will be considered the auxiliary flame. The angle between the average axis of the test flame and the horizontal plane will be called Φ and the heat fluxes per unit length of burner of the test and auxiliary flame Q and q respectively. Then Φ could be either ϕ_L or ϕ_R and Q and q either q_L and q_R or q_R and q_L respectively. Dimensional analysis for such a system leads a general relationship of the form

$$\Phi = \Phi(M, N)$$

among the three dimensionless quantities

$$\Phi, \quad M = \frac{q}{Q}, \quad N = \frac{1}{y_o g^{1/3}} \left(\frac{Q}{\rho_o C_p T_o}\right)^{2/3}$$

where
g - the gravitational acceleration
ρ_o - density of ambient air
C_p - specific heat of air at constant pressure
T_o - temperature of ambient air

First, let the left flame be considered the test flame and the right flame the auxiliary flame. Then in this case

$$\Phi = \phi_L, \quad Q = q_L \text{ and } q = q_R.$$

The values of the dimensionless quantity N calculated for the various combinations of the values of Q ($= q_L$) and those of y_0 selected in the experiments as indicated in Figures 4 through 7 are tabulated in Table 1. The dimensionless angle between the average axis of test flame and the horizontal plane, Φ, is plotted against the dimensionless quantities M and N as shown in Figure 8.

Next, let the right flame be considered the test flame and the left flame the auxiliary flame. Then in this case

$$\Phi = \phi_R, \quad Q = q_R \text{ and } q = q_L.$$

If the previously calculated set of values of the dimensionless quantity N, as shown in Table 1, are retained for the present case, pairs of values of the dimensionless quantities M and Φ for each value of N can be obtained from the experimental curves for ϕ_2 in Figures 4 through 7. The results are plotted in Figure 9.

Finally, a normalized dimensionless plot of the flame orientation obtained by combining results for $M \geq 1$ and $M \leq 1$, Figures 8 and 9 respectively, with the values of N rounded to round numbers is presented in Figure 10. From these results, it is of great interest to note that we have established a "flame orientation amplifier" in our present set-up. For a fixed distance between the two parallel flames, the amount of tilting of the larger flame is found to be sensitively controlled by the strength of the smaller flame, which itself in all cases leans at a relatively small angle from the horizontal.

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	Q = 1.44 Btu/sec-ft	Q = 2.20 Btu/sec-ft	Q = 2.64 Btu/sec-ft
y_o = 0.5 ft	$N = 3.91 \times 10^{-2}$	$N = 5.10 \times 10^{-2}$	$N = 5.75 \times 10^{-2}$
y_o = 1.0 ft	= 1.96 "	= 2.55 "	= 2.87 "
y_o = 1.5 ft	= 1.305 "	= 1.70 "	= 1.915 "
y_o = 2.0 ft	= 0.987 "	= 1.275 "	= 1.435 "

Table 1. CALCULATED VALUES OF DIMENSIONLESS QUANTITY N WITH LEFT FLAME CONSIDERED AS TEST FLAME

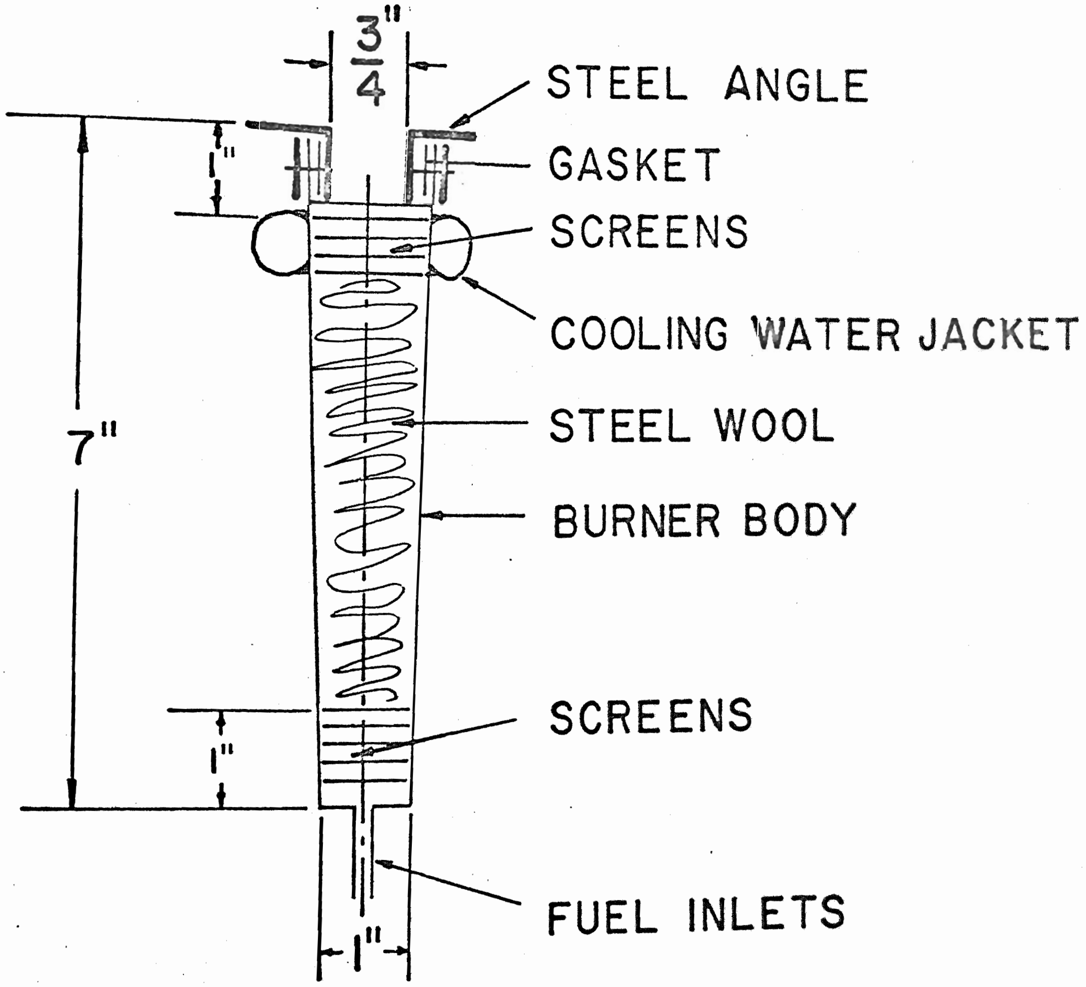

Figure I, SKETCH OF BURNER CROSS SECTION

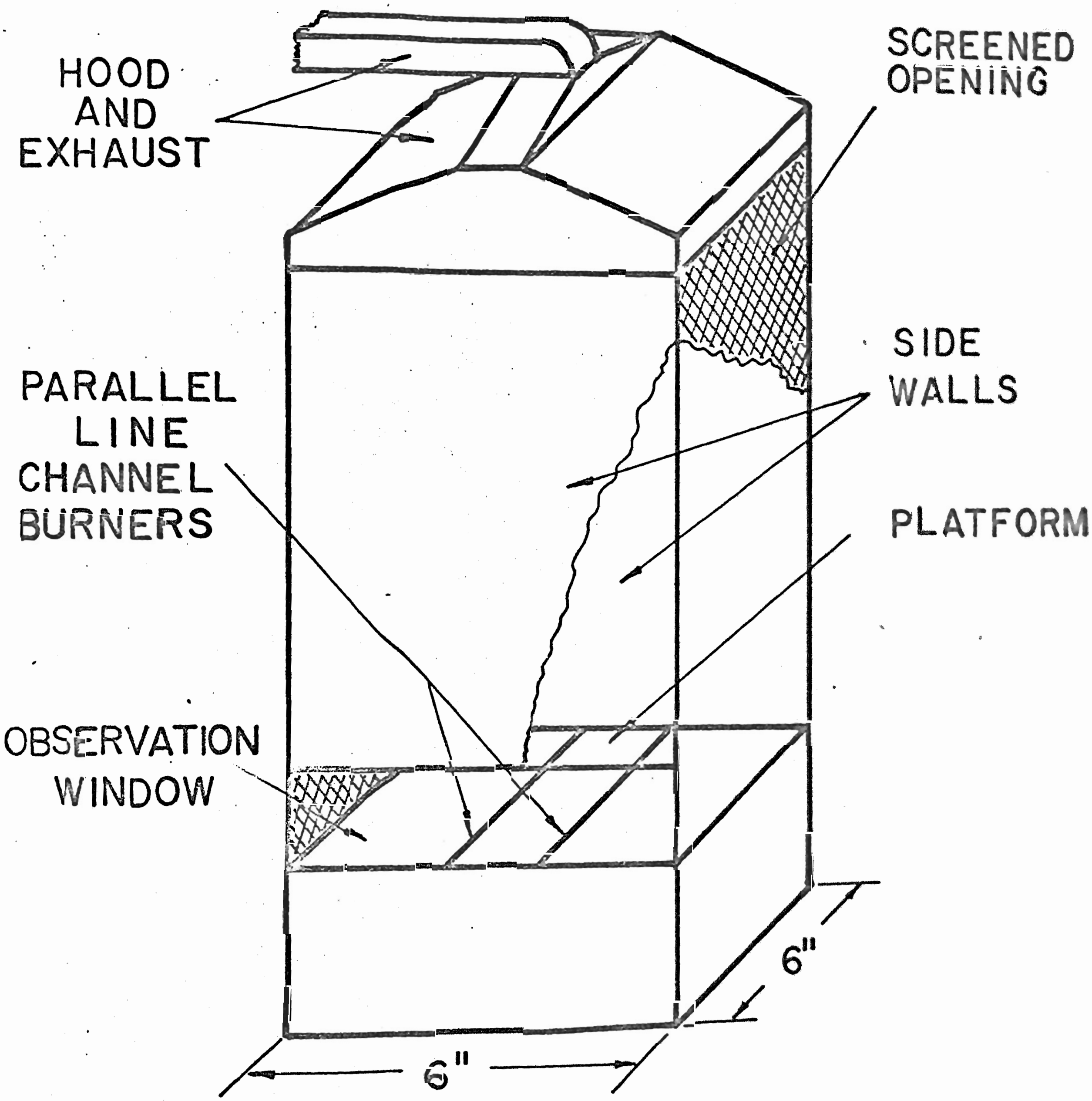

Figure 2, GENERAL VIEW OF EXPERIMENTAL CAGE

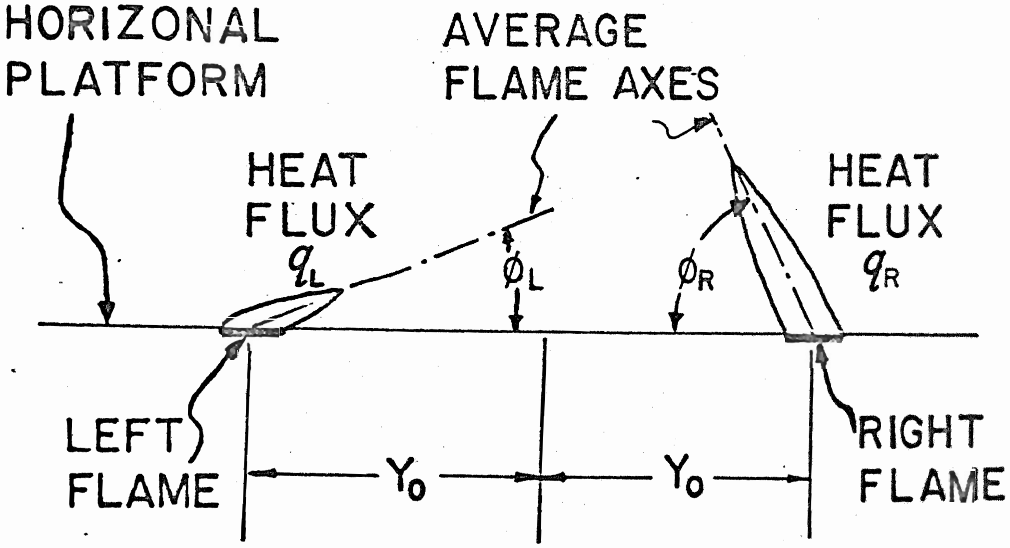

Figure 3, DEFINITION SKETCH

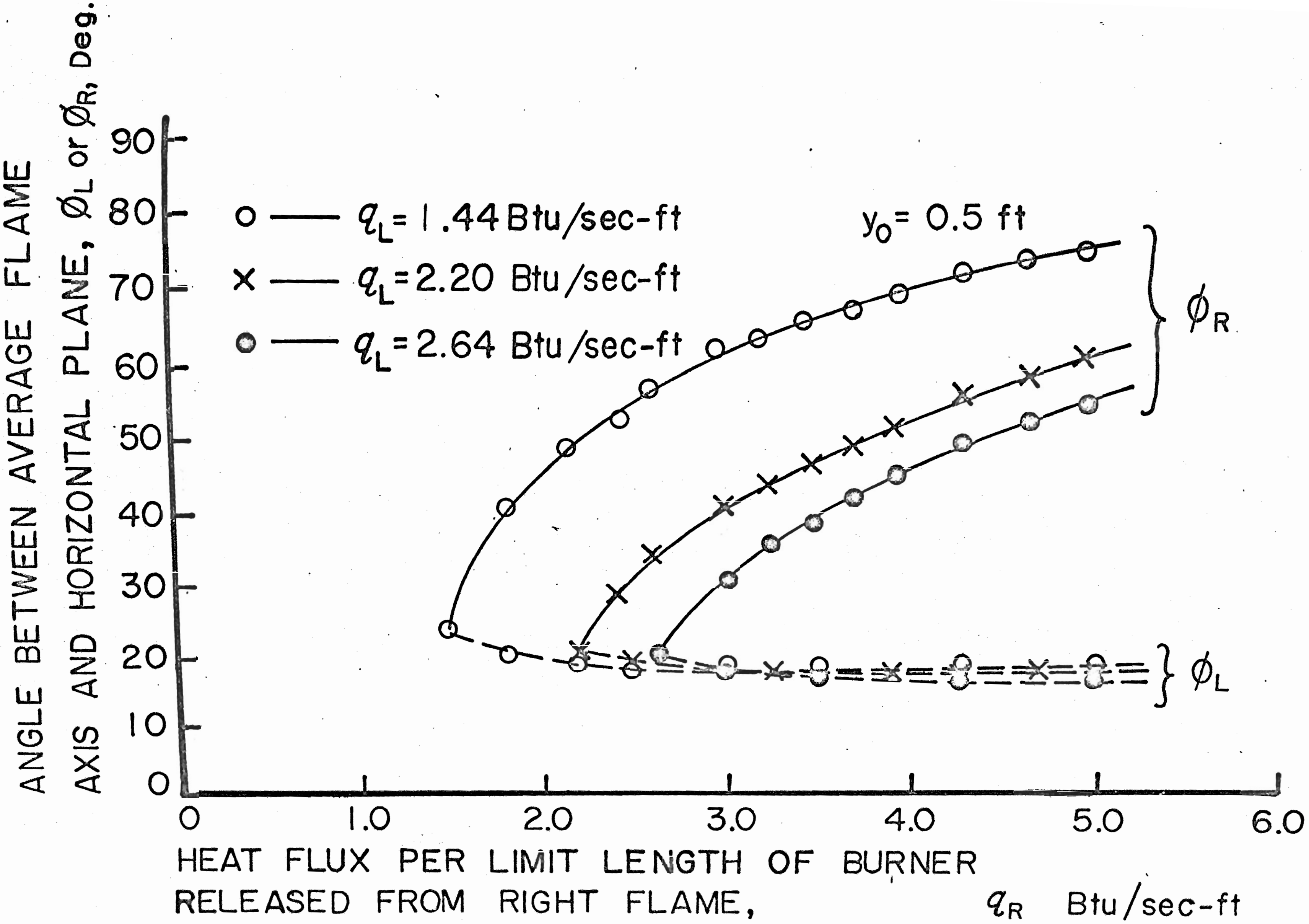

Figure 4, RESULT OF MEASURED ORIENTATION OF FLAME (y_o = 0.5 ft)

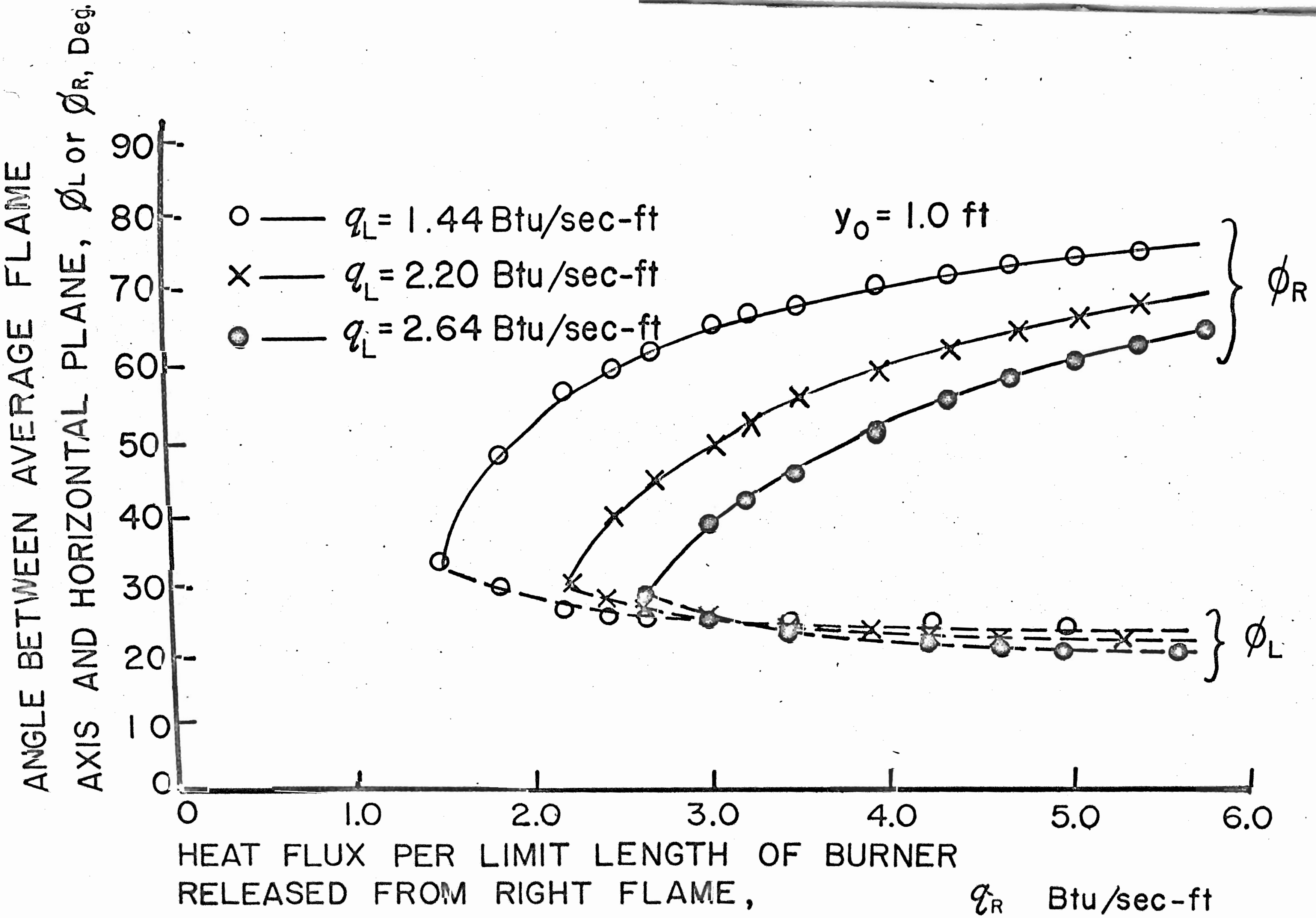

Figure 5, RESULT OF MEASURED ORIENTATION OF FLAME (y_0 = 1.0 ft)

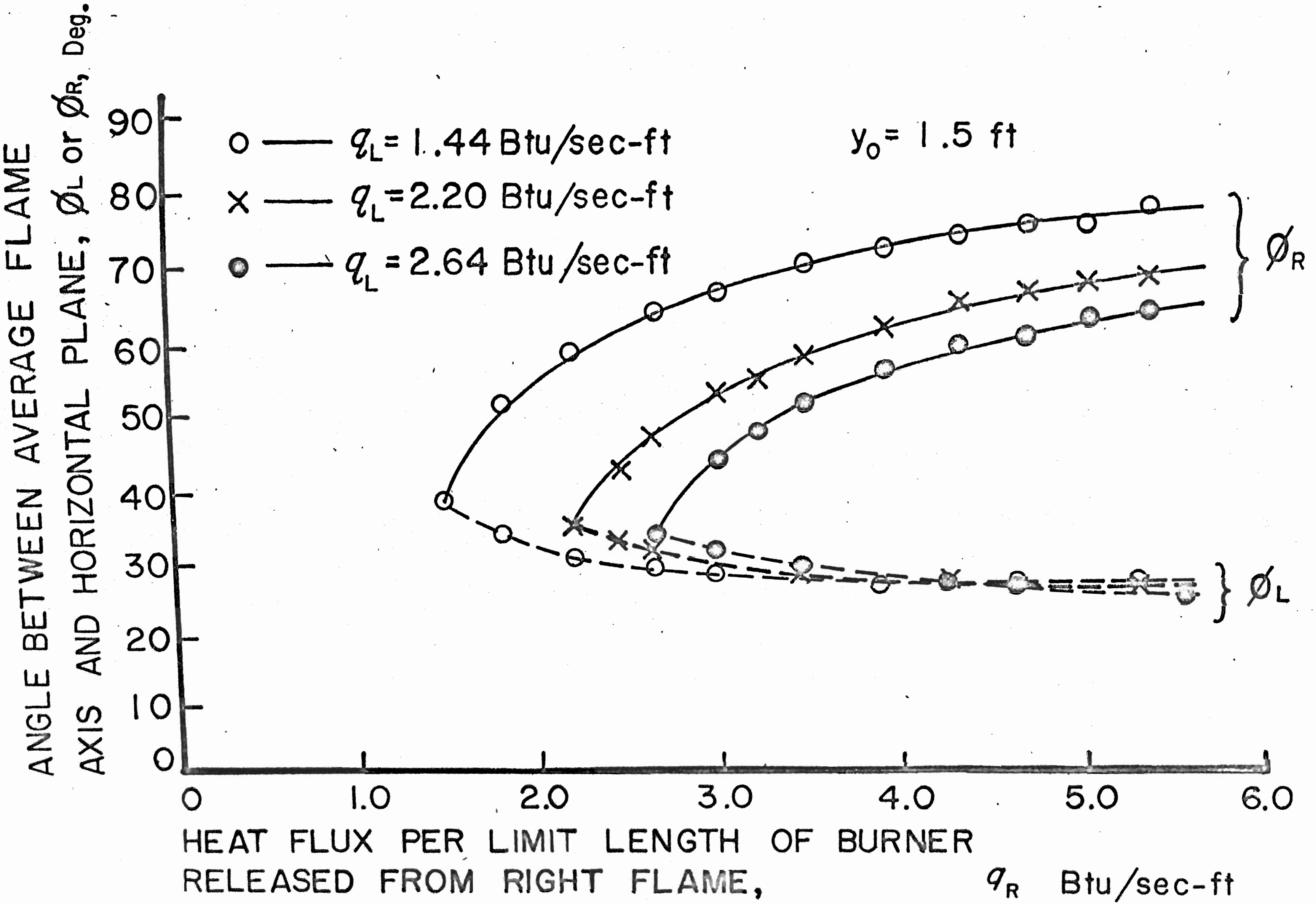

Figure 6, RESULT OF MEASURED ORIENTATION OF FLAME (y_o= 1.5 ft)

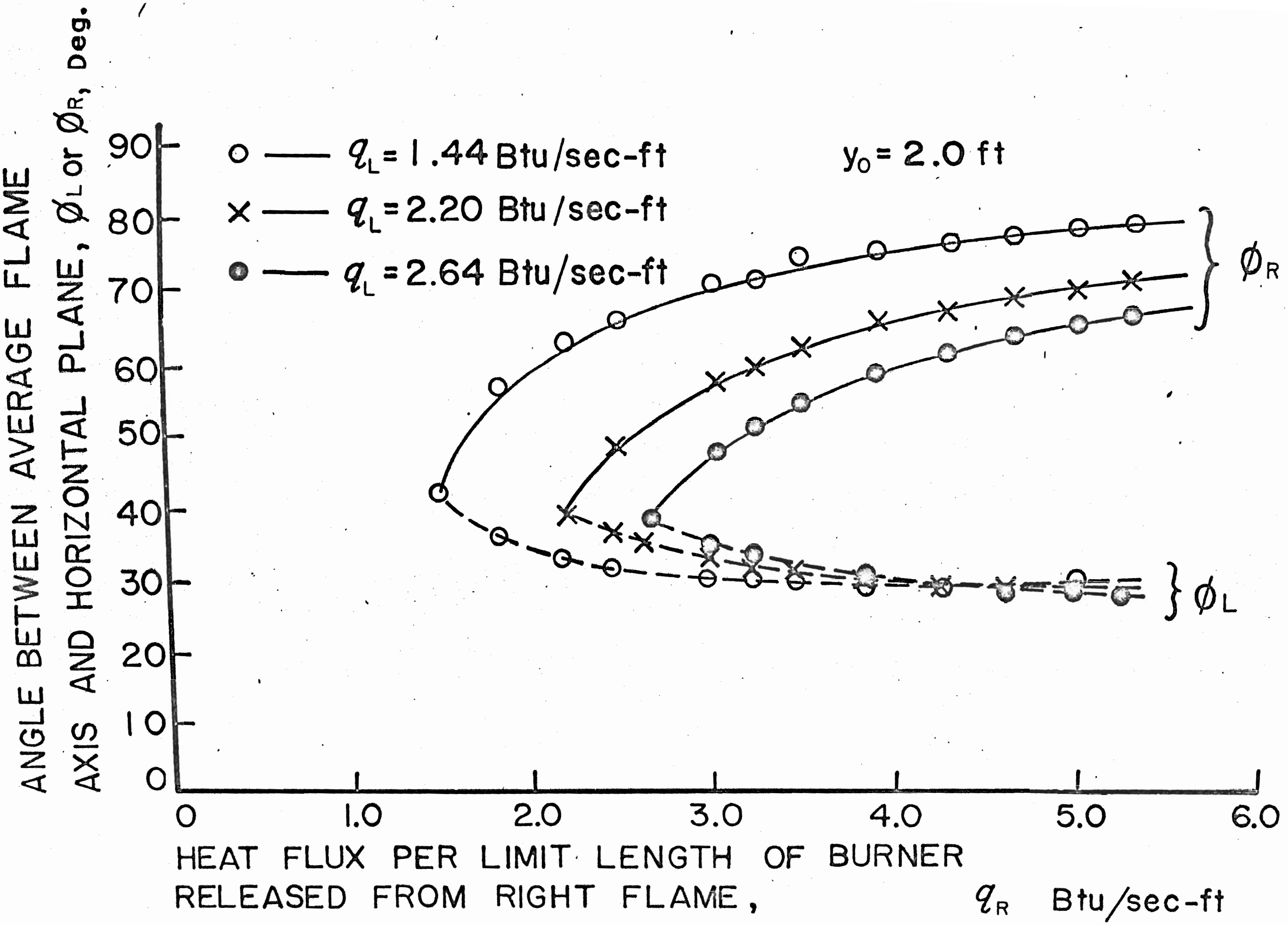

Figure 7, RESULT OF MEASURED ORIENTATION OF FLAME (y_0 = 2.0 ft)

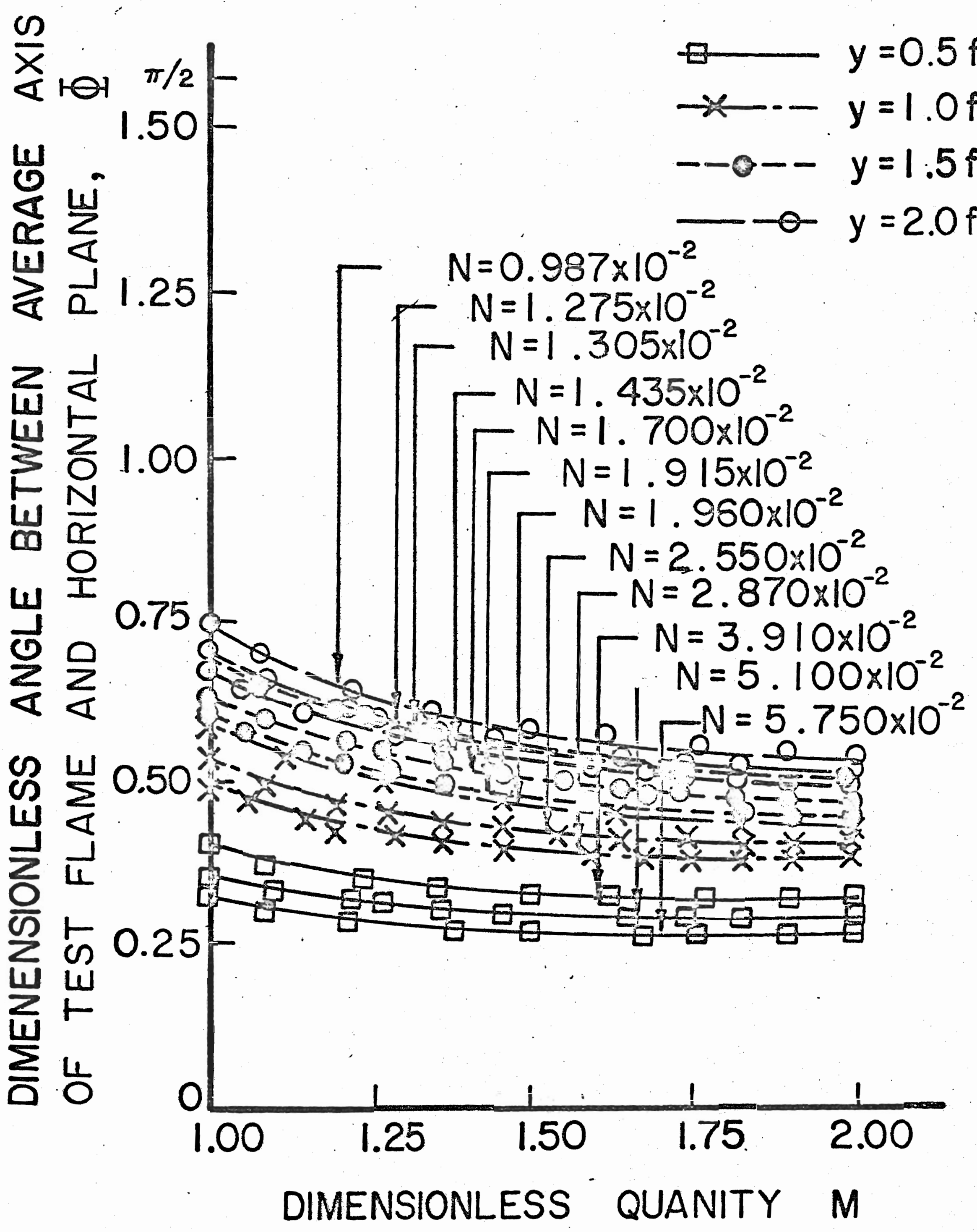

Figure 8, DIMENSIONLESS PLOT OF FLAME ORIENTATION WITH LEFT FLAME CONSIDERED AS TEST FLAME

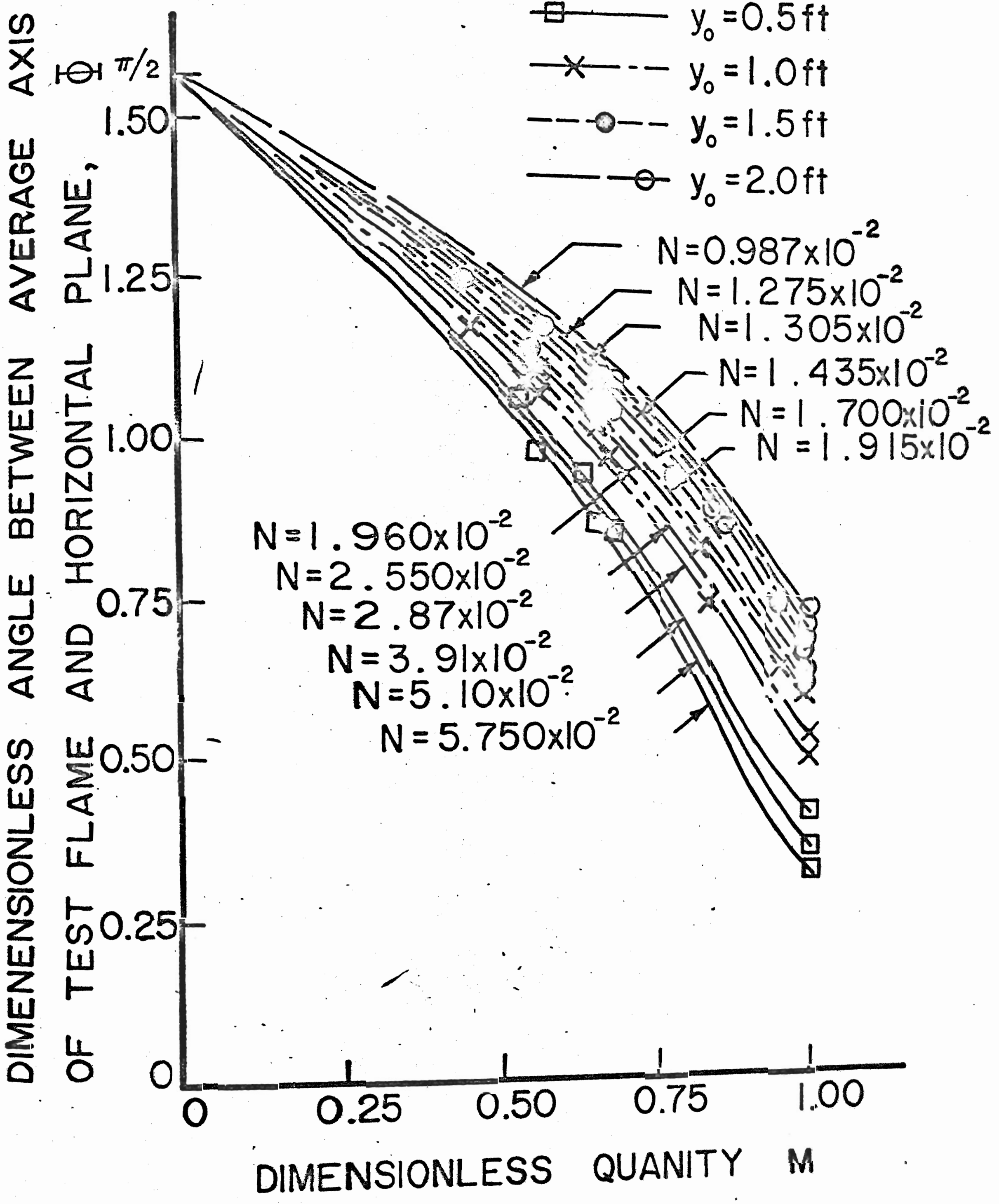

Figure 9, DIMENSIONLESS PLOT OF FLAME ORIENTATION WITH RIGHT FLAME CONSIDERED AS TEST FLAME

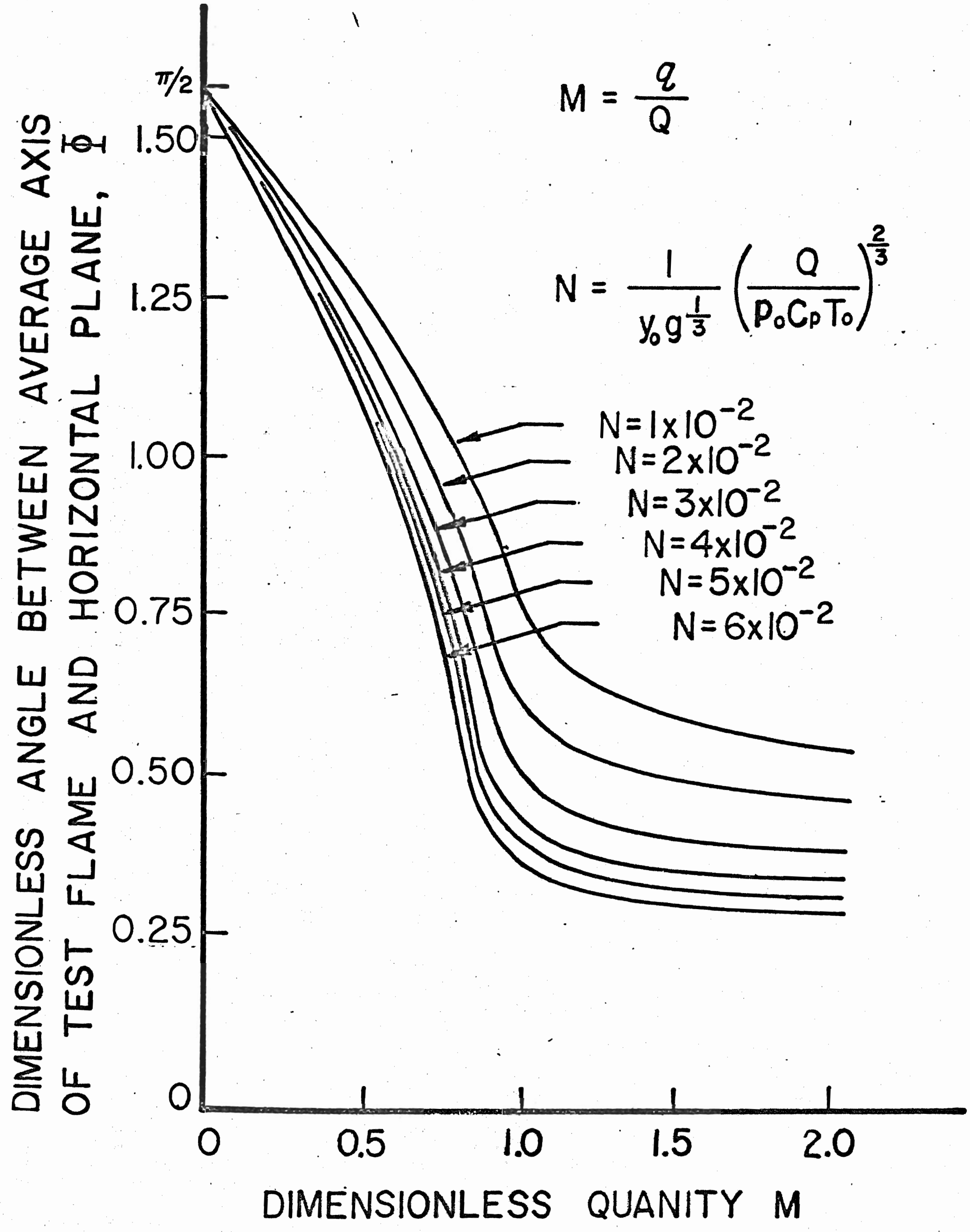

Figure 10, NORMALIZED DIMENSIONLESS PLOT OF FLAME ORIENTATION