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NATURAL CONVECTION PLUME ABOVE A CIRCULAR RING FIRE

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Richard Shao-lin Lee
(Shao-lin Lee)

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Richard Shao-lin Lee*
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Associate Professor
Department of Mechanics
State University of New York at Stony Brook

* In collaboration with Chi-hai Ling, Instructor,
Department of Mechanical Engineering, Christian Brothers College

SUMMARY

An investigation is made of the flow field of the turbulent natural convection plume above a circular ring fire. It is hoped that such an investigation will contribute to the understanding of some of the mechanisms by which a fire spreads. Results are found to agree qualitatively with fragmentary data from full-scale large fire tests available in the literature.

INTRODUCTION

In recent years, the control of forest fires has become a problem of increasing concern and consequently the understanding of the mechanisms by which a free burning fire spreads has been the central objective of much directed efforts. A systematic examination of the fundamental problems of the free burning fire was made by Emmons (1965) [1]. It is generally accepted that such a fire spreads essentially in either one of two different ways or sometimes in a combination of the two, both intimately related to the convective air movements in and above the fire.

In one way, a fire front is moved through the forest by the same principles of feedback of heat and materials that move a fire front through a premixed gas mixture or along a wall board. The unignited trees and brush in the immediate neighborhood of the fire are heated largely by radiation from the flames and embers in the fire and the flames above the trees. In the absence of a strong wind, the unignited trees will be cooled some by air entrained into the fire. The net heating causes first drying and then pyrolysis of the fuel to support the combustion in the flames of the advancing fire front. Hottel and Williams (1965)[2] studied the effects of artificial irradiation and of humidity on the propagation of a line fire through a fuel bed. In the presence of a strong wind, the flames in the plume as blown toward or away from the advancing fire exert a considerable influence on the heating, drying, and pyrolyzing of new fuel and thus on the movement of the fire front. Anderson and Rothermel (1965) [3] and Putnam (1965) [4] studied the characteristics of free burning fires under controlled wind velocities.

In another way, firebrands are transported by the convective air currents to places at distances of up to several miles ahead of the fire front and start new fires there. Tarifa, Del Notario, and Moreno (1965) [5] investigated the burning properties, flight paths and lifetimes of firebrands under controlled wind velocities.

With the exception of the very few meager attempts to investigate the interaction between two parallel short line flames, made by Thomas, Baldwin, and Heselden (1965) [6] and Putnam (1965) [4], most of the previous works are dealing with fires of regular pattern. The experimental investigations are usually made with laboratory-size apparatus and naturally the physical models used to attempt the corresponding theoretical analysis are based on investigations made with laboratory-size apparatus. There is considerable question as to the validity of the modeling law which relates small fires to the large, intense fires.

The only experimental investigation using full-scale large fires to date was reported by Countryman (1964) [7]. According to this investigation, characteristics observed on small fires cannot be extrapolated to those on large, intense fires mainly due to the difference in the fire patterns involved. The large, intense fires are usually referred to as mass fires and exhibit violent fire behavior. Two broad classes of mass fires are generally recognized: fire storms and conflagrations. Fire storms occur when there are many ignitions over a wide area that quickly coalesce into a single fire, burning intensely over a large area. Convective activity in these fires is very great, tall convective columns develop, and fire-induced winds become very strong. There is usually little outward spread of fire in a fire storm due probably to the strong indrafts. Conflagrations are hot burning fires with definite and moving fronts. The depth of the intensely burning area is usually relatively narrow and tall convection columns may or may not develop. Moreover, there is no clear cut line of demarcation between fire storms and conflagrations. An ordinary fire may also develop in intensity and activity to a conflagration or fire storm and back again as conditions vary. Under certain conditions, both fire storms and conflagrations can develop at the same time. On the test fires, the tendency for the fire to break up into small convection columns has been found. After the initial intense burning, which lasts for only a relatively short time, mass fires will usually develop hot spots and separate convection columns. Occasionally, the hot spot will shift from place to place. A few fragmentary temperature measurements at interior spots in the fuel beds indicate that the temperature level there usually attains its maximum during the initial intense burning period and gradually diminishes as the fuel is being burned out. Since such fires are the result of intimate interaction of geometry, chemistry, thermodynamics, fluid mechanics and heat transfer, each at an advanced level, to understand them in a rigorous, analytical way at this point of development would present a rather formidable problem.

The main interest of the above-quoted experimental work is to investigate the behavior of an intense fire over a large but isolated fuel bed rather than the mechanisms by which such a fire spreads through an unrestricted fuel bed. However, from the results of that investigation, a seemingly reasonable extrapolation can be made in a qualitative way for the development of a fire and its spread through an unrestricted fuel bed. Let us consider that a normal fire similar in gross pattern to those observed in laboratory tests first establishes itself over a relatively small area of the fuel bed. As it grows in intensity and in size due to the spread of its front, it will gradually develop into a mass fire of the previously described, complicated pattern. Later on, as the front of the fire still keeps on spreading out, the interior region will cease burning due to the complete consumption of fuel and the fire will have the look of a narrow, intensely burning ring spreading into the surrounding unignited portion of the fuel bed. In the absence of significant side winds, if the initial small fire covers an approximately circular area and if the topography and fuel characteristics of the fuel bed are fairly uniform, the intensely burning region of the fire can be expected to be of the shape of a narrow circular ring. And, the spread of such a fire can be expected to be carried out in either one or both of the two previous mentioned ways, ignition due to transportation of fire brands and movement of fire front through unignited fuel bed by the principles of feedback of heat and materials from the circular ring flame. Therefore, the convection plume above a circular ring flame can be expected to play a paramount role in the spread of such a fire. The same line of reasoning can also be applied to the case of a ring flame propagating into the unignited interior region.

Analyses of the convection plume above a single flame have been formulated reasonably well as can be seen from the works of Morton, Taylor and Turner (1956) [8], Morton (1959) [9, 10], Lee and Emmons (1961) [11], and Nielsen and Tao (1965) [12]. The only work in the field of a plume above a region bounded by thin flames to date is the experimental investigation of the convection plume over two parallel lines of small flames reported by Rouse, Baines, and Humphreys (1953) [13]. However, they simulated the situation by the method of images by using only one line of flames and inserting a vertical wall at the plane of symmetry between these flames and a hypothetical line of flames. The plume flow fields of the two cases cannot be the same due to their difference in turbulent mixing mechanisms at the plane of symmetry. Because they used a line of small flames, significant amount of air can be expected to have been entrained into the plume through spaces between the flames. Furthermore, their velocity measurements fail to describe the lateral velocity field which could turn out to be significant.

Chigier and Beér (1964) [14] measured the velocity and pressure fields of a circular turbulent ring jet. They found that since there was no available supply of fluid in the central region to satisfy the entrainment requirements of the inside boundaries of the ring jet, it was forced to draw the fluid from the mainstream itself with the result that a zone of subatmospheric pressure was set up, and the radial pressure forces draw in the ring jet toward the axis. The level of the pressure forces which was responsible for the rather significant radial velocity field thus induced was found to be only a few milimeters of water column. Since turbulent jets and turbulent plumes have much in common in their mechanism of spread, it is reasonable to expect that in a qualitative way the flow field of a turbulent ring plume would exhibit similar behavior.

THEORETICAL CONSIDERATION

Let us assume that the flow field is fully turbulent and as a consequence the molecular effects can be neglected in comparison with the turbulent effects and the vertical rate of mixing due to turbulence is small in comparison with the lateral rate and therefore the usual boundary layer approximations can be made. Let us also assume that the local density variations are everywhere small in comparison with some reference density in the flow field. Even though a source of heated fluid is causing the natural convection, it is the buoyancy rather than the thermal properties of the flow which is fundamental to the phenomenon. Therefore, although the buoyancy force due to density difference is sufficiently great to contribute to vertical acceleration, the corresponding variation in the mass density of the fluid undergoing acceleration is sufficiently small, in comparison with the density itself, to be neglected in the governing continuity and energy equations and the inertia terms of the momentum equations.

If we let u and v be the components in the x-(axial) and r-(radial) directions respectively of the time-mean velocity of the fluid at a point inside the plume flow field as shown in the definition sketch of Figure 1, the governing equations for the plume flow field are then as follows:

Continuity Equation:

$$\frac{\partial}{\partial x}(ru) + \frac{\partial}{\partial r}(rv) = 0 \qquad (1)$$

x-direction Momentum Equation:

$$\frac{\partial}{\partial x}(ru^2) + \frac{\partial}{\partial r}(ruv) = -\frac{r}{\rho_1}\frac{\partial p}{\partial x} - \frac{\partial}{\partial r}(r\overline{u'v'}) + \frac{r\Delta\gamma}{\rho_1} \qquad (2)$$

r-direction Momentum Equation:

$$\frac{\partial}{\partial x}(ruv) + \frac{\partial}{\partial r}(rv^2) = -\frac{r}{\rho_1}\frac{\partial p}{\partial r} - \frac{\partial}{\partial r}(r\overline{v'^2}) \qquad (3)$$

Energy Equation:

$$\frac{\partial}{\partial x}(ru\Delta T) + \frac{\partial}{\partial r}(rv\Delta T) = -\frac{\partial}{\partial r}(r\overline{v'\Delta T'}) \qquad (4)$$

where ρ_1 = density of the undisturbed ambient fluid

p = local time-mean pressure

$\Delta\gamma = g\Delta\rho = g(\rho_1 - \rho)$ = local buoyancy

ρ = local time-mean density

$-\rho_1\overline{u'v'}, -\rho_1\overline{v'^2}$ = Reynolds stresses

$-\rho_1 C_p \overline{v'\Delta T'}$ = eddy heat transfer

u' = fluctuation velocity in the x-direction

v' = fluctuation velocity in the r-direction

$\Delta T = T - T_1$ = local time-mean temperature increment

T = local time-mean temperature

T_1 = temperature of the undisturbed ambient fluid

$\Delta T'$ = fluctuation temperature increment

C_p = specific heat at constant pressure

If we further assume that the local temperature increment is small as compared to some reference temperature, say T_1, and that the local pressure change is small enough not to cause any significant change of the thermodynamic properties of the fluid but large enough to influence the dynamic behavior of the fluid, the equation of state of an ideal gas reduces to the following:

$$\frac{\Delta T}{T_1} = \frac{\Delta \rho}{\rho_1} = \frac{\Delta \gamma}{g \rho_1}$$

and the x-direction momentum equation, Equation (2), reduces to

$$\frac{\partial}{\partial x}(r u^2) + \frac{\partial}{\partial r}(r u v) = -\frac{r}{\rho_1}\frac{\partial p}{\partial x} - \frac{\partial}{\partial r}(r \overline{u'v'}) + r g \frac{\Delta T}{T_1} \qquad (5)$$

Integrate Equation (5) from 0 to ∞ with respect to r. The radial velocity v(x, r) and the Reynolds' stress vanish at r = 0 due to symmetry and the Reynolds' stress vanish at r = ∞ in the ambient fluid. The resulting equation takes the form:

$$\frac{d}{dx}\int_0^\infty u^2 r\,dr = -\frac{1}{\rho_1}\frac{d}{dx}\int_0^\infty p\,r\,dr + \frac{g}{T_1}\int_0^\infty \Delta T\,r\,dr \tag{6}$$

Integrate Equation (3) from 0 to ∞ with respect to r. The radial velocity v(x, r) and the Reynolds' stress again vanish at r = 0 due to symmetry and the Reynolds' stress again vanish at r = ∞ in the ambient fluid. The resulting equation takes the form:

$$\frac{d}{dx}\int_0^\infty uv\,r\,dr = -\frac{1}{\rho_1}\int_0^\infty \frac{\partial p}{\partial r}\,r\,dr \tag{7}$$

Integrate Equation (4) from 0 to ∞ with respect to r. The radial velocity v(x, r) and the eddy heat transfer vanish at r = 0 due to symmetry and the temperature increment Δ T (x, r) and the eddy heat transfer vanish at r = ∞ in the ambient fluid. The resulting equation takes the form:

$$\frac{d}{dx}\int_0^\infty u\Delta T\,r\,dr = 0 \tag{8}$$

which can be immediately integrated to give

$$\int_0^\infty u\Delta T\,r\,dr = \frac{Q}{2\pi C_p \rho_1} \tag{9}$$

where Q is the total vertical heat flux across any horizontal plane.

Let us introduce the following transformations to eliminate the constant coefficients from the governing equations:

$$
\begin{aligned}
x &= r_o X \\
r &= r_o R \\
u &= \omega U \\
v &= \omega V \\
\Delta T &= \frac{T_1 \omega^2}{g r_o} \Theta \\
p - p_1 &= \rho_1 \omega^2 P
\end{aligned}
\qquad (10)
$$

where p_1 = pressure of the undisturbed ambient fluid

and $\omega = \left[\frac{g Q}{2 \pi r_o C_p \rho_1 T_1} \right]^{1/3}$ which has the dimensions of a velocity and can be considered as a characteristic velocity for the natural convection problem.

With these transformations, Equation (10), the governing equations, Equations (1), (6), (7) and (9), become

$$\frac{\partial}{\partial X}(RU) + \frac{\partial}{\partial R}(RV) = 0 \qquad (11)$$

$$\frac{d}{dX}\int_0^\infty U^2 R\,dR = -\frac{d}{dX}\int_0^\infty P R\,dR + \int_0^\infty \Theta R\,dR \qquad (12)$$

$$\frac{d}{dX}\int_0^\infty UVR\,dR = -\int_0^\infty \frac{\partial P}{\partial R} R\,dR \tag{13}$$

$$\int_0^\infty U\theta R\,dR = 1 \tag{14}$$

which relate the four non-dimensional dependent variables, U, V, θ and P, to the two non-dimensional independent variables, X and R. We can therefore write

$$\begin{aligned} U &= f_1 (X, R) \\ V &= f_2 (X, R) \\ \theta &= f_3 (X, R) \\ P &= f_4 (X, R) \end{aligned} \tag{15}$$

These functional relationships are to be determined experimentally.

EXPERIMENTAL INVESTIGATION

The circular ring flame is provided by a circular ring burner set flush with the horizontal asbestos platform at the center of the test cage located in the central portion of a large laboratory room. The circular ring burner is of plate steel construction, 6 inches deep and 1 inch in opening width, and measures 29 inches in diameter at the center line of the opening. A layer of fine mesh stainless steel screen is stretched across the opening to act as a flame holder and a thin copper tubing is soldered onto each side of the burner top to provide a water-cooling jacket to prevent the burner body from overheating. A distribution tank supplies a propane-air mixture to the burner through thirty-two evenly spaced inlets at the bottom of the burner. To further ensure the uniform distribution of combustible mixture along the opening of the burner, steel wool wigs are used to fill the lower portion of the burner.

The test cage is a rectangular steel frame structure 6 feet long, 6 feet wide and 12 feet tall. A horizontal asbestos platform with a 1 inch wide, 29 inch diameter circular opening for the ring burner is set at a level about 3 feet above the floor and covers the whole horizontal cross section of the cage. The vertical surfaces of the cage are covered with a layer of aluminum window screen to reduce the undesirable disturbances from the surrounding air. 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. Parallel to but 2 feet away from each side of the cage, a vertical baffle wall, 10 feet wide and extending from 2 feet to about 8 feet above the floor, is set to further reduce the undesirable disturbances from the surrounding air.

A traverse mechanism for carrying the temperature and velocity measuring probe is set on one side of the cage. This mechanism is capable of traveling up and down vertically from the level of the platform to a level approximately 60 inches above the platform and in and out horizontally covering the entire length of the cage. A protected slot is cut in the screen and in the baffle wall on the side of the traverse mechanism to make possible the motion of the mechanism.

The temperature and velocity measuring probe used in this investigation consists primarily of a V-shaped hot wire and a thermocouple. The hot wire is a piece of pure nickel wire, 0.002 inch in diameter and about 5/16 inch in total length, soldered to three stainless steel wire supports in a 60-degree V shape. A copper-constantan thermocouple is put slightly behind but directly above the hot wire. The probe assembly can be remotely rotated around its axis which remains horizontal but perpendicular to the axis of the probe carriage of the traverse mechanism. A combined constant current of 0.6 amperes is maintained in the two sections of the hot wire by a steady direct current source and the electrical potential changes at the three terminals are compared by an outside circuit. When the readings are properly calibrated against the local time-mean static temperature, the probe measures the magnitude and direction of the local time-mean velocity as well as the local time-mean temperature. The calibration of the probe is carried out with the aid of a calibration tunnel which produces an air stream of known velocity and temperature.

The flame established at the ring burner in all cases encountered in this investigation is found to be fairly uniform in height along the peripherical length of the burner and leans toward the burner axis at such a small angle relative to the horizontal plane of the platform that it seems to lie on the platform. The average flame lengths vary from about 1 1/2 inchs for the weakest flame to about 3 inches for the strongest flame. The propane-air ratio of the combustible mixture supplied to the ring burner is so adjusted that the flame becomes faint blueish in color. Measurements of the time-mean temperature, $T(x, r)$, and the axial and the radial components of the time-mean velocity, $u(x, r)$ and $v(x, r)$ respectively,are made at consecutive radial stations across the plume at eight selected heights above the platform. Measurements are not made at levels lower than the lowest of the selected levels to prevent the probe from being overheated. The temperature measurements at the lowest selected levels are checked against those made with a thermocouple with radiation shield for the detection of possible influence on the readings due to the radiation heat transfer from the flame to the probe. It is found that these two measurements agree closely with each other in all cases. The total vertical heat flux across the horizontal plane at each fixed height, Q, is then computed by performing a numerical integration of the measured axial velocity and temperature distributions according to Equation (9). For each of the three plumes investigated, the computed values of Q at various levels are not found to differ significantly from each other, and the average values of Q are thus established to be 9.95 $^{Btu}/_{sec.}$, 29.6 $^{Btu}/_{sec.}$, and 35.2 $^{Btu}/_{sec.}$ for the three plumes respectively. The corresponding values of the characteristic velocity ω are then 1.64 $^{ft}/_{sec}$, 2.36$^{ft}/_{sec}$, and 2.50 $^{ft}/_{sec}$ respectively. Examples of experimental results of the axial velocity, the radial velocity, and the temperature increment are plotted in Figures 2, 3, and 4 respectively. The corresponding generalized results are plotted in Figures 5, 6, and 7 respectively. Results of the plume characteristics are plotted in Figure 8.

From these plots, several observations can be made about the general behavior of the plume above a circular ring flame. For the ranges of the non-dimensional variables covered, the experimental results are found to support the suggestion of the universal distributions from the theoretical consideration as expressed by Equations (15), and reveal the functional forms of the distributions of the axial and radial velocities and the temperature increment. For higher levels covered, the maximum of either the axial velocity or the temperature across a horizontal plane is found to fall along the axis as in the case of the plume above a simple flame. However, for lower levels covered, the axial velocity distribution has a significantly flatened region around the axis and the maximum of the temperature profile is found to be at a radial station significantly away from the axis. The radial velocity distribution, on the other hand, seems to have an approximately similar outlook for all levels with a maximum at some radial distance away from the axis.

CONCLUDING REMARKS

Several comparisons can be made on a qualitative basis between the results of this investigation and those of the only available full-scale fire tests reported by Countryman [7].

a. In large fires, it was observed that the movement of fire front through the fuel bed and the transport of firebrands were the two most important mechanisms for the spread of a fire. In the case of a fire with a tilted convection column, there was a marked difference in the width of the region of fuel bed ignited by radiation from the flame, 3 to 5 feet on the wind ward side to less than 15 feet on the downwind side. These observations strongly support the proposition that the natural convection plume flow field plays an important role in the spread of a fire which has led to this investigation.

b. Small subatmospheric pressures were detected in the wake of a tilted large fire. This observation supports the arguments concerning the pressure field in the theoretical consideration of the convection plume of this investigation.

c. In large fires, normally ambient air is entrained into the plume However, in the case of a fire with a strongly tilted convection plume, wind blowing out of the plume has been observed. This observation agrees qualitatively with results of this investigation on the distribution of lateral velocity as described in Figure 6.

d. Fragmentary temperature and velocity measurements above the middle of the opening between two burning blocks in a simulated city fire indicate that the velocity increases drastically while the temperature decreases drastically with height in the convection flow field. These observations agree qualitatively with results of this investigation on the distributions of vertical velocity and temperature as described in Figures 5 and 7 respectively.

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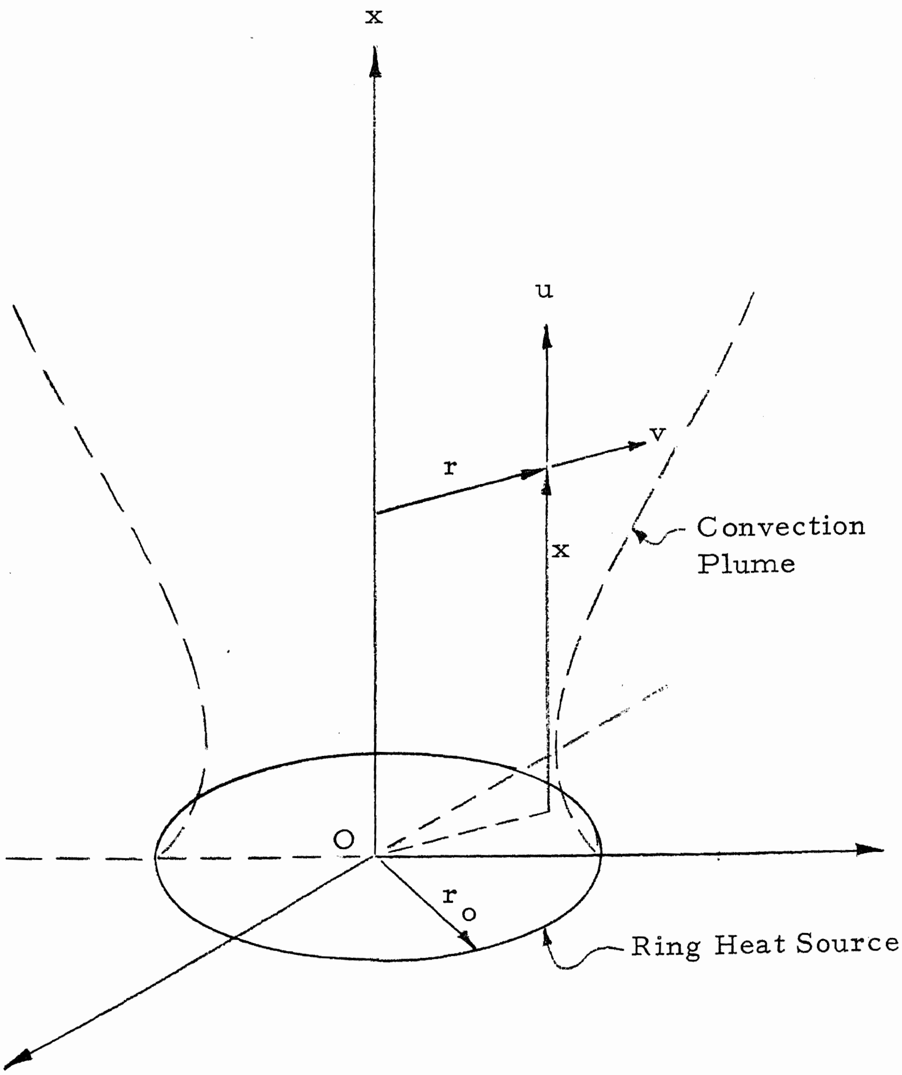


Figure 1. Definition Sketch

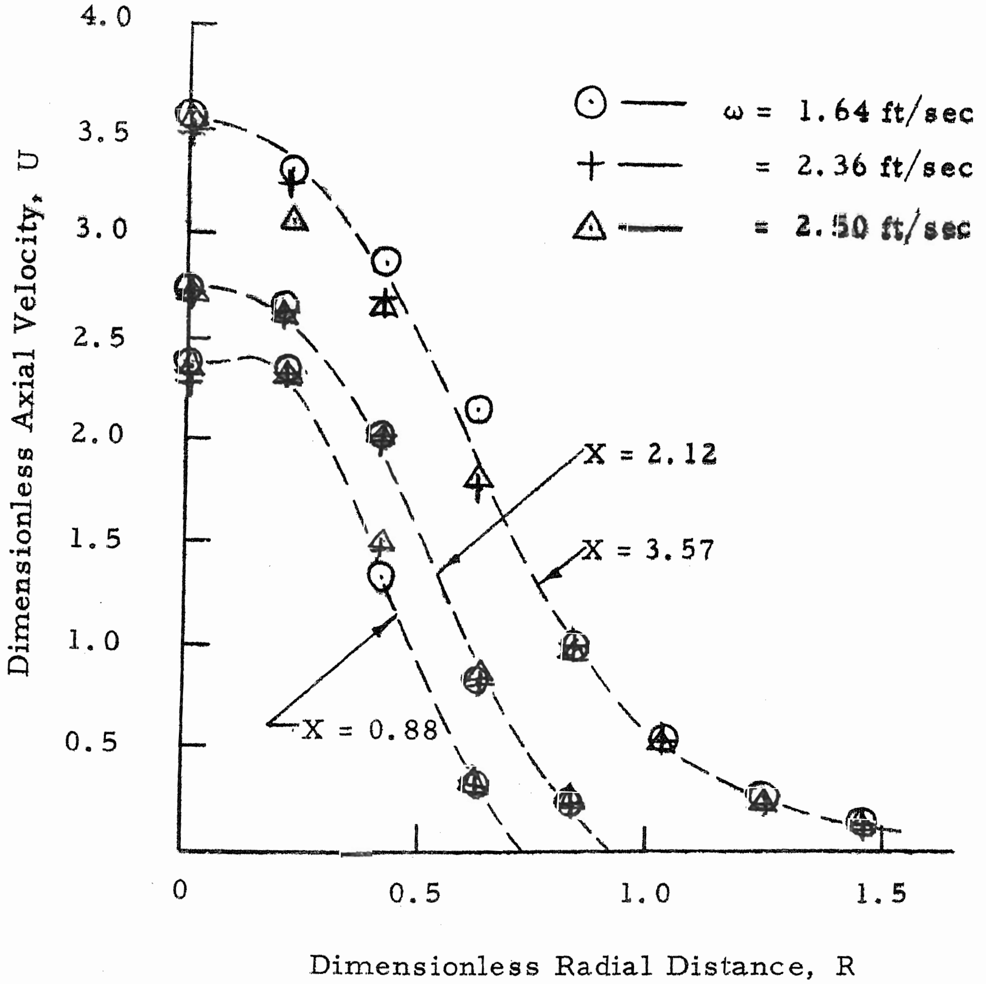


Figure 2. Examples of Experimental Results of Axial Velocity

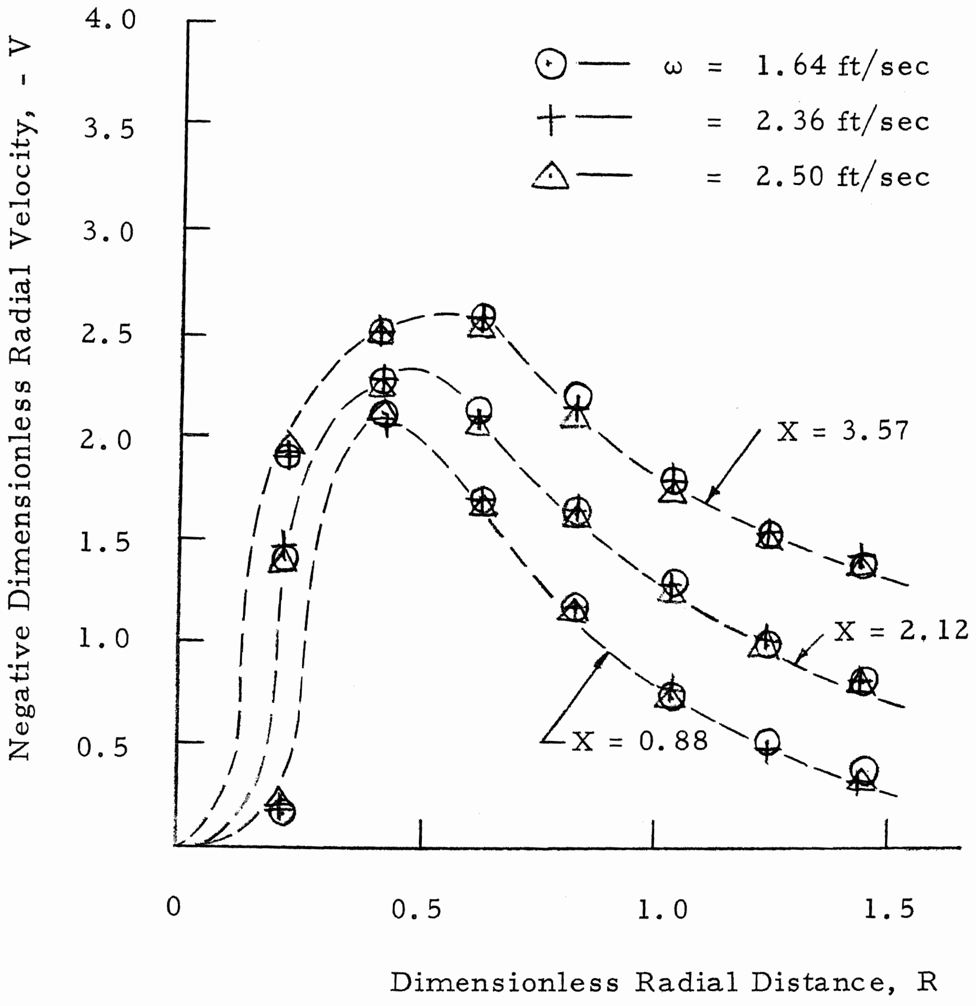


Figure 3. Examples of Experimental Results of Radial Velocity

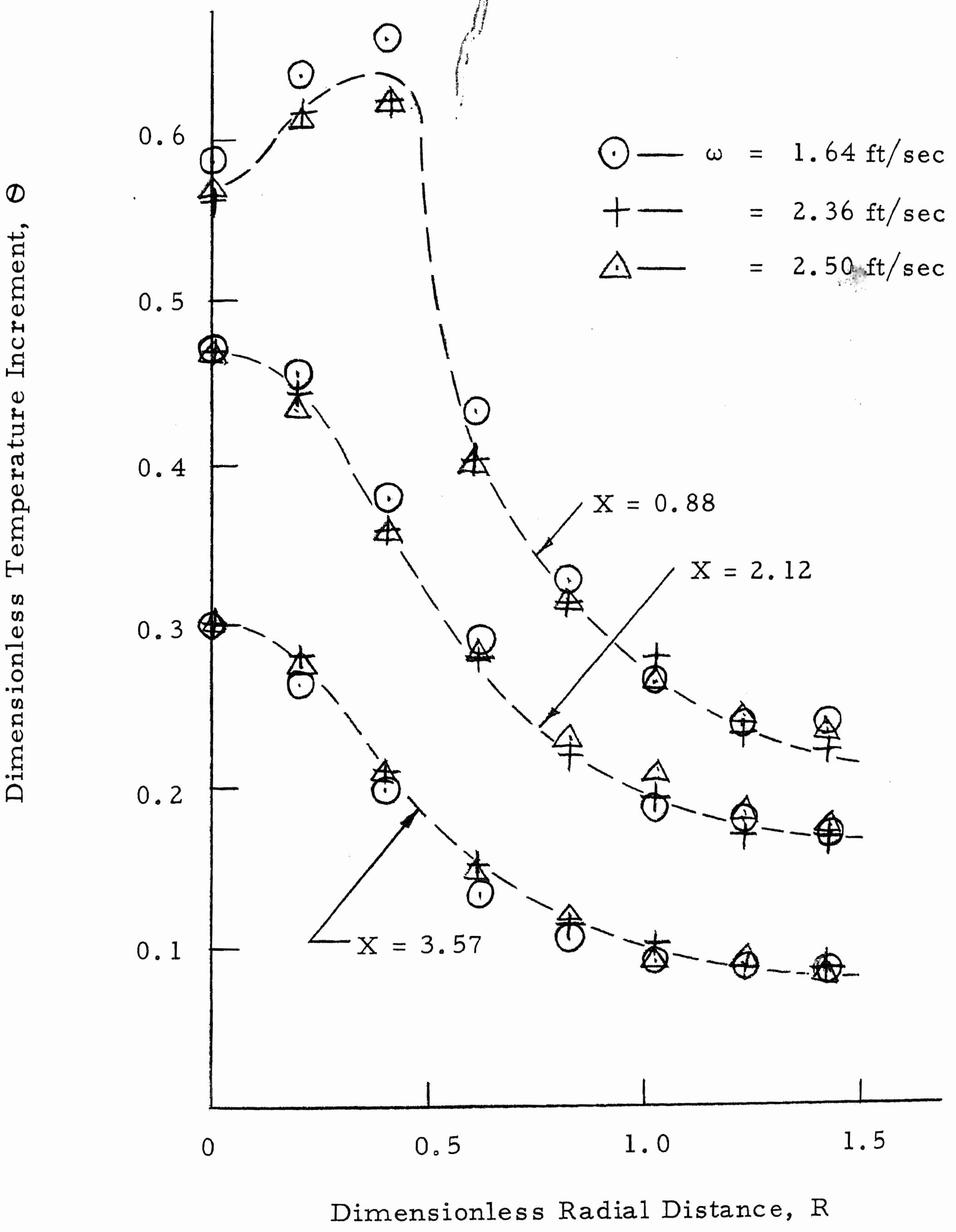
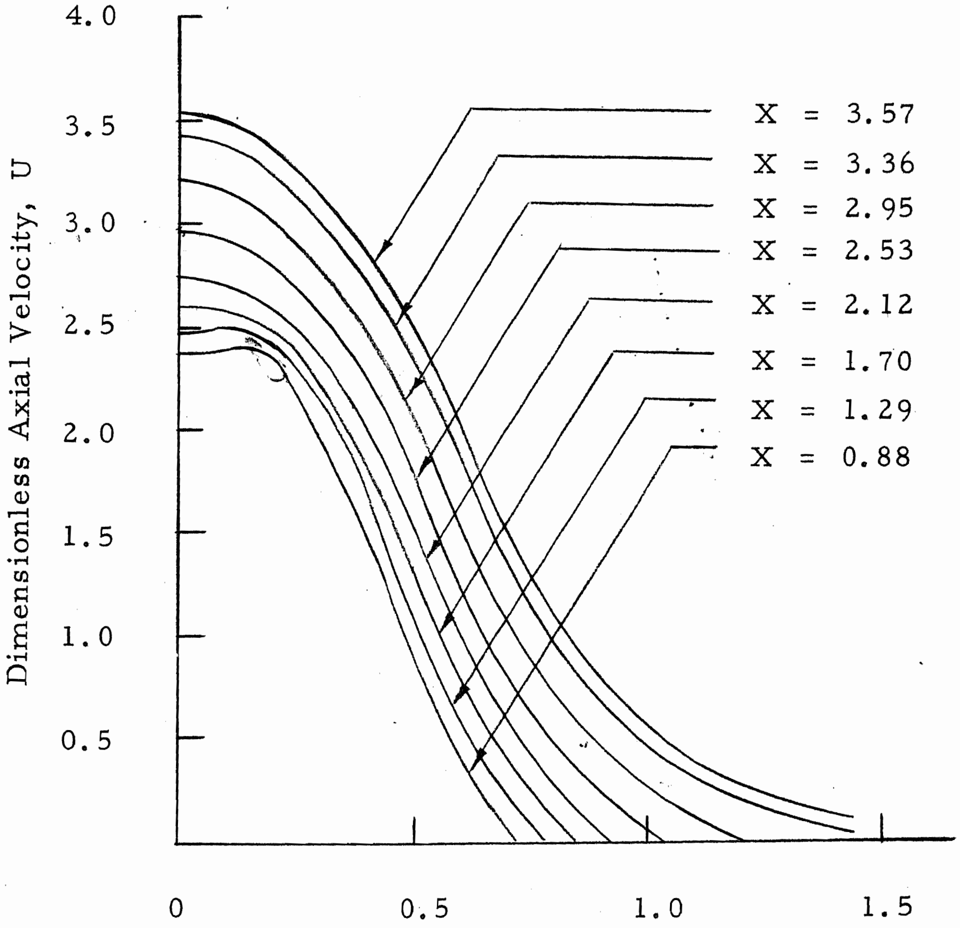


Figure 4. Examples of Experimental Results of Temperature Increment



Dimensionless Radial Distance, R

Figure 5. Generalized Experimental Results of Axial Velocity

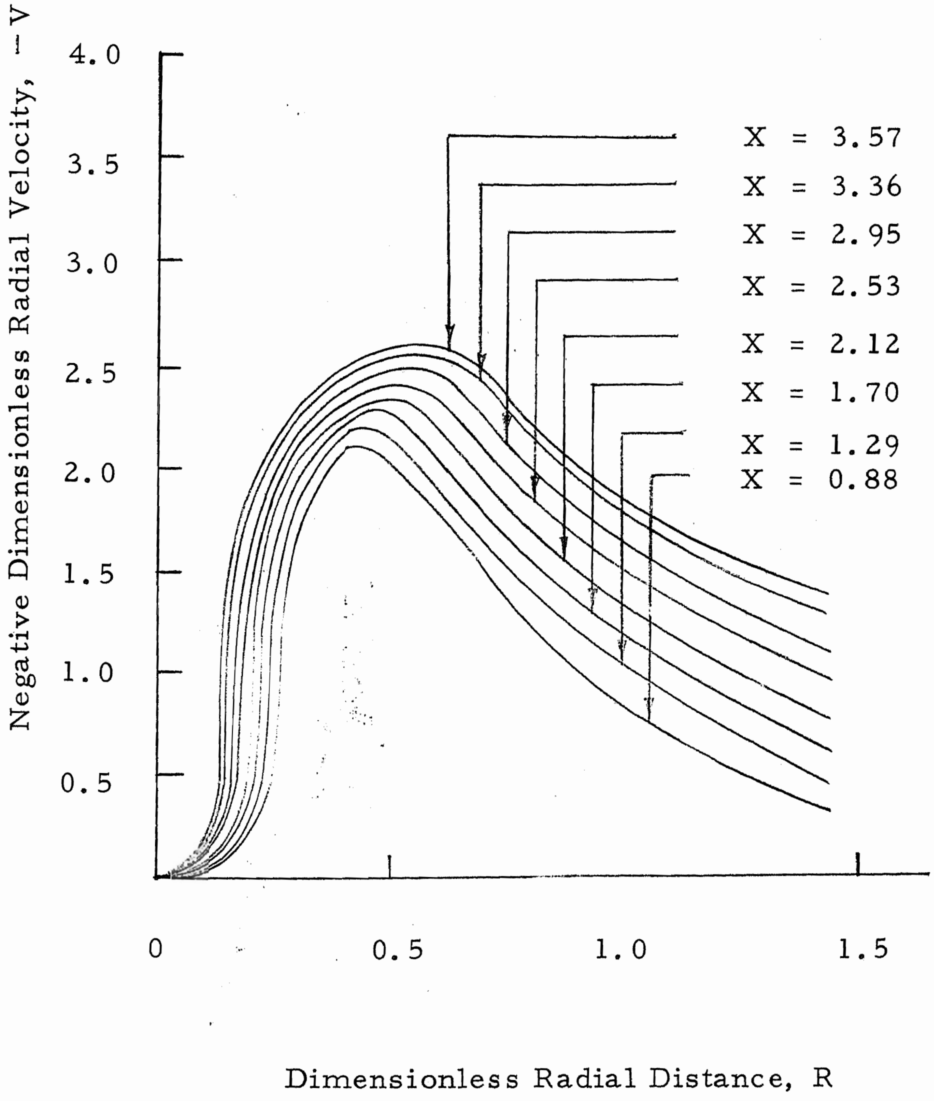


Figure 6. Generalized Experimental Results of Radial Velocity

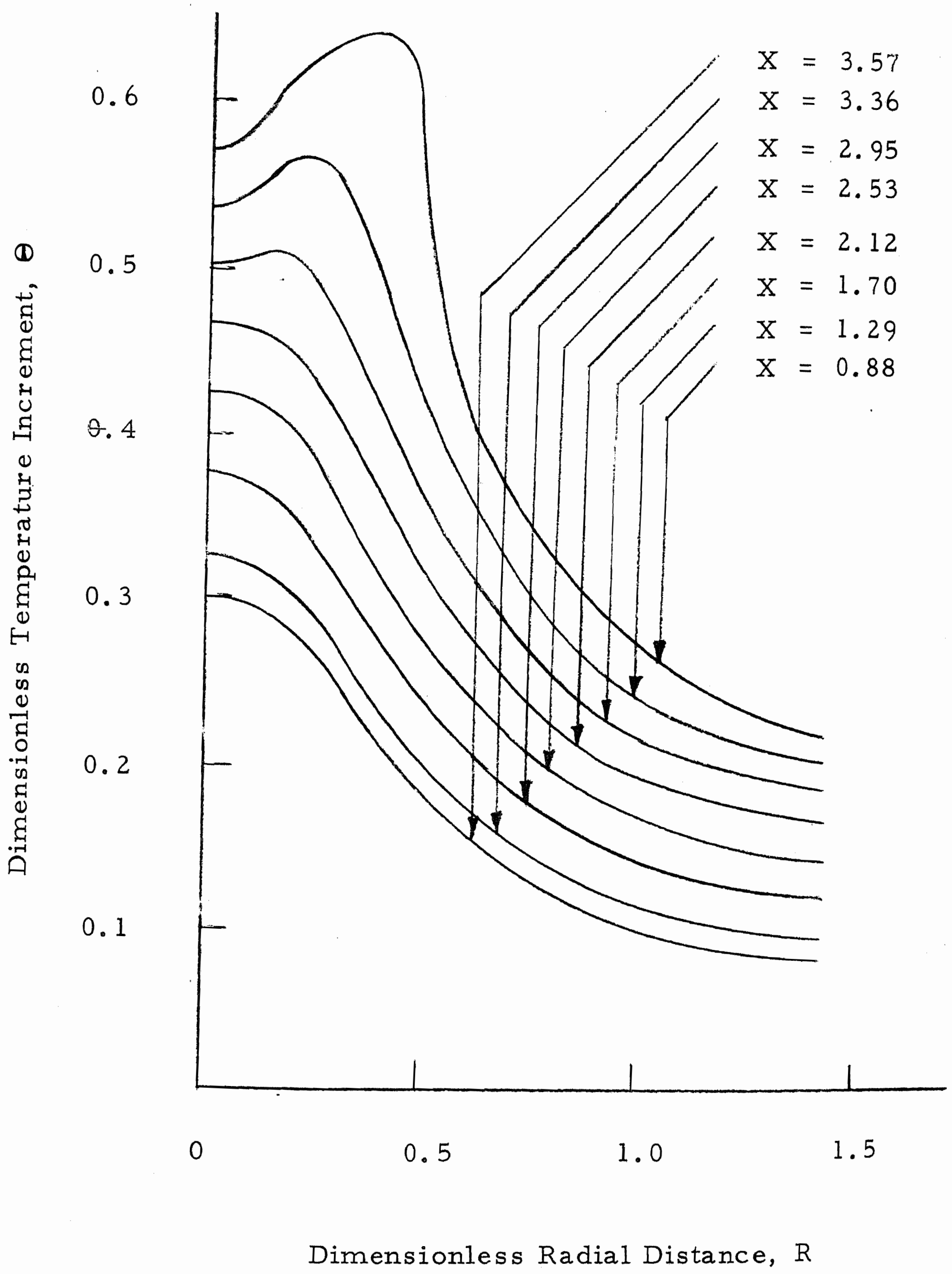


Figure 7. Generalized Experimental Results of Temperature Increment

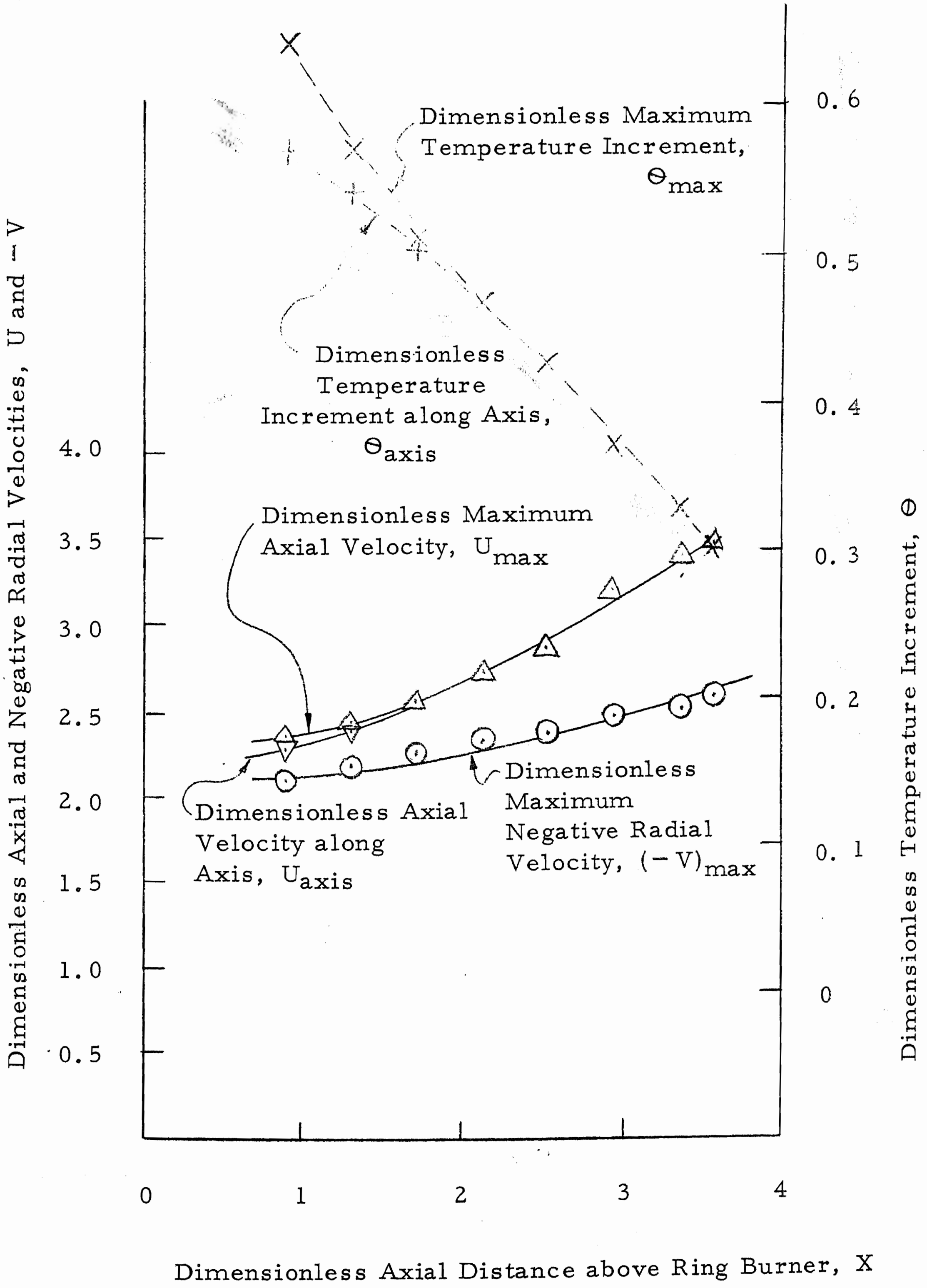


Figure 8. Results of Plume Characteristics