STATE UNIVERSITY OF NEW YORK
AT STONY BROOK

COLLEGE OF
ENGINEERING

Report No. 61

THE ROLE PLAYED BY NATURAL CONVECTION

IN A FREE BURNING FIRE

by

Richard Shao-lin Lee
(Shao-lin Lee)

MARCH 1966

3176 - 2 - 17

THE ROLE PLAYED BY NATURAL CONVECTION

IN A FREE BURNING FIRE[*]

By

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

PREFACE

Investigations contained in the present report were originally carried out at the North Carolina State University, Raleigh, North Carolina, under the sponsorship of the National Science Foundation in the form of a two-year research grant (NSF - G 24455) entitled "Convection Plume Above a Diffusion Fire" over the period of from July, 1962 through June, 1964. The additional portion of the work has been performed since then at the State University of New York at Stony Brook, Stony Brook, New York. The person in charge of all of these endeavors is the author, Richard Shao-lin Lee (Shao-lin Lee).

The research projects quoted here can be placed in the following categories in the projected table of contents:

Topic: 1. Studies of ignition and growth of fire

(including heat transfer).

Subtopic: c. In forested environments.

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 effort. 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 fuel bed 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. 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. Therefore, a thorough understanding of the natural convection flow field associated with a free burning fire is of utmost importance in the control of such a fire.

Investigations of this report can be classified into four different categories:

a. An axisymmetrical swirling plume.

b. The plume above a circular ring fire.

c. Interaction between two parallel line fires.

d. An elliptical plume.

A list of technical papers resulting from these investigations can be found in the attached references.

AN AXISYMMETRICAL SWIRLING PLUME

A free burning fire releases thermal energy due to chemical reactions which heat up the products of combustion as well as some amount of the entrained ambient air to form a natural convection plume above the fire. The plume in turn will induct fresh air and fuel into the fire for further combustion. In an unobstructed atmosphere, the inducted air will move radially toward the axis of the fire while in the meantime its direction will be lifted upward when its temperature is raised due to either being heated by or mixing with the hotter gases from the fire. On the other hand, it has been established in laboratory experiments that a fire whirl can be formed when some amount of circulation is introduced in the ambient air either by employing a ring of directional vanes to guide the inducted air or by rotating a vertical circular screen coaxial with the fire. From the results of some recent full-scale experiments, it is observed that quite frequently an intensely burning fire develops into a fire whirl as a result of the whirling motion of the entrained air within a relatively restricted vertical region close to the ground. Consequently, in the region above, the flow situation can be visualized as that of a swirling natural convection plume spreading into the stationary ambient air.

A Swirling Turbulent Jet (Reference 1)

To pave the way for the study of a swirling plume, the seemingly less complicated problem of a swirling jet was first studied. A swirling jet presents the interesting combination of the motion of a free jet and the motion of a rotating fluid, each of which presents a complex problem by itself. The situation is complicated further by the fact that under most circumstances the flow field becomes turbulent. A simple closed form solution has been obtained for such a jet issuing into a motionless ambient fluid by introducing the assumptions of similar axial and swirling velocity profiles and lateral entrainment of ambient fluid into the integrated governing equations following the Kármán integral method. Results for the decays of the axial and swirling velocities and the spread of the jet agree closely with the existing experimental findings on the velocity fields of a swirling round turbulent jet of air generated by flow issuing from a rotating pipe into a reservoir of motionless air.

Theoretical Study of a Swirling Plume (Reference 2)

A theoretical investigation is made of the behavior of an axisymmetrical turbulent swirling natural convection plume in an otherwise motionless ambient fluid. With the introduction of the assumption of similar axial and swirling velocity profiles and similar buoyancy profiles, and the assumption of lateral entrainment of ambient fluid, the order of the governing differential equations is reduced by one after

6

the initial integration following the Kármán integral method. The behavior of the swirling plume is found to depend solely on two physical parameters associated with the source characteristics, the source Froude number and the source swirling velocity parameter which has the form of the reciprocal of a source Rossby number. A series solution developed in the vicinity of the source of the swirling plume is obtained for any values of these two physical parameters. Numerical solutions for extended range of axial distance from the source of the swirling plume and for wide ranges of selected representative values of these two physical parameters are obtained with the use of a digital electronic computer. The behavior of the swirling plume is found to approach that of a non-swirling jet, a swirling jet, or a non-swirling plume when these two physical parameters are assigned values approaching those designating each of the aforementioned simpler, boundary situations.

Experimental Study of a Swirling Plume (Reference 3)

An experimental investigation is made of the behavior of an axisymmetrical turbulent swirling natural convection plume in an otherwise motionless ambient fluid. The swirling plume is issued from the exit of a swirling plume generator which couples the hot gases from a Bunsen burner flame and the swirling mass of air from a ring of distributed tangential jets. Temperature and velocity fields of the swirling plume are measured by the use of a temperature-

calibrated, V-shaped hot-wire probe. Measured results of the vertical and swirling velocities, the temperature, and the characteristic radius of the swirling plume are found to agree closely with the theoretical predictions.

THE PLUME ABOVE A CIRCULAR RING FIRE

According to a recent exploratory investigation using full-scale large fires, 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 main interest of that investigation is to examine 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. We can 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, it will gradually develop into a large, intense fire. Later on, as the front of the fire keeps 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 region 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. The spread of such a fire for the above mentioned reasons will depend very much on the convection currents above a circular, essentially ring-shaped intense flame. The same line of reasoning can also be applied to the case of a ring flame propagating into the unignited interior region.

Natural Convection Plume Above a Circular Ring Fire (Reference 4)

From the theoretical consideration, the non-dimensional axial velocity, radial velocity, temperature increment and pressure increment are dictated to be sole functions of the nondimensional axial and radial coordinates. In the experimental investigation, temperature and velocity measurements of the plume above the propane air flame from a thin circular ring burner are made with a copper-constantan thermocouple and a specially calibrated, V-shaped hot-wire annemometer. Results are reduced to universal nondimensional forms as suggested by the theoretical consideration, and are found to agree qualitatively with fragmentary data from existing full-scale large fire tests.

INTERACTION BETWEEN TWO PARALLEL LINE FIRES

Investigations of the turbulent natural convection plume above two parallel line heat sources were originated in World War II in connection with a method of using two parallel lines of petrol burners as a means of

vertical and the horizontal velocity profiles were made respectively with a thermocouple and a V-shaped, temperature-calibrated hot-wire for the plume above two parallel line fires of equal strength and for the plume above two parallel line fires of non-equal strength. Similar measurements were also made for the plume above a line fire facing a parallel vertical wall inserted at a desired location of the imagined plane of symmetry for the comparison of the case of the two fires and the case of one fire facing a vertical wall. Results are put into non-dimensional form and discussed.

Interaction Between Two Parallel Line Fires (Reference 6)

An experimental investigation was made of the angle of inclination of two long parallel line fires confined between two parallel vertical insulated walls in a direction perpendicular to the line fires. Results reveal that such angles depend very sensitively on the distance between the line fires, the combined heat flux per unit length of the two line fires, and the ratio of the heat fluxes of the two line fires. Over the range of these parameters covered by this investigation, the weaker fire is found in all cases to incline at a very small angle from the horizontal towards the stronger fire while the stronger fire inclines at an angle from the vertical towards the weaker fire depending sensitively on the values of the aforementioned parameters. In fact, a flame amplifier is obtained in this experimental investigation.

The experimental results are properly non-dimensionized based on the aforementioned parameters and a set of universal plots have been obtained.

AN ELLIPTICAL PLUME

Plumes of simpler geometries such as axisymmetrical and two-dimensional plumes have been extensively studied, both theoretically and experimentally, and satisfactory results have been found. However, the geometrical shape of a natural convection plume suggested by nature, such as that above a forest fire, very seldom falls into the category of being either axisymmetrical or two-dimensional. With the knowledge already gained for both the axisymmetrical and the two-dimensional plumes, a plume of the elliptical geometry would seem to be the next logical step in the general direction of studying plumes of more compli-cated geometry. A problem involving an elliptical geometry will cover much more ground than one involving either an axisymmetrical geometry or a two-dimensional geometry. But, an elliptical geometry still main-tains the nice property of geometrical symmetry and thus makes the theoretical analysis of the problem comparatively less formidable. On the other hand, the elliptical geometry can be degenerated into the simpler geometries. The existing solution of each of these boundary situations will then serve as a check for the solution of the elliptical problem.

An Elliptical Jet (Reference 7)

To pave the way for the study of an elliptical plume, the seem-
ingly less complicated problem of an elliptical jet, although itself by
far a very complicated problem in the field of jets, was first studied
both theoretically and experimentally. In the theoretical investiga-
tion, a generalized entrainment assumption was introduced into the
Kármán procedure and simple closed form solutions were obtained.
In the experimental investigation, the velocity field was measured of
an air jet issuing from an elliptical nozzle. Theoretical and experi-
mental results were found to agree with each other.

Theoretical Investigation of an Elliptical Plume (Reference 8)

With the assumption of similar velocity and buoyancy profiles
and a generalized assumption of the lateral entrainment of ambient
fluid, the complexity of the analysis was greatly reduced. The behav-
ior of the elliptical plume was found to depend solely on two physical
parameters associated with the source characteristics, the source
Froude number and the source eccentricity parameter which was the
ratio of the characteristic minor to major axes of the source. Numeri-
cal solutions for extended range of axial distance from the source of
the plume and for wide ranges of selected representative values of these
two physical parameters were obtained with the use of a digital
electronic computer.

The behavior of an elliptical plume will asymptotically approach that of an axisymmetric plume at large axial distances in all ranges of these two physical parameters. Furthermore, the behavior of an elliptical plume actually approaches that of an axisymmetrical plume, a two-dimensional plume, or an elliptical jet when these two parameters are assigned values approaching those designating each of these simpler boundary cases.

Experimental Investigation of an Elliptical Plume (Reference 9)

An experimental investigation was made of the behavior of a turbulent natural convection plume above an elliptical propane-air flame from an elliptical burner in an otherwise motionless ambient air. Temperature and velocity fields were measured with the use of a temperature-calibrated, constant-current hot-wire probe. Results for three different plumes on the decays of the maximum velocity and the maximum temperature and the spread of the plume as characterized by a characteristic major semi-axis and a characteristic minor semi-axis were found to agree closely with the theoretical predictions.

REFERENCES

A List of the Completed Reports on Research Done under the Support of National Science Foundation Research Grant No. NSF-G 24455:

1. "Axisymmetrical Turbulent Swirling Jet", Shao-lin Lee, Journal of Applied Mechanics, Vol. 32, Series E, No. 2, 258-262, June, 1965.

2. "Axisymmetrical Turbulent Swirling Natural Convection Plume, Part I, Theoretical Investigation", Shao-lin Lee. Accepted for publication by Journal of Applied Mechanics. Also State University of New York at Stony Brook College of Engineering Report No. 57, November, 1965.

3. "Axisymmetrical Turbulent Swirling Natural Convection Plume, Part II, Experimental Investigation", Shao-lin Lee. Accepted for publication by Journal of Applied Mechanics. Also State University of New York at Stony Brook College of Engineering Report No. 58, November, 1965.

4. "Natural Convection Plume Above a Circular Ring Fire", Shao-lin Lee and Chi-hai Ling. Accepted by 11th International Symposium on Combustion, 1966. Also State University of New York at Stony Brook College of Engineering Report No. 60, January, 1966.

5. "Turbulent Natural Convection Plume Above Two Parallel Line Diffusion Flames", Shao-lin Lee and Yi-chien Wu, in preparation for publication.

6. "An Experimental Investigation of Interaction Between Two Parallel Line Diffusion Flames", Wen-chen Huang and Shao-lin Lee, in preparation for publication.

7. "Elliptical Turbulent Jet", Shao-lin Lee, in preparation for publication.

8. "Elliptical Turbulent Natural Convection Plume, Part I - Theoretical Investigation", Shao-lin Lee, in preparation for publication.

9. "Elliptical Turbulent Natural Convection Plume, Part II - Experimental Investigation, Shao-lin Lee, in preparation for publication.