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In order to finalize this agreement and make final payment, the following documents are required by this office,close of business:March 31,1992.
Closeout documents were due 31 May 91.

Reference: ~~[illegible]~~ GRANT **#NOO014-90-J-2001**

____ Final Voucher,Contractor's Assignment of Refunds,Rebates,and Credit,Contractor's Release

____ Final Report required by PATENT Right Clause DD Form 882

__X__ Final Technical Report or transmittal letter and SF Form 298

____ Final Property Inventory- A negative reply is required if appropriate

____ Certification that Disposal of Classified Material is complete

____ Final Federal Cash Transaction Report (SF 272) and a Summary of Grant Costs

____ Financial Status Report

Any funds excess to the requirements of the agreement should be promptly reported to the contract administrator.

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I. OBJECTIVE

The objective of this research is to develop a fundamental understanding of the behavior of buoyancy controlled axi-symmetric gas flames and liquid pool fires, in both an open and enclosed environment. Specifically, we attempt to simulate two-dimensional axi-symmetric profiles of the velocity, temperature, species, and soot concentration. Knowing these profiles, we can determine the main characteristics of the flame: the heat feed back which in turn determines the mass burning rate of a liquid pool, the height of the flame, and the power output of the fire to the surrounding environment.

II. ACCOMPLISHMENTS

(December 15, 1989 - December 31, 1990)

A. Numerical simulation of vapor phase behavior of liquid pool fires.

In previous work we have developed a general model for examining pool-like gas flames and obtained promising results. Our work considered simplified model elements such as a parabolic flow field, a $\kappa-\epsilon$ turbulence model, a phenomenological soot formation scheme, and a radiation flux model using the absorption and emission coefficients for the soot plus gas mixture derived from a weighted-sum gray gas model. The conservation expressions for all of the variables for an axi-symmetric flame are written using boundary layer forms of Navier-Stokes equations and conservation expressions for the energy, species, turbulence, and mean square fluctuation of scalar properties. The model requires certain empirical input quantities such as the flame base absorption and emission details, the initial conditions for turbulence, the radiative fraction, the completeness of combustion, and soot formation parameters, etc. Details of our model have been presented several times in previous proposals and papers.

In this contract period four liquid fuels have been considered based on their widely varying thermochemical and fuel combustion properties. The liquid fuels are methanol (a non-sooting oxygenated fuel), kerosene and petrol (sooting, moderately burning hydrocarbon fuels), and benzole (a fast burning, sooting hydrocarbon fuel). A considerable amount of data on these fuel fires have been reported in the literature for comparison with our results.

Our numerical model was successful in reproducing the mean temperature, velocity and species fields which in turn confirm well established scaling laws. The agreement of experiment with predicted flame shapes, soot formation and radiation behavior were encouraging. A comprehensive analysis of the structure of these pool flames revealed certain basic features unique to pool fires; namely, the visible flame volume and flame reaction volumes have been observed to be proportional to the stoichiometric air requirement of the fuels (see Fig. 1). Furthermore, the volumetric air consumption rate of all the fuels are nearly constant irrespective of the nature of the liquid fuels. The volumetric heat release rates of all the hydrocarbon fuels are also similar.

A detailed analysis of the thermal radiation and convective transport behavior in these pool fires clearly indicate that the heat feedback flux is dominated by convection for the methanol fire while for the hydrocarbons fuels it is radiation. As shown by Fig. 2, the radiative feed back flux distribution at the blame base is very non-uniform. This is caused by radiative energy blockage by the cold fuel vapor and soot in the core.

B. The implication of elliptic flow behavior on the structure of pool fires

All of our previous work on pool-like gas flames as well as that described in Sec. A above, assumed a parabolic flow field, and boundary layer forms of the Navier-Stokes equations as indicated above. In this work we examined the role of elliptic behavior on the near field pool flame structure for a pool-like methane flame with heat release rate of 28 kW (base diameter of 0.25 M). The Navier-Stokes equations and conservation expressions for all the variables in the elliptic form, not invoking a boundary layer assumption, are now solved for an axi-symmetric buoyant turbulent flame utilizing an alternating tridiagonal matrix algorithm method.

The results for the field quantities (velocity and temperature) and flame shapes were compared with experimental results and with predictions from the parabolic model in Figs. 3 through 5. The analysis confirms that some parts of the flame, particularly near the pool base, are not adequately treated within a parabolic model; however, the parabolic model does appear to give reasonable results near the center line. It also does appear to give the gross features of the flame structure throughout.

C. Comparison between experimental and theoretical results for air entrainment in a heptane pool fire.

The entrainment of air into pool fires is induced by the buoyant upward flow of hot gases, which are replaced by the cold ambient air drawn into the flame zone. Air entrainment is one of the important properties in pool fires, which influences the burning rate, velocity and temperature distributions in flames.

In this work, we examined the air entrainment behavior in a heptane pool fire for different diameter pool sizes using our theoretical model as described briefly above. The dimensionless air entrainment rate is defined as M_O/M_S, where M_S denotes the theoretical air entrainment rate needed for complete combustion of the vaporized fuel and M_O is the actual air entrainment rate. Fig. 6 shows this ratio plotted vs. the dimensionless height H/R, where H and R are the height above the liquid surface and pool radius respectively. The agreement with experiment is not good, particularly above $H/R > 3$. This disagreement may be due to the parabolic formulation used in our theoretical model, or perhaps due to experimental measuring difficulties arising from flame fluctuations; but most probably it is due to some more fundamental aspect of our model. Obviously more work is required in this area.

III SUMMARY

Our accomplishments during this contract year can be summarized as follows:

1. We have performed numerical simulations of the vapor phase behavior of various liquid pool fires.

2. We have studied the implications of elliptic flow on the structure of pool fires, and

3. We have compared experimental and theoretical results for air entrainment in a heptane pool fire.

These accomplishments have been communicated in the following papers:

1. "Direct numerical simulation of vapor phase behavior of liquid pool fires and analysis of flame structure", and

2. "The implications of elliptic flow behavior on the structure of pool fires",

Both of these manuscript were submitted to the 23rd International Symposium on Combustion, but were not accepted. They still need to be modified for submission to other journals.

During this period the following paper was published:

3. "Numerical Predictions for a Simulated Methane Fire", K.C. Adiga, D.E. Ramaker, P.A. Tatem and F.W. Williams, Fire Safety Journal 16, 443, (1990).

and the following manuscripts submitted:

4. "A Comprehensive Theoretical Analysis of Fires Over Liquid Pools", K.C. Adiga, D.E. Ramaker, P.A. Tatem, and F.W. Williams, submitted to Fire Safety Journal.

5. "A Theoretical Treatment for Heptane Pool Fires", K.C. Adiga, D.E. Ramaker, P.A. Tatem, and F.W. Williams, submitted to Fire Safety J.

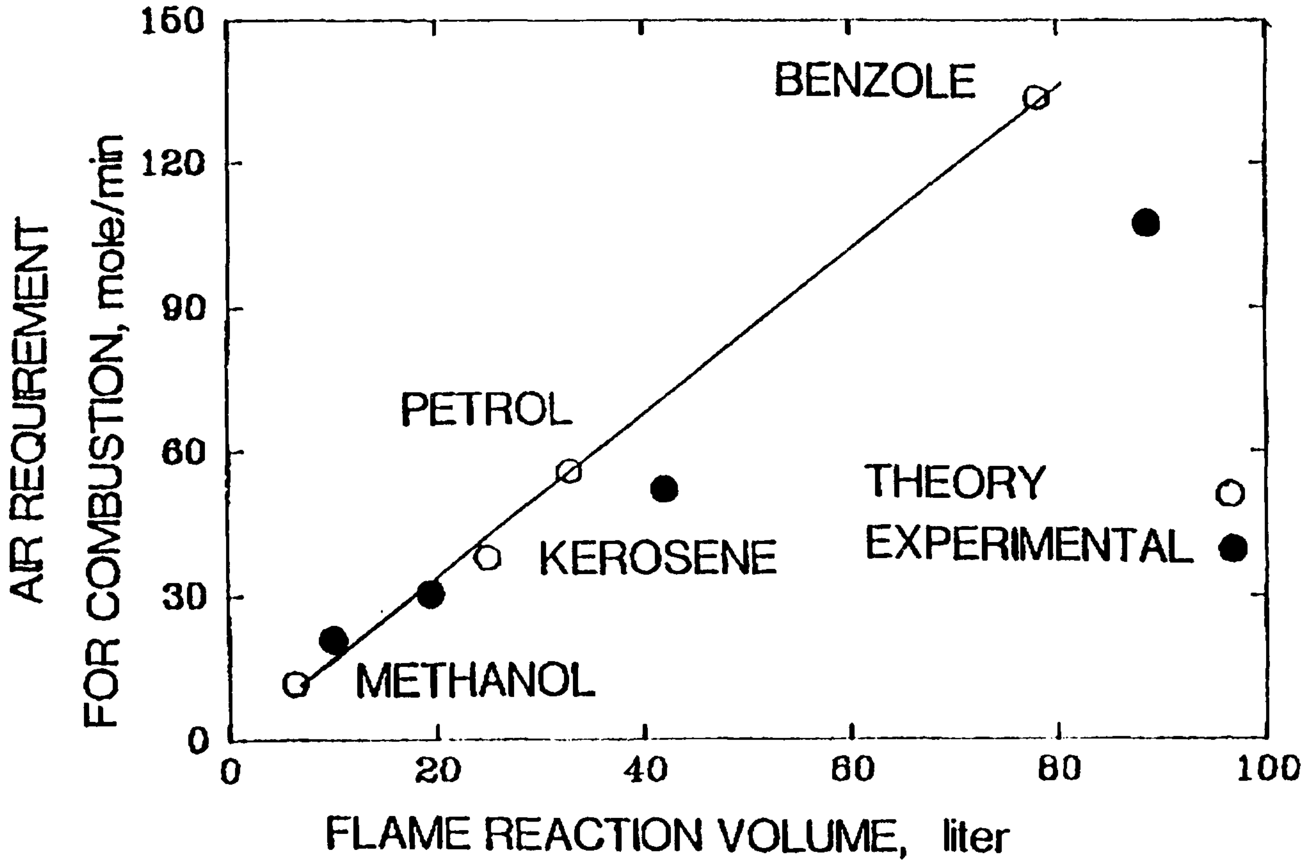
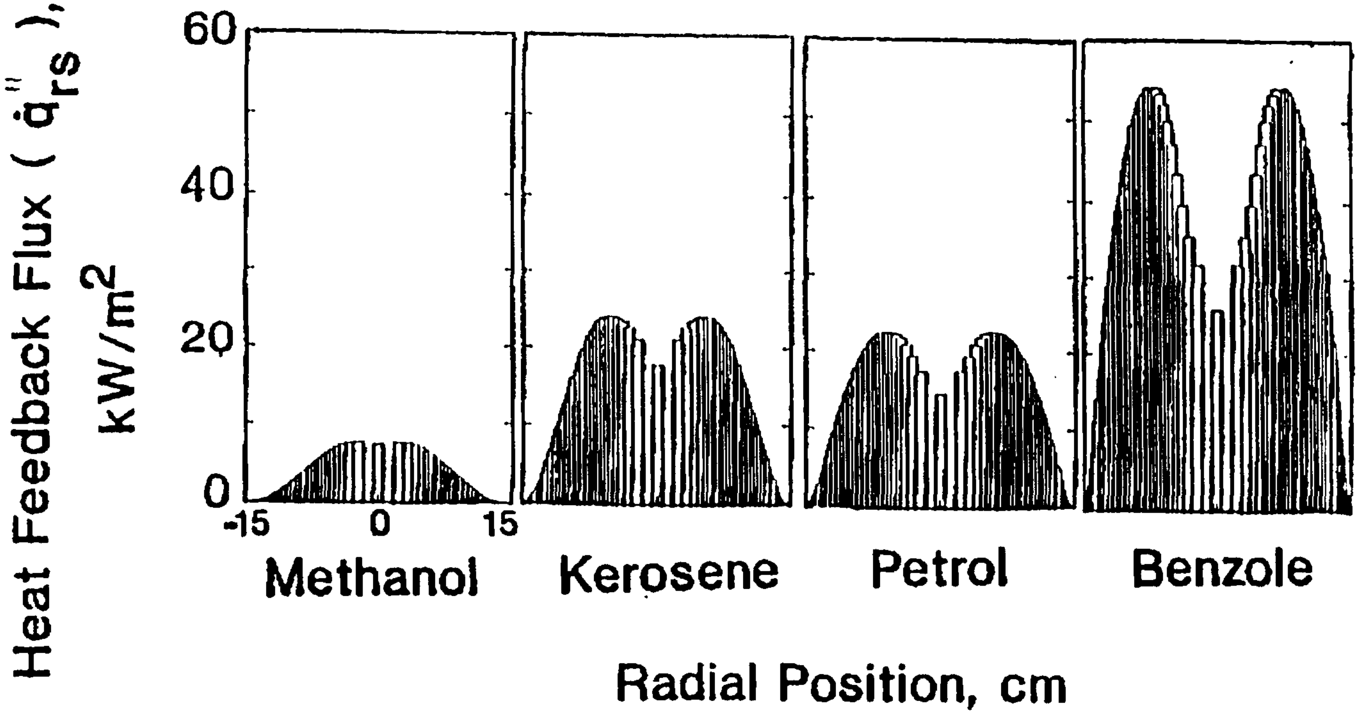

AIR REQUIREMENT FOR COMBUSTION, mole/min
160
120
90
60
30
0
BENZOLE
PETROL
KEROSENE
METHANOL
THEORY
EXPERIMENTAL
0
20
40
60
80
100
FLAME REACTION VOLUME, liter

Figure 1.



Heat Feedback Flux ($\dot{q}''_{rs}$), kW/m^2
60
40
20
0
-15
0
15
Methanol
Kerosene
Petrol
Benzole
Radial Position, cm

Figure 2.

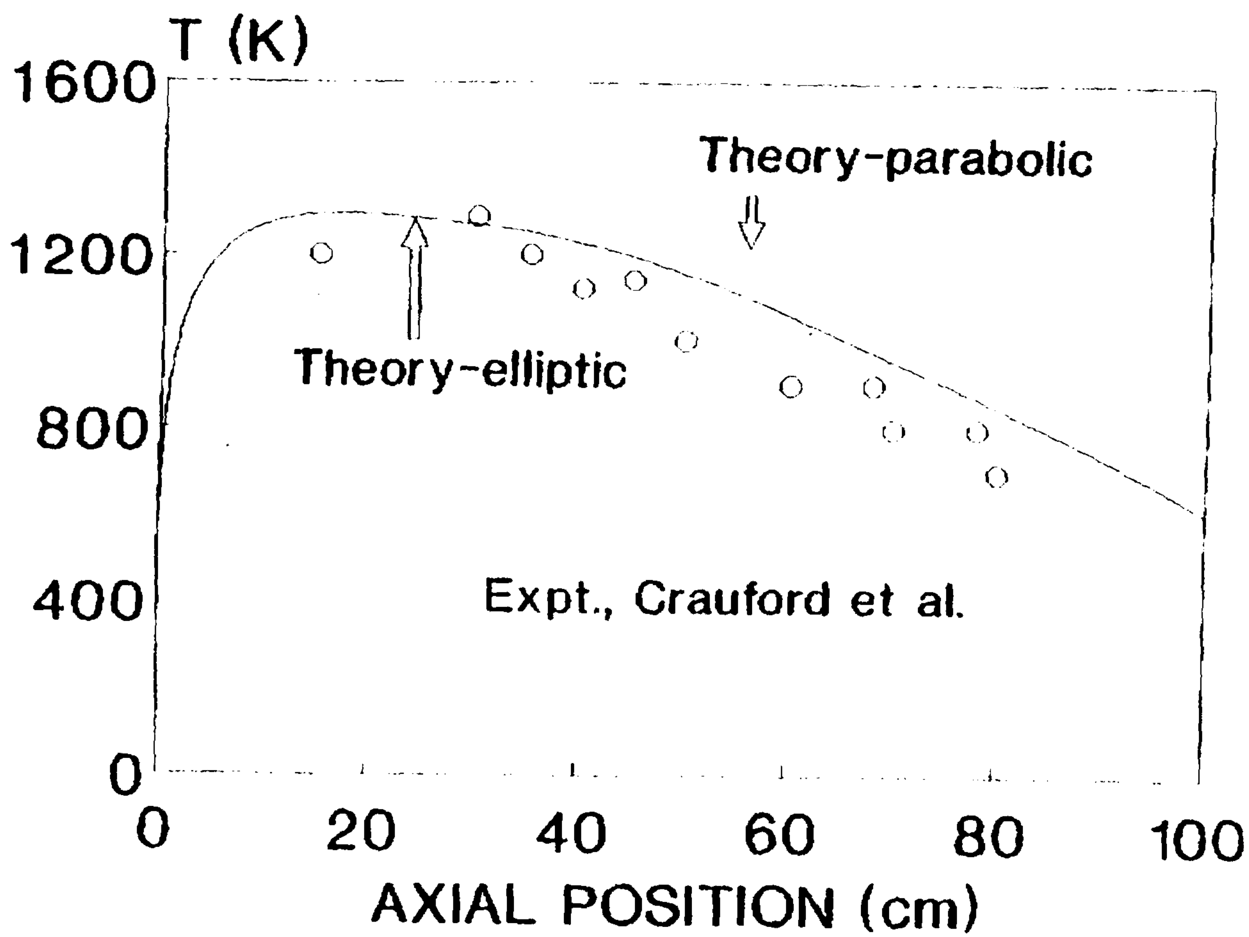

T (K)
1600
1200
800
400
0
Theory-parabolic
Theory-elliptic
Expt., Crauford et al.
0
20
40
60
80
100
AXIAL POSITION (cm)

Figure 3.

8

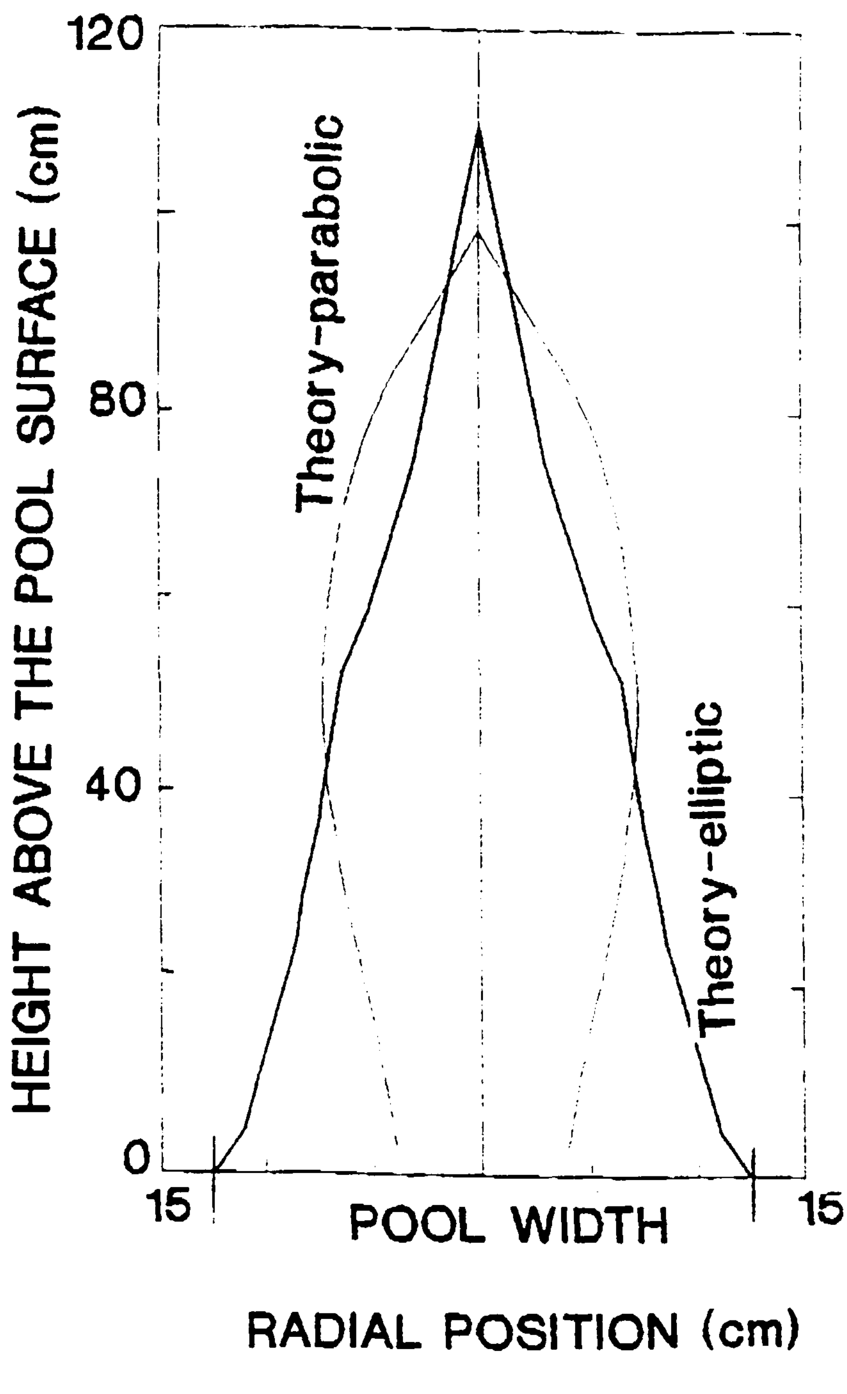

120
80
40
0
HEIGHT ABOVE THE POOL SURFACE (cm)
Theory-parabolic
Theory-elliptic
15
15
POOL WIDTH
RADIAL POSITION (cm)

Figure 4.

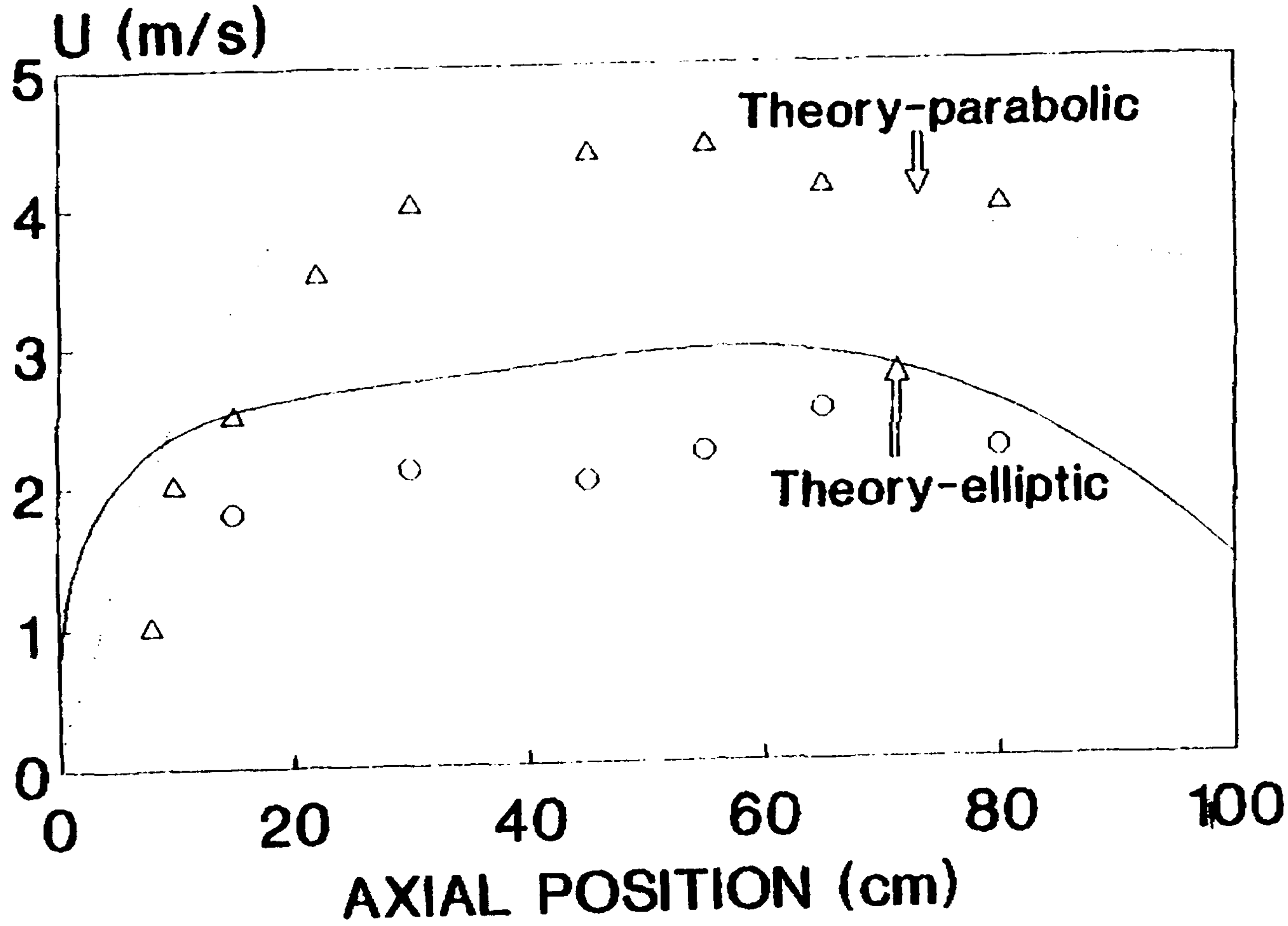

U (m/s)
5
4
3
2
1
0
0
20
40
60
80
100
AXIAL POSITION (cm)
Theory-parabolic
Theory-elliptic

Figure 5.