

DIMENSIONAL ANALYSIS
OF
FLAME ANGLES VERSUS WIND SPEED¹

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ABSTRACT: Dimensional analysis has potential to help explain and predict physical phenomena, but has been used very little in studies of wildland fire behavior. By combining variables into dimensionless groups, the number of variables to be handled and the experiments to be run is greatly reduced. A low velocity wind tunnel was constructed, and methyl, ethyl, and isopropyl alcohol were used as buoyancy sources. Three diameters of pans, 4, 10, and 15 cm, were used and the order of six wind speeds was randomized in three replications. Flame angle was plotted against Byram's dimensionless group $gI/\rho C_p T_v^3$ (1959) in this preliminary study. Flames remained almost vertical at low wind speeds, inclined rapidly after critical wind speeds were attained, then inclined only slightly more as wind speeds continued to increase. A critical point in the value of the Byram number appears to be at a value of about 100.

KEYWORDS: dimensional analysis; flame angle; fire behavior

INTRODUCTION

Dimensional analysis (DA) has received relatively little attention from the wildland fire behavior research community. Yet it has the potential to contribute to the solution of some of the most perplexing fire behavior problems.

Observed fire behavior and mathematical modeling of fire behavior have produced excellent results for some fire situations (Rothermel 1972, Andrews 1986, Sneeuwjagt and Peet 1985). There are some areas, such as critical conditions for spread in discontinuous fuels, behavior of large scale fires, fire-fire interaction, and fire whirl formation where dimensional analysis has potential.

Dimensional analysis consists of developing relationships among variables combined into dimensionless groups or numbers, producing what some refer to as natural variables (Langhaar 1951). Grouping reduces the numbers of variables with which one has to deal, thus reducing the numbers of experiments needed. Since each of the groups is dimensionless, the dimensional integrity of equations can be maintained regardless of the powers to which the groups are raised. A disadvantage of dimensional analysis is that one does not know the effects of changing a single physical variable such as density or viscosity.

Dimensional analysis has proved to be of immeasurable value in many aspects of engineering research. The ability to scale from laboratory-sized models to full scale machinery such as airplanes or landscapes such as entire watersheds are two of the notable areas of success. Forced and natural convection studies have used dimensional analysis to great advantage.

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Another aspect of dimensional analysis is that one need not be able to develop the equations governing the situation to be studied. It is sufficient to make educated guesses as to the variables which are important to the situation being studied. This aspect is quite important where complex flow phenomena are involved, where the equations are not developed or not solvable.

PREVIOUS WORK

Use of dimensional analysis (DA) in forest fires first began with the suggestion by Byram (1959) that blow-up fire behavior might be related to the ratio of what he called the power of the fire (P_f) and the power of the wind (P_w). Although he did not combine the two, their ratio forms a dimensionless group (see Procedure). Thomas (1965) published a similar number for flame angle. Raj et al. (1979) used this number and predictions of plume velocity (McCaffrey 1979) to predict flame angle from burning liquified natural gas.

Byram (1966) discussed scaling laws for modeling mass fires. He used the Buckingham Pi Theorem and matrix analysis to arrive at many dimensionless groups of possible uses in modeling large fires. Williams (1967) looked at broader aspects of scaling mass fires and covered the literature pertaining to this field. From the governing physical equations, he arrived at 29 dimensionless groups of possible use. From these he recommended using 11 groups, many of which could be combined.

Byram and Nelson (1970) used DA to model the natural pulsation of fires. They used a subset of groups from Byram's 1966 paper. The use of dimensional analysis in fire behavior was also discussed by de Ris (1973). Most recently, Nelson and Adkins (1988) used DA to predict fire spread. It is a limited but very important example of the potential use of DA in wildland fire behavior. Raupach (1990) has considered similarity analysis in the interaction of bushfire plumes and winds.

METHODS

Equipment

The experiments were conducted entirely indoors under controlled conditions, and field verification of the scaling model will be conducted at a later date.

The basic device in the laboratory was the "breeze box", which is defined as a "short, stubby wind tunnel with low wind velocities" (Figure 1). The box was constructed primarily of 0.63 cm (1/4 in) plywood, but with a 1.27 cm (1/2 in) thick plywood floor. The test section has sides and top of 0.63 plexiglas, with one side removable as a door for access.

Each section of the box was reinforced with nominal 2.54x10.16 cm (1x4 in) frame for rigidity. The sections are 81 cm (32 in) long for portability, because that is the width of the door frame to the laboratory. The cross section of the box is approximately 122 cm (48 in) both horizontally and vertically.

The intake to the box used quarter sections of 25.4 cm (10 in) PVC pipe to smooth air flow around the edges. Hardware cloth supports furnace filters intended to reduce air fluctuations from entering the box. A window fan, controlled by a Variastat, provides a selection of airspeeds continuously from zero to 0.35 meters per second (1.15 feet per second).

Procedure

Rate of Combustion

One early concern was the rate of combustion in the pans, and the constancy of this throughout the duration of an experiment. Two factors could influence the mass loss rate. First, the pool of liquid fuel could warm as the experiment proceeded. Second, the lip of the pan could influence the burn rate. Mass loss rate was measured over time under constant wind conditions. The mass loss rate was plotted over time to evaluate the linearity of the loss rate.

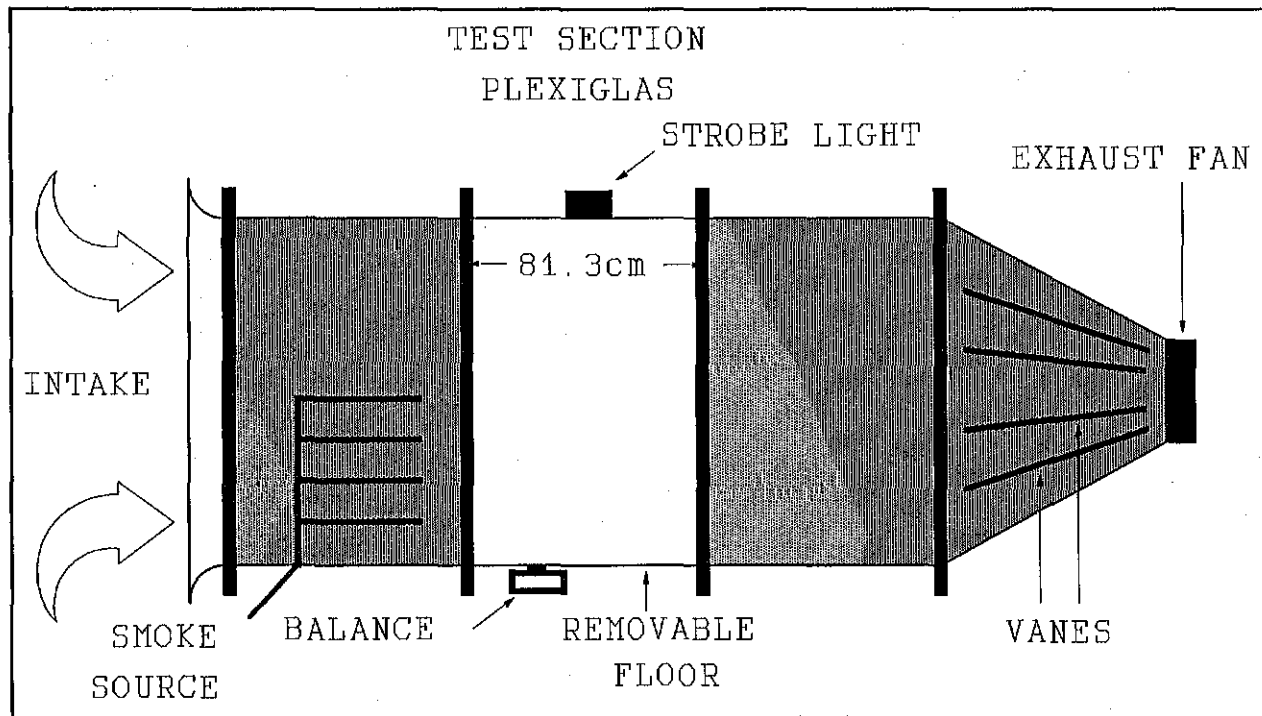


Figure 1 - The breeze box was constructed of plywood with a plexiglas test section.

Intensity

The intensity used was the standard fireline or Byram's intensity, in kiloWatts per meter (BTU/ft-sec) of fireline. For the circular pans, we made the calculation that the depth and width of the flames was that of a square pan with the same area as that of the circular pan. Setting $\pi D^2/4$ equal to L^2 , the two sides of the assumed square pan were calculated as $0.886D$. Thus, the 10cm diameter pan was calculated to be a square pan with sides 8.86 cm long.

Dimensionless groups

In modeling with dimensionless groups, a large number of groups may be important (Byram 1966, Williams 1967, Drysdale 1985). Some may enter directly into the analysis, others may influence the validity of the modeling. For instance, the Reynolds number which predicts transition from laminar to turbulent flow, could be very important in later aspects of this research. For simplicity, to begin with, we had to ignore many as relatively unimportant. We took the approach that viscous forces are relatively unimportant and that only the Froude number, U^2/lg , needs to be preserved. Thus the velocities are scaled with the square root of the principal dimension (l) so that the ratio of the two remains constant. The assumption that viscosity is relatively unimportant may become a problem as the research progresses.

Because Byram (1959) was trying to predict wildfire behavior, we considered the usefulness of his number, which is as follows:

$$N_{By} = \frac{gI}{\rho C_p (v-r)^3 T}$$

where:

I = fireline intensity, kW/m

C_p = specific heat of gases, kJ/Kg°K

T = absolute temperature, °K

ρ = density of air, kg/m³

v = velocity of wind, m/s

r = rate of fire spread, m/s

g = gravity, m/s²

We have combined here the two equations Byram used, thus forming the dimensionless group. It has never been tested in fire behavior. It may be a combination of other dimensionless groups, however, and thus not a new dimensionless group. We have dropped the 2 which would have appeared from the ratio. Since the fires were stationary in our work, the r becomes zero and drops out of the number.

Buoyancy Sources

Laboratory experimental work involved the burning of methyl, ethyl, and isopropyl alcohol for the buoyancy required. Circular pans 4, 10, and 15 centimeters were used, and the burning rate for the three alcohols in the three sizes of pans was recorded by weight loss at 5 second intervals. The energy release rate was calculated from the mass loss rate times the heat of combustion, with allowance for moisture in the fuel. Heats of combustion for the three alcohols are:

Methyl	19,745 kJ/kg
Ethyl	27,215
Isopropyl	30,535

Flame Angle

The laboratory work was divided into three blocks of two persons each. Each block was assigned a randomly chosen order of wind speed. Each of the two observers made independent estimations of flame angle after allowing a stabilizing period of about 30 seconds after each change of wind speed. The six wind speeds were from 0.10 to 0.35 meters per second in 0.05 m/s increments. The total number of observations made was thus three pan sizes times three alcohols times six wind speeds times six observers or $3 \times 3 \times 6 \times 6 = 324$ observations.

RESULTS

Rate of Combustion

The rate of combustion of the three alcohol fuels was quite uniform throughout the burning period (Figure 2). This simplified our experimentation by providing a long "steady state" and allowing us to vary wind speeds periodically while having a constant intensity.

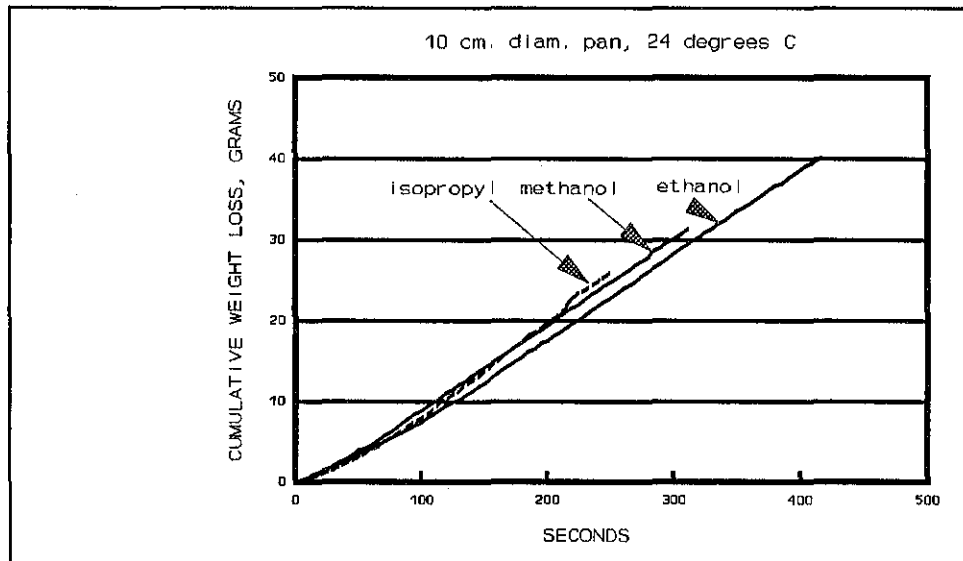


Figure 2. - The rate of combustion of the three alcohols was quite linear with time.

Flame Angle

Flame angle from the horizontal as plotted over Byram's number was very small at high wind speeds (Figure 3). The angle then increased rapidly with decrease in windspeed before finally reaching a stage where little further change in angle occurred. A change in the rate of inclination occurred at a Byram number value of about 100. Total heat outputs were from .331 to 8.044 Kj/s, a range of 24 to 1, and winds were from .1 to .35 m/s, a range of 3.5 to 1. Dispersion in the values is quite wide, however, and further analysis will be needed. Preliminary perusal of the data suggests that some observers consistently recorded different angles than others.

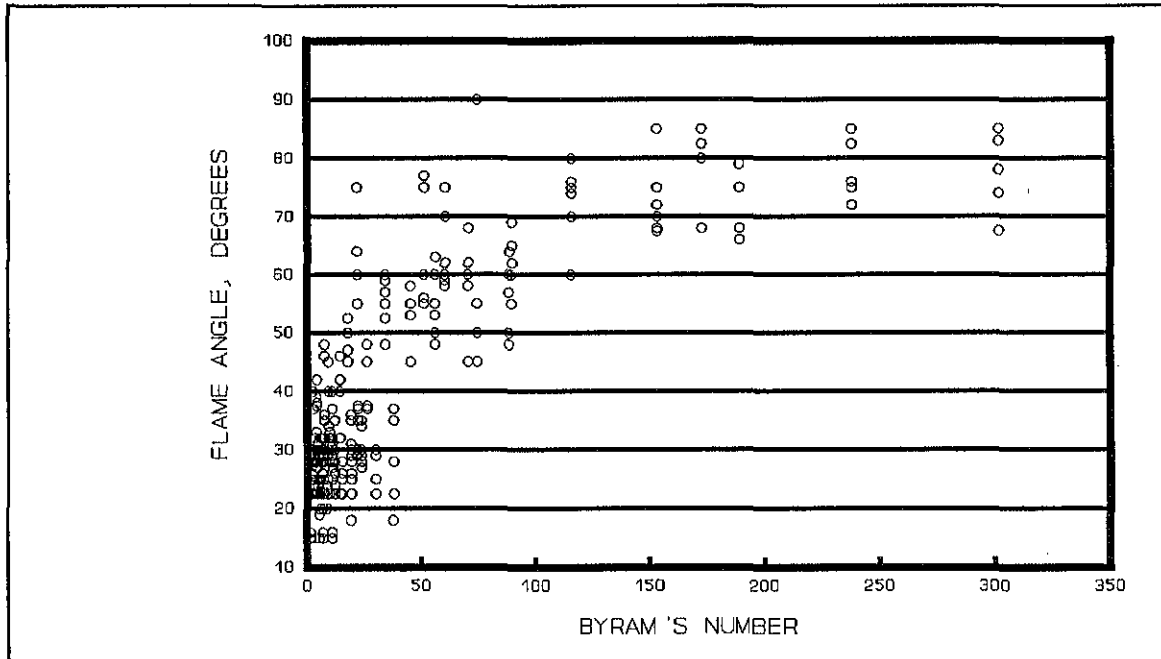


Figure 3. - The rate of flame inclination related to wind changed rapidly at a Byram number value of about 100.

SUMMARY

The Byram dimensionless number has been used for the first time in relating flame angle to windspeed. Although the study is preliminary, the results are promising in the possible usefulness of his number in flame angle and fire interaction studies. For three different but similar fuels and three pan sizes, a critical value of about 100 for Byram's number seems to indicate a point where the rate of flame inclination with increasing wind changes rapidly.

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